

Scientific Research with the

(NASA-CP-2111) SCIENTIFIC RESEARCH WITH THE SPACE TELESCOPE: INTERNATIONAL ASTRONOMICAL UNION COLLOQUIUM NO. 54 (NASA) 331 p MF A01; SOD HC CSCL 03B

N80-22130
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N80-22144
Unclas
63/88 46716



Space Telescope

IAU Colloquium

Number 54

NASA CP-2111

**SCIENTIFIC RESEARCH WITH
THE SPACE TELESCOPE**

International Astronomical Union
Colloquium Number 54
Co Sponsored by COSPAR

Held at the Institute for Advanced Study
Princeton, N.J. August 8-11, 1979

M.S. LONGAIR
Mullard Radio Astronomy Observatory
Cavendish Laboratory
Cambridge, England

J.W. WARNER
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama

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DEDICATED TO THE MEMORY OF

ROBERT E. DANIELSON

1931 - 1976

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PREFACE

This volume contains the proceedings of IAU Colloquium No. 54, "Scientific Research with the Space Telescope." The editors feel no need to describe the nature of the colloquium or its scientific significance since these are eloquently described by Professor Lyman Spitzer in his opening remarks.

The formal scientific programme of the colloquium lasted 3½ days and consisted of 7 sessions of three hours. The 14 invited lectures delivered surveys of broad fields of importance for observations with the Space Telescope, each presentation lasting about 45 minutes. The remaining 45 minutes of each half-session was coordinated by a discussion leader who, besides keeping contributors to the discussion in order, generally commented on the subject area. We have included all the questions and discussion in this volume since the fields covered in the surveys were very broad and the discussions complemented the main presentations. We have concentrated upon scientific matters concerned with the astronomical and astrophysical use of the Space Telescope. Many of the contributors to the discussion kindly provided us with written versions of their comments. In other cases, the comments were transcribed, abridged and edited by the editors from the tapes of the discussion. Any misrepresentation of the significance of these comments is the fault of the editors who herewith offer their apologies in advance. We have not included discussions of purely technical questions concerning the operation of the telescope and its scientific instruments nor of the way in which the Space Telescope project will be organised in the operational phase. Discussion of many of these topics insofar as they are understood in mid-1979 can be found in the article by Bahcall and O'Dell, "The Space Telescope Observatory," which is included in the present volume. The contents of this article were not described in the formal sessions but were the subject of a lively discussion on the evening of Wednesday, August 8, 1979.

We are also fortunate in being able to include the address entitled "NASA In-House Astronomers Capabilities - Verse and Converse" given by Dr. Hinners, former NASA Associate Administrator for Space Science, at the banquet on the evening of Friday, August 10, 1979.

We are particularly grateful to all the invited lecturers for having responded so positively to our request that they provide us with camera-ready versions of their presentations. We have also received generous help and support from many other people. Mary Wisnowsky, the colloquium coordinator, solved all problems at superluminal velocity. In particular, she arranged for the preliminary typing of many of the hand-written comments by her expert staff. Don Hortenbach and his assistants ensured that the discussion was recorded and participants discreetly requested to write down their significant contributions. Molly Jones and Marion Childs typed all the discussions with amazing accuracy and speed at Cambridge. Virginia Bobo completed the typing of preface, contents, list of participants, etc. We thank all these people for their efforts which we greatly appreciate.

MSL also thanks Mr. and Mrs. A. K. Longair for hospitality in Ottawa during the period immediately following the General Assembly of the IAU in Montreal when the bulk of the scientific editing of the proceedings was completed.

Finally, we gratefully acknowledge the generous efforts of the Marshall Space Flight Center which has taken on the responsibility of publishing and disseminating the colloquium proceedings speedily and efficiently.

Malcolm Longair
John Warner

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J. AUDOUZE	Paris
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W. A. BAUM	Lowell Observatory
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S. VAN DEN BERGH	Dominion Astroph. Observatory
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R. C. BLESS	University of Wisconsin
R. C. BOHLIN	GSFC
A. BOKSEBERG	U College, London
R. M. BONNET	Verrières-le-Buisson
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P. CRANE	ESO, Geneva
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A. DOLLFUS	Paris
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N. HINNERS	Smithsonian Institution, Washington DC
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J. HUCHRA	Harvard
R. HUMPHREYS	University of Minnesota
G. ILLINGWORTH	KPNO
E. B. JENKINS	Princeton University
M. JURA	UCLA
F. J. KERR	University of Maryland
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R. KIRSHNER	University of Michigan
K. KODAIRA	Tokyo
H. C. VAN DE HULST	Leiden
P. VAN DER KRUIT	Groningen
V. G. KURT	USSR Academy of Sciences
H. VAN DER LAAN	Leiden

D. LAMBERT	University of Texas
C. LAURENT	Verrières-le-Buisson
D. S. LECKRONE	GSFC
J. LEIBACHER	Lockheed Research Lab.
P. O. LINDBLAD	ESO, Geneva
M. S. LONGAIR	Mullard Radio Astron. Observatory
F. MACCHETTO	ESA, Paris
H. W. MOOS	Johns Hopkins
D. MORRISON	University of Hawaii
D. C. MORTON	Anglo-Australian Observatory
A. G. OEMLER	Yale
J. B. OKE	Caltech
D. E. OSTERBROCK	University of California, Santa Cruz
J. P. OSTRIKER	Princeton University
T. C. OWEN	SUNY
F. PACINI	Florence
P. J. E. PEBBLES	Princeton University
M. PEIMBERT	University of Mexico
V. PETROSIAN	Stanford University
C. B. PILCHER	University of Hawaii
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M. TARENGHI	ESO, Geneva
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H. VAN WOERDEN	Groninger
D. G. YORK	Princeton University

OPENING REMARKS

Lyman Spitzer, Jr.
Princeton University Observatory
Princeton, New Jersey, U.S.A.

As Chairman of the Scientific Organizing Committee it is my responsibility to open this Colloquium on the scientific uses of the Space Telescope. The enormous astronomical potentialities of a large orbiting telescope constitute a fascinating subject that goes back more than half a century. H. Oberth, the German pioneer in rocketry, pointed out in 1923 the advantages of an orbital telescope, out in space where the stars do not twinkle and where ultraviolet and infrared radiation can be measured with negligible absorption. A trickle of interest in this topic can be followed through the ensuing 40 years. At two summer studies for NASA, in 1962 and 1966, the Space Telescope as we now visualize it, was first proposed and its astronomical advantages were discussed. In 1967 and 1968 an ad hoc committee, organized by the National Academy of Sciences, promoted a number of small seminars on how ST (then designated as LST, the "Large Space Telescope") could best be used in astronomical research. The first of these seminars was on extragalactic astronomy, the second on planetary research and the third on stellar, interstellar and galactic structure problems. A fuller discussion of these topics was held in 1974 at a symposium on the Large Space Telescope organized by the American Institute of Aeronautics and Astronautics. Talks on the ST and its uses have since been presented at other scientific meetings.

It seemed to the Scientific Organizing Committee that the present was an appropriate time for a fresh look at this problem. Congressional approval for the 2.4-meter Space Telescope was given in 1977, a favorable action which was due in large part to enthusiastic and strongly expressed support by the entire astronomical community. The design of the Telescope and its instruments is now in nearly final form. Indeed, rough grinding of one of the two quartz blanks for the main mirror is nearly complete. The characteristics of the instruments are now reasonably well known, although firm information will not be available until this pioneering observatory is operating in orbit. Launch of the Space Shuttle is confidently expected in late 1983. Now, in 1979, it seems time for individual astronomers to start laying definite plans for observing programs that they may propose for this facility. Some

proposals must be submitted almost a year before the launch of ST, and we hope that this Colloquium will encourage the proposal of imaginative and well considered research programs.

I should say a few words about the nature of the present meeting, which clearly differs from the normal scientific symposium in that there are essentially no scientific results to report. The emphasis is entirely on future plans. As you will note from the Program, a number of survey papers will be given on the types of research that can be carried out in different fields. The coverage of fields is deliberately not complete. To keep the size and length of the meeting within practical bounds we have deliberately omitted a number of fascinating and important areas of research, such as astrometry and stellar atmospheres, including the spectra of the close binary systems which produce X-rays.

Each survey paper for a particular area will be followed by a general discussion of how Space Telescope can best be used to increase our knowledge of astronomy in that area. We ask that participants do not attempt to present, during this discussion, research results which they have obtained. While astronomical research work in almost any field has some relevance to Space Telescope plans, we believe the discussion will be most useful if it is specifically directed towards the observations that Space Telescope can carry out and how they can be interpreted.

It is a pleasure to acknowledge our indebtedness to the organizations that have helped with this Colloquium and in particular to those which have provided financial support. The IAU has provided some travel funds, and a substantial NASA grant has provided partial financial support for some 20 participants. The two Patrons of the meeting, Lockheed and Perkin-Elmer, have made generous donations which will, I am sure, make the meeting much more memorable. As you all know, the Lockheed Missiles and Space Company has a contract for the Space Telescope system and is building the Support Systems Module, which provides power, communications, orientation and other necessary engineering functions, while the Perkin-Elmer Corporation is building the diffraction limited Ritchey-Chretien telescope in what is called the Optical Telescope Assembly. The financial support from these two Patrons is providing the concert tomorrow night, the cocktail party and banquet on Friday and other amenities for the meeting.

It is a pleasure also to acknowledge our indebtedness to Director Harry Wolf, Professor John Bahcall and, in general, to the Institute for Advanced Study, our hosts for this Colloquium. Mary Wisnovsky, Assistant to the Director of the Institute, and her staff have worked closely with Professor John Rogers and his Local Organizing Committee in all the detailed planning. Close collaboration in many of the arrangements has been provided by Donald Hortenbach, my Assistant at the University.

To conclude these introductory remarks I would like to inform you that the Scientific Organizing Committee has agreed to dedicate this meeting, and in particular the published Volume of the Proceedings, to Professor Robert E. Danielson, who played such an important role in the ST planning until very shortly before his death in April 1976. Bob's experience with the development and operation of Stratoscope II and the interpretation of the high-resolution images obtained on the Seyfert galaxy NGC 4151 and the planet Uranus gave him a unique background for assisting in plans with the ST. He was a member of the Space Telescope Working Group under Bob O'Dell during the period 1973-76. In this capacity he headed the Instrument Definition Team which formulated the scientific requirements for the imaging instruments on ST. It is this Team that drew up plans for the three cameras that are now part of the Space Telescope panoply of instruments, -- the f/24 Wide-Field Camera, the f/48 Planetary Camera and the f/96 Faint Object Camera. He also served as Chairman of the Committee on Space Astronomy under the Space Science Board of the National Academy of Sciences and played a central role in generating astronomical support of the ST. His imaginative and pathbreaking contributions to a program whose fruition he knew he would not witness provide for all of us an inspiring example of dedication and heroism.

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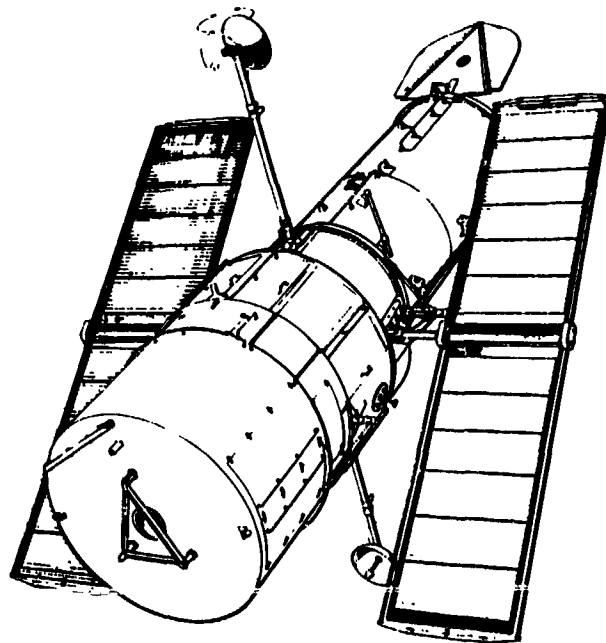
THE SPACE TELESCOPE OBSERVATORY

by

John N. Bahcall
Institute for Advanced Study, Princeton, N.J. 08540

and

C. R. O'Dell
Marshall Space Flight Center, Huntsville, Ala. 35812



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I. INTRODUCTION

The purpose of this review is to provide a convenient guide to the expected characteristics of the Space Telescope Observatory for astronomers and physicists. We have tried to provide enough detail so that a professional scientist, observer or theorist, can plan how the observatory may be used to further his observing program or to test theoretical models. Further detail is available in NASA documents that are referenced throughout this report.

The plan of this review is given below. The general objectives of the ST observatory are summarized in § II. The plans for the development of the observatory are described in § III; this section includes a brief history of the scientific activities; an account of the scope of the present program; a summary of the major responsibilities of the contractors; and a list of the project milestones. The overall performance characteristics of the observatory are given in § IV; these include imaging and stray light characteristics, pointing capability, and operational access. The expected performance characteristics of all six of the first-generation science instruments are summarized in § V. This section is intended to enable potential users of ST to decide whether or not observations which they would like to perform are feasible with the available ST instruments. The mode of operations is described in § VI, which includes a discussion of program options, guide star selection, methods of acquisition, and "quick-look" data capabilities. Section VII describes present plans for the Science Institute, including observer selection, scheduling, observational procedures, data handling, data archiving, and the acquisition and use of serendipity data.

II. OBSERVATORY OBJECTIVES

Large optical telescopes have often been supported on the basis of "bigger is better" or because of a scarcity of observing time. The Space Telescope program has had to provide (for sound political, technical and scientific reasons) a clear scientific rationale and also to develop a set of specific objectives in the area of performance and operations. We will discuss the goals in this section.

The performance goals can be stated as follows: Development of a telescope of at least 0.1 arcseconds resolution, capable of integrating images for 10 hours of observation, reaching a stellar magnitude of 27 m_v at a

signal-to-noise ratio of 10 in 4 hours, able to perform surface brightness photometry and to operate over the entire range of wavelengths from about 1150 Å to 1 mm. The expected operating lifetime of the ST Observatory is at least fifteen years.

The operations goals are less quantitative. Obviously, we must be able to control and receive data from the observatory. We must be able to point to any region of the sky and place the correct astronomical objects in the field of view of a scientific instrument, even if the entrance aperture is the same size as a stellar image. We must control the amount of light which enters the Space Telescope from the Sun, Earth, and Moon so that stray light does not become brighter than 23^m (visual), thus permitting the Space Telescope to be used for measurement of faint sources throughout much of each orbit.

An independent Space Telescope Science Institute will be responsible for the scientific aspects of operations. This means that the Science Institute must play an integral role in scheduling, in the execution of observations and in data reduction and analysis. The existence of an independent institute is expected to maximize the scientific usefulness of the ST and to provide the user community with fundamental input to the science operation.

III. DEVELOPMENT PLANS

A. History of the Scientific Activities

The NASA space telescope project was initiated officially by an advanced study activity in 1971-1972. This advanced study (Phase A) investigation was headed by a science steering group chaired by Dr. Nancy Roman of NASA Headquarters. The group consisted of approximately ten optical and space astronomers and engineers, including the following astronomers: A. Code, A. Meinel, C. R. O'Dell, J. B. Oke, L. Spitzer, A. B. Underhill, and E. J. Wampler. Representatives from various academic institutions, several NASA centers, and some industrial contractors assisted in this initial effort. The study confirmed the previously-expressed opinion of a number of astronomers that a large orbiting telescope in space would be both feasible and of great scientific importance. The results of this study are summarized in an interesting form (for the ST aficionado) in NASA Technical Memorandum TMX-64726, the Large Space Telescope Phase A Final Report, Vol. I (1972); this docu-

ment contains the justification for many of the decisions that have shaped the ST program.

The scientific definition (Phase B) study was led by Dr. C. R. O'Dell of Marshall Space Flight Center (and the University of Chicago). The study was conducted during the years 1973-1976. The scientific goals, mode of operation, and preferred instruments were defined during this Phase B activity by a panel of fourteen competitively chosen scientists who served on a space telescope working group. The scientific members of this working group included: J. N. Bahcall, R. Bless, A. Boggess, E. M. Burbidge, A. Code, R. Danielson, G. Field, L. Fredrick, G. Neugebauer, R. Noyes, C. R. O'Dell, N. Roman, L. Spitzer, Jr., and R. West. A readable summary of some of the early Phase B scientific and technical considerations are contained in the document Large Space Telescope - A New Tool For Science (1974).

The final Design and Development activities (Phase C and D) began officially in 1977. These activities will continue until the launch of the ST. The identification of the scientific requirements for the ST observatory is the responsibility of a Science Working Group (SWG), which is again headed by C. R. O'Dell. There are eighteen members of the SWG including principal investigators of the instrument development teams, the data and operations team leader, telescope scientists, and interdisciplinary scientists. The individual members of the SWG are listed in Appendix A. The SWG is assisted by individual instrument teams consisting of some 52 scientists and engineers under contract to NASA, which represent 26 separate academic or research institutions. The ST Project Manager has established several other working groups that assist in the design and development of the ST Program. The working groups which are of particular relevance to science operations include the Data and Operations Team, the Software Working Group, and the Missions Operations Working Group. In addition, the European Space Agency (ESA) has approximately 12 scientists and engineers working on their science instrument (the faint object camera).

B. Scope of the Present Program

The basic program policy is defined by NASA Headquarters, which also allocates the resources that can be used for developing ST. Several people at NASA headquarters have a continuing, frequent responsibility for helping to develop ST policy. These include the Associate Director for Space Science (Dr. N. Hinners until April 1979), as well as W. Keller, B. Norris, and N. Roman.

SPACE TELESCOPE CONFIGURATION

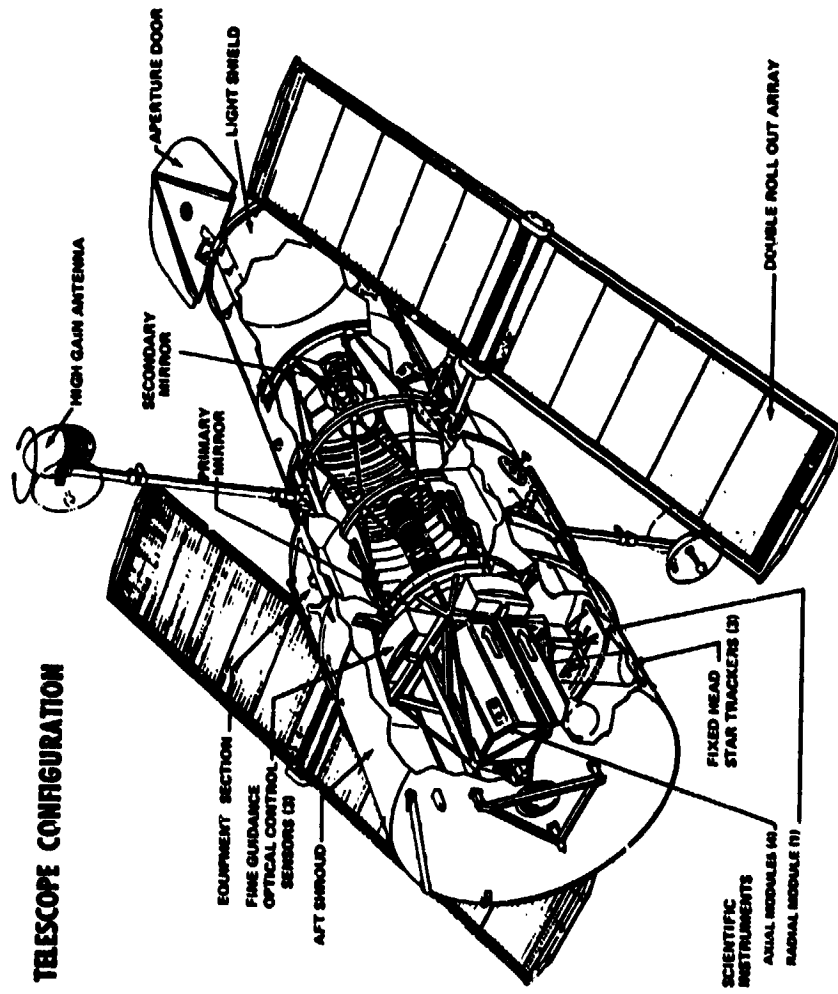


Figure 1. Space Telescope Configuration

The total program is expected to cost 0.44 billion dollars (1979 dollars), of which 0.09 billion dollars is to be used for designing, building and testing the scientific instruments and for interpreting the data obtained.

The overall responsibility for implementing the ST design and development rests with the Project Manager, Mr. W. Keathley, of Marshall Space Flight Center (MSFC). There are approximately one hundred people working on the ST project at the MSFC. The chief scientific advisor to Keathley is Dr. C. R. O'Dell, the Project Scientist; the chief engineer is Mr. J. R. Olivier (also of MSFC). The development of the scientific instrumentation is under the direction of Mr. G. Levin of the Goddard Space Flight Center (GSFC); the missions operations are under the direction of Mr. J. Martin (also of GSFC). There are approximately fifty people working at GSFC on problems related to the scientific instrumentation and mission operations. The ST advisory group for the ESA (the ST-WG) is chaired by Dr. F. Pacini, who reports to the Director General of ESA on all aspects of European participation in the ST program. When appropriate, Dr. Pacini also attends meetings of the NASA SWG; there are, in addition, three European members of the SWG, including the ESA Project Scientist, Dr. F. Macchetto.

C. The Contractors and their Responsibilities

For administrative purposes, the ST Observatory is considered to consist of four separate parts. These components are: (1). the Optical Telescope Assembly (OTA), the telescope itself (see § IV below); (2). the Scientific Instruments, (see especially § V below); (3). the Support Systems Module (SSM), the supporting systems that make possible the operation of the telescope, the scientific instruments, and the data handling equipment; and (4). the Solar Array, supplied by ESA, which provides the electrical power for the observatory. This is illustrated in Figure 1.

The principal contractor for the OTA is the Perkin-Elmer Corporation and for the SSM, the Lockheed Missiles and Space Corporation. The contractors are committing about 420 man years in fiscal 1979 to the development of the OTA and SSM. This number will increase to of the order of 700 man years in the peak contract year. The solar array is being built by British Aerospace under contract to the ESA. The scientific instruments were selected in 1977 by NASA after an extensive competition and peer review, which also

made use of the Phase B recommendations. Contracts with various suppliers have been negotiated by NASA and the Principal Investigators of the instruments. In one case, the High Speed Photometer, the instrument is being built in a university laboratory (at the University of Wisconsin). There are about 300 man years of contract effort involved in the design of the scientific instruments during fiscal 1978-1979.

The overall integration of the component parts is the responsibility of the NASA and is under the direction of the Project Manager.

D. Project Milestones (1979-1984)

The anticipated schedule of major events is shown in Table 1.

The Preliminary Design Review (PDR) of each of the scientific instruments was completed in January 1979. Each science team participated with a NASA evaluation committee in a review of how well the presently proposed instrument meets the original science goals and in an identification of the principal engineering and technical problems. The design recommendations must be approved by the Associate Administrator for Space Science. The Preliminary Design Review of the OTA was held in April 1979; the PDR for the spacecraft will occur in July 1979.

The Critical Design Reviews of the scientific instruments will be held in early 1980. The instruments which successfully pass this review will arrive at GSFC for initial testing in December 1981. The flight complement of instruments will arrive in November 1982 at Lockheed Missiles and Space Corporation (California) for integration with the other observatory components.

The entire ST observatory will be shipped to Cape Kennedy in October 1983 for an anticipated December 1983 launch.

An independent Science Institute (SCI) will operate the ST Observatory after launch, (see § VII for a detailed discussion of the SCI); an appropriate managing entity will be selected by NASA to oversee the SCI under contract to NASA. The request for proposals (RFP) for the SCI will be pre-released by NASA in July, 1979. The final RFP will be released by NASA in November 1979 (or somewhat later). Requests for clarifications and suggestions related to the

Table 1. Major Milestones (Tentative): 1979-1894

<u>Year</u>	<u>Mon' h</u>	<u>Event</u>
1979	January	Preliminary Design Review (PDR's) of Science Instruments
	April	PDR of the Optical Telescope Assembly (OTA)
	July	PDR of the spacecraft Pre-release of the Request for Proposal (RFP) of the Sci
	November	RFP for the Sci
1980	February	Sci proposals submitted
	January-April	Thermal Studies of the Instruments
	March	Critical Design Review
	May	RFP for the Combined Overall Ground System (COGS)
1981	November	Sci contract award
	March	COGS contract award
	December	Instruments arrive Goddard Space Flight Center (GSFC); begin testing.
1982	June	COGS hardware available for installation in Sci
	November	Science Instruments arrive Lockheed (California); mated to OTA
1983	September	Entire COGS available
	October	ST Observatory shipped to Cape Kennedy
	December	Launch

RFP may be submitted to NASA prior to the final release date. The proposals to manage the Sci at a designated site will be submitted to NASA in February 1979. It is expected that the Sci contract award will be made in November 1980.

The Combined Overall Ground System (COGS) will be supplied by a contractor to be selected by NASA by about March 1981. The COGS contractor will develop, for both the Sci and the Science Support Center (SSC) at GSFC, the following subsystems: major hardware (including automatic data processing equipment and operational consoles); software systems (except that developed by the PI's or Sci); and system engineering and integration. The COGS hardware for the Sci will be ready for installation in the Institute by June 1982. The entire COGS will be completed by September 1983.

E. Postlaunch Activity

After launch, the ST science program will be conducted by the Science Institute, which will operate (see § VII) in much the same way as do other national observatories and laboratories in the United States.

The ST may be visited from time to time, for maintenance and refurbishment, by Space Shuttle personnel. It is estimated that every two or three years, at least, repairs and maintenance will be carried out by a space-suited astronaut. Existing instruments may be replaced by new instruments. In addition, many support subsystems are replaceable in orbit. The Sci, with appropriate NASA headquarters support, will take the lead in encouraging the development by the outside scientific community of new instrumentation for the ST. Approximately every five years, the ST Observatory may be returned to the ground with the aid of the Space Shuttle for major refurbishment.

IV. PERFORMANCE OF THE OBSERVATORY

A. Imaging Performance

The true diffraction-limited telescope exists only in theory; any real telescope has some imperfections. In the Space Telescope program, the performance goals were brought as close as practical to the theoretical limit; any further increase in performance would cause the cost to rise rapidly. It is expected that the Ritchey-Chretien optical system will produce on-axis images with the point spread func-

tion shown in Figure 2. Images of this quality will be guaranteed throughout ten hours of exposure, which will be about 24 hours of clock time.

The Ritchey-Chrétien optical system produces excellent quality images over a large field of view. At large distances from the optical axis astigmatism begins to become important, although the images are very narrow in the sagittal or tangential surfaces. Figure 3 shows the change of the image radius (the radius containing 70% of the energy) across the field of view. The focal surface has been divided so that the central region feeds the radial scientific instrument bay, while the remainder of the inner region is shared by the four axial scientific instruments. The outer astigmatic region is used by the Fine Guidance Sensors for providing guiding signals from field stars and for performing astrometric measurements. The reimaging optics of off-axis instruments are capable of forming stigmatic stellar images.

Space Telescope optical performance has been specified at the same wavelength as it will be tested, $\lambda 6328 \text{ \AA}$. The performance at longer wavelengths should monotonically and quickly approach the diffraction limit; at shorter wavelengths, the improvement in image quality that is expected eventually becomes offset by the fact that the imperfections in the mirrors become larger fractions of these smaller wavelengths. Exactly where this transition from improvement to degradation occurs will not be certain until we know the final characteristics of the finished mirrors. We expect that below the transition wavelength the images will be approximately constant in size down to about 1200 \AA .

B. Stray Light

In its low earth orbit (from 500 to 600 km above the earth's surface), the Space Telescope will be moving rapidly between conditions of direct sunlight and earthlight into night operation. In order to make maximum use of each orbit, Space Telescope will employ an internal light baffle system that will diminish the stray-light effects to acceptable levels. The specification calls for stray light to be no brighter than $23^m / [^m]$ (Visual) whenever the distance from the sun is $\geq 50^\circ$, or $\geq 70^\circ$ from the bright limb of the earth or $\geq 15^\circ$ from the full moon. This level was set recognizing that the zodiacal light will be the primary source of background radiation and that it diminishes to a surface brightness of $23^m / [^m]$ (Visual) for two small regions in the antisolar hemisphere.

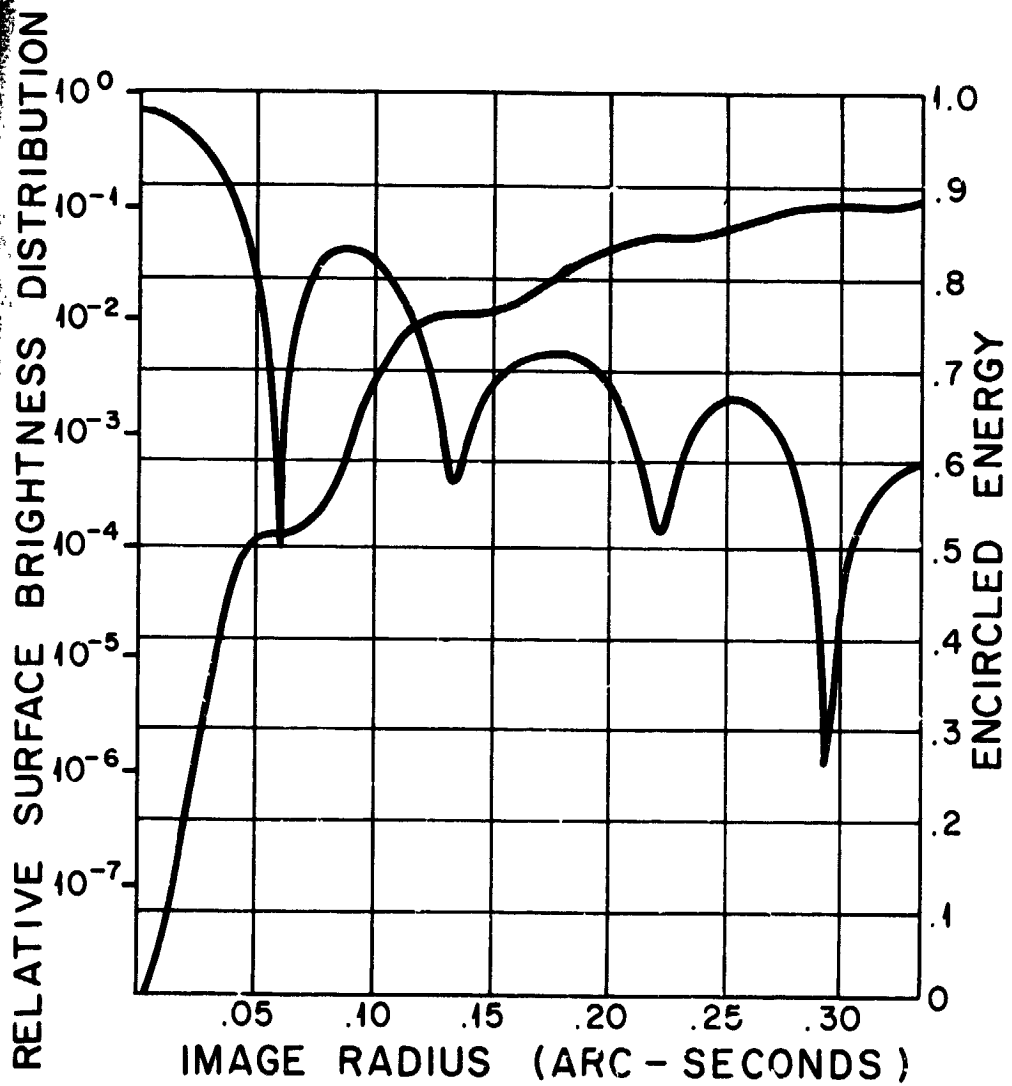


Figure 2: The expected optical performance ($\lambda 6328\text{\AA}$) is illustrated in terms of the image surface brightness distribution and the encircled energy. The central obscuration and deviations from perfect mirror figure and alignment have been incorporated in these predictions.

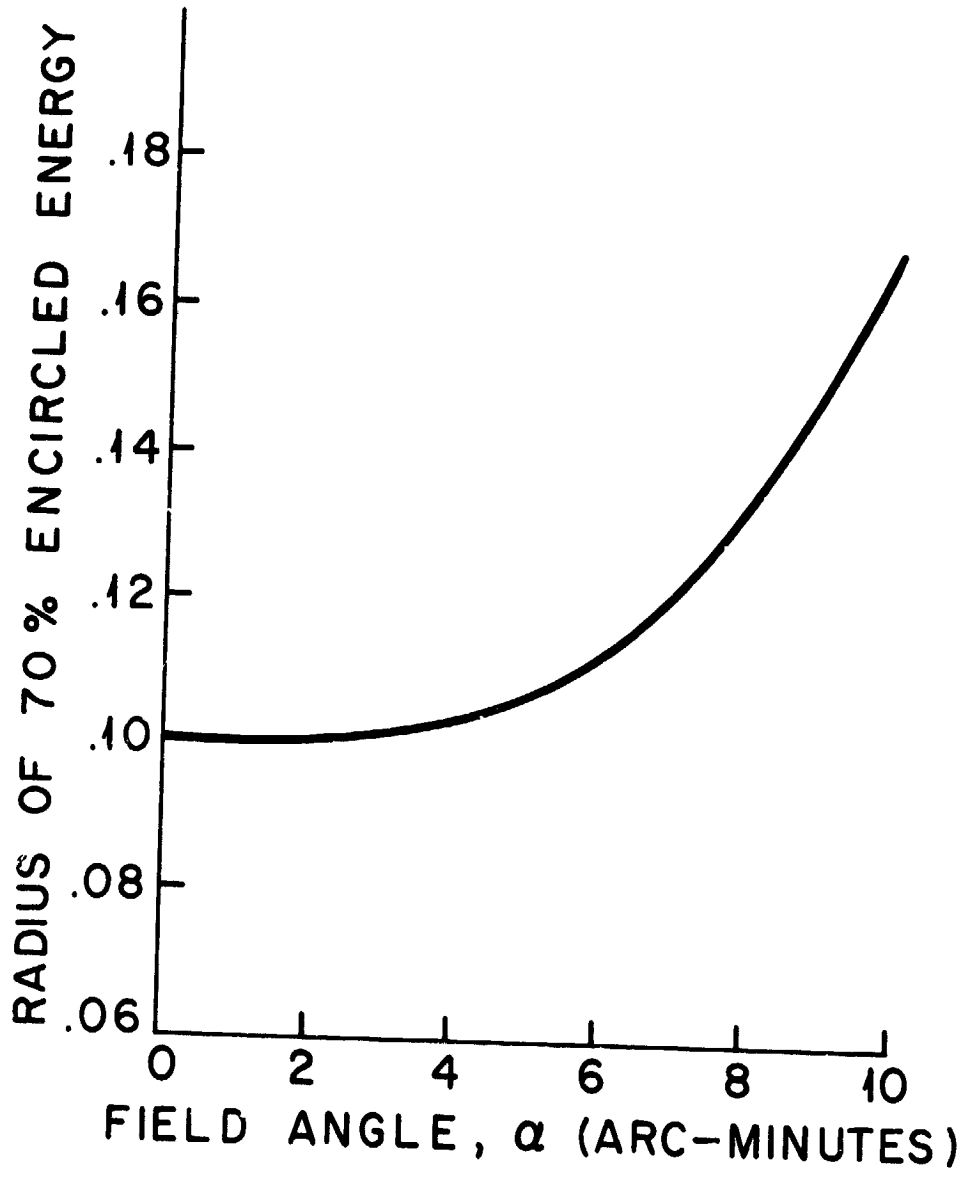


Figure 3: The variations of the image quality as a function of off-axis distance are shown for the expected flight conditions.

This day/night pattern, combined with blocking of parts of the sky by the Earth, gives a definite seasonal pattern to the periods when the faintest objects can be observed.

C. Pointing Capability

Space Telescope has three sources of information on its orientation: the Rate Gyroscopes, the Star Trackers and the Fine Guidance Sensors. Since the primary goal is the prompt and accurate acquisition of preselected guide stars, all three sources of information are used when Space Telescope is pointed to a new object. The slewing rate is determined by the reaction wheels that are used and is specified to allow movement to an object 90° away in no more than 20 minutes, including angular acceleration and deceleration, with the reference frame provided by the Rate Gyroscopes. The Star Trackers then use bright stars to determine the pointing to a few arcminutes, which is sufficient to place the guide stars in the field of view of the Fine Guidance System. Following a scan to select the correct guide star, the guide-star images are put through a 1" aperture and fed to an interferometric device which gives the fine error signal that results in the overall guiding stability of 0.007" rms. The positioning of the Fine Guidance Sensors can be set to an accuracy of 0.01".

D. Operational Access

Operational control of Space Telescope will come from the ground and the scientific information from the observatory will be sent to the ground; a two way communication link must be established. This will be done using antennae on both the ground and the spacecraft; a pair of geosynchronous relay satellites, the Tracking and Data Relay Satellite System (TDRSS), will allow radio-wavelength "viewing" of the Space Telescope for about 85% of each orbit. The capabilities of this system are finite and there are many potential users. It is expected that commands can be sent to Space Telescope about 20% of the time. Data will be stored on-board the Space Telescope on tape recorders or sent directly to the ground. In any event, it is expected that a transmission rate of one megabit/second will be available about 20% of the time and four kilobits/second for about 70% of the time. These constraints impose important but not severe restrictions on the process of scheduling observations. Real-time control of the Telescope will not be possible except for small corrections in positioning, although pre-programmed options can be included if required for special observations.

V. THE SCIENCE INSTRUMENTS

There are six first-generation science instruments that are scheduled to be included in the ST Observatory from the time of its launch through the first few years of ST operation in orbit. The Wide Field/Planetary Camera is the radial bay instrument to which the central 3 arc-min of the f/24 focal surface is relayed by a pick-off mirror. There are four axial bay instruments: the faint object camera, the faint object spectrograph, the high resolution spectrograph, and the high speed photometer. The four axial bays view the unvignetted field at distances of 3 arc-min or greater off-axis. Compensation for astigmatism and field curvature of the Optical Telescope Assembly is achieved within the scientific instruments. Also, the Fine Guidance System can be used for astrometric observations, an effective sixth instrument. The ST project has made certain that all aspects of the Observatory are consistent with the possible future inclusion of an infrared instrument operating anywhere in the range from 1 μ to 1 mm. The entrance apertures of all of the instruments are effectively located in the focal plane of the telescope, which has a scale of 3.58 arcseconds per millimeter. The four axial bay configurations are modular and can be exchanged one for the other. The typical weight of an axial bay instrument is about 700 pounds with dimensions of 0.9 by 0.9 by 2.2 meters; the Wide Field/Planetary Camera is somewhat smaller and lighter. All instruments will draw of the order of 110 to 150 watts during observations. They are designed so that removal, or installation, of a new instrument can be achieved in-orbit by a suited astronaut operating from the Space Shuttle.

We describe below the expected basic performance characteristics of all six of the first-generation science instruments. The cited characteristics are, in most cases (see references to Tables 2-7), minimum performance characteristics specified in the current contracts for the hardware of the science instruments. The final ground-based tests of the instruments will not be carried out at GSFC until early 1982. There may also be some adjustments in details of the designs before this date (e.g., in the choice of filters or gratings). The performance characteristics in orbit will not be known for certain until the instruments are tested under orbital conditions in 1984.

The four axial bay instruments are designed to count individual photons. Thus the limiting magnitudes and signal-to-noise ratios given below and in the tables of performance characteristics can be scaled using the "most-optimistic"

formulae: $m \propto 2.5 \log(\text{time})$ and $S/N \propto (\text{time})^{1/2}$. These relations are based only on Poisson statistics and they neglect, among other things, background noise from the detector, sky background, and radiation effects (see sections on the individual instruments for estimates of these quantities), but are probably adequate for rough estimates of what may be feasible (and may be almost as accurate as the available data on the performance characteristics of the instruments warrant). The above scaling relations can be used for crude estimates of the sensitivity as a function of time of the Wide Field/Planetary Camera although readout noise and radiation effects will limit the usefulness of combining exposures for this instrument (the detailed data in §V A below on read out noise, sky background, and dark count for the Wide Field/Planetary Camera can be used to compute more accurately the performance characteristics of this detector).

With the above cautionary remarks, the characteristics given here should be sufficient for advanced planning of ST observations.

Some science programs that have been identified by the instrument development teams are described briefly. These programs are listed for illustrative purposes only. General observers can, and in most cases will, carry out significant parts of these programs.

A. Wide Field/Planetary Camera (WF/PC)

The Wide Field/Planetary Camera can be operated in two modes that are characterized loosely by the two names: Wide Field Camera (WFC) and Planetary Camera (PC). The WFC mode will be used primarily for deep sky surveys (field: 2.7×2.7 (arcmin)²). The PC mode will provide high-resolution imaging over a moderate field of view for faint sources or objects requiring a wide dynamic range (field: 1.2×1.2 (arcmin)²) and/or wavelengths beyond 6000 Å. The basic performance characteristics in both these modes are given in Table 2.

The WF/PC is unique among the ST science instruments in several ways. It is located in a radial (not an axial) bay; light is transferred into the instrument by means of a pick-off mirror centered on the optical axis of the optical telescope assembly. An external thermal radiator, which will be a part of the exterior surface of the ST, will be used for cooling. The wavelength range is larger than for any of the other instruments; the red response is particularly crucial for many scientific problems. The quantity of data (bits per year) generated by the WF/PC in the pri-

Table 2. Wide Field/Planetary Camera*

This instrument can operate at two different focal ratios: $f/12.88$ or $f/30$. In the first mode, the instrument is referred to as the Wide Field Camera (WFC) and, in the second mode, as the Planetary Camera (PC). Pictures can be taken, in either mode, with any one of a wide variety of spectral filters or transmission gratings.

<u>Characteristics</u>	<u>WFC</u>	<u>PC</u>
Field of View	2.67×2.67 (arcmin) ²	1.15×1.15 (arcmin) ²
Angular Resolution (1 pixel)	0.1×0.1 (arcsec) ²	0.043×0.043 (arcsec) ²
Bandwidth (quantum efficiency $\geq 1\%$)	$1.15 \times 10^3 \text{ \AA}$ to 1.1μ	$1.1 \times 10^3 \text{ \AA}$ to 1.1μ
Photometric Accuracy	$\sim 1\%$	$\sim 1\%$
Dynamic range (S/N > 3)	$9.5 \leq m_V \leq 28.0$	$8.5 \leq m_V \leq 28$

*References: (1). J. A. Westphal, et al. (1977), Technical Proposal - Instrument Definition Team, WF/PC for ST, submitted by the California Institute of Technology to NASA; (2). J. A. Westphal et al. (1979), WF/PC GSFC Preliminary Design Review Package (CM-04).

mary and serendipity modes is expected to exceed that of the other instruments.

In both the WFC and PC modes, the detectors are four (800×800) charge-coupled devices (CCDs). The incoming light can be directed onto either the four WFC CCDs or the four PC CCDs by means of a pyramid mirror that can be rotated about its apex. The WF/PC contains two complete optical relay and detector systems, each capable of producing a four-part image mosaic. The CCDs are being developed by Texas Instruments for both the Galileo and the ST Projects. The center-to-center pixel separation is 15 μ . The CCDs will be cooled to -95° ± 0.5° C in order to reach a small, known dark current. The wide wavelength coverage is possible because the CCDs are coated with an organic phosphor, coronene, which converts ultraviolet photons into visible photons; the intrinsic long wavelength response of the CCDs is very good (see below). The optical performance in the visible band of the WF/PC will be approximately equivalent to that of an optical system with a total wavefront error of $\lambda/10$. Because of a slight overlap between the edges of the different 800×800 arrays, it will be possible accurately to register and reassemble the four pictures to form one large picture without any significant loss of data.

The WF/PC will provide a sensitive and highly linear detector over a broad wavelength region (1,150 Å to 1.1 μ) and a wide dynamic range (8^m to 28^m in the visual band). The minimum exposure time is 0.1 sec (determined by the speed with which the shutter can be opened and closed). The typical long exposure will be of order 3,000 seconds (corresponding to one-half an orbital period). A read-out noise of about 15 electrons per pixel, and radiation effects, limit the advantage of stacking different exposures (the OTA plus WF/PC optical throughput is ~ 0.33 and the CCD quantum efficiency ~ 0.55 at 5500 Å). The following typical results can be obtained for observations of single stars through a V filter (assumed to be an 890 Å bandpass centered at 5500 Å) all with a signal to noise ratio greater than or equal to three (sky = 23 m_V/(arcsec)², dark count = 0.01 electrons per pixel per second, image = 5 pixel patch at f/12.9):

<u>0.1 second exposure</u>	- WFC	9 ^m to 17 ^m
	- PC	8.5 to 16 ^m
<u>3,000 second exposure</u>	- WFC	21 ^m to 28 ^m
	- PC	20 ^m to 27.5 ^m

Note that planets, because they are not point sources, will be observable with short observing times in the planetary mode even though their integrated brightnesses exceed the 7.5 magnitude limit. The full throughput quantum efficiency of the flight WF/PC is expected to exceed the following requirements: 3% from 1200 Å to 3,000 Å; a peak value in excess of 40% in the region 3,000 Å to 7,000 Å; and 8% from 7,000 Å to 1 μ. The above data allow the computation of rough performance characteristics for intermediate exposure times and for a variety of wavelengths. Absolute photometric calibration will be achieved primarily by observation of standard stars; flat-field calibrations will be made using the limb of the illuminated earth.

A large number of filters, transmission gratings, and polarizers will be available for special purpose observations. Filters having a bandwidth $\Delta\lambda/\lambda = 0.2$ will be provided throughout the range 1200 Å to 1.1 μ, including U, B, V, R, and I filters; also filters with $\Delta\lambda/\lambda = 0.1$ will be available from 3400 Å to 1,050 Å. A number of special line filters (typical widths 20 Å to 60 Å) may be available including: Ly-α, C IV λ 1550, [O III] λ 3727, [Ne III] λ 3870, [O III] λ 4363, H-β, [O III] λ 5007, [O I] 6300 Å, H-α, and He I λ 10830. There will be 0° and 60° polarizers in U and R, a visible/IR transmission prism (~ 1200 Å to 1.1 μ) and a visible/IR transmission grating. The prism and grating can be used to produce low dispersion spectra of the objects in the field.

The instrument development team listed a number of important scientific applications of the WF/PC in their original technical proposal to NASA and in the preliminary design review. These objectives include: determination of H_0 ; tests of cosmological models; comparative studies of distant and faint galaxies; stellar population studies to faint magnitudes; high resolution luminosity profiles of galactic nuclei; energy distributions of stars and compact galactic and extragalactic objects; dynamic motions in supernovae remnants and proto-stars; search for extra-solar planets; synoptic studies of planetary atmospheres; and high resolution and uv studies of comets.

B. The Faint Object Camera (FOC)

The primary purpose of the FOC is to utilize the full optical performance of the ST, reaching the faintest limiting magnitudes and highest angular resolution possible. The basic performance characteristics of the FOC are summarized in Table 3. The FOC is being developed (and will be furnished) by the European Space Agency to the NASA ST program.

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Table 3. The Faint Object Camera (FOC) *

The faint object camera consists of two independent camera systems that operate, respectively, at f/96 and f/48. The f/96 system contains a coronagraphic facility that can be used to mask the light from bright objects. The f/48 system also provides for long-slit (10×0.1 (arcsec)²) spectroscopy with a fixed grating.

Characteristic	f/96	f/48
Field of view (see text)	11×11 (arcsec) ²	22×22 (arcsec) ² 44×44 (arcsec) ² at slightly degraded resolution
Pixel Size	0.022×0.022 (arcsec) ²	0.045×0.045 (arcsec) ²
Wavelength Range (quantum efficiency $\geq 1\%$)	$1,200 \text{ \AA} - 6,000 \text{ \AA}$	$1,200 \text{ \AA} - 6,000 \text{ \AA}$
Dynamic range (cumulative 10 hour observations without attenuating filters or combining pixels; S/N=4)	point sources: 21 mv to 28 mv extended sources: 15 mv/(arcsec) ² to 22 mv/(arcsec) ²	point sources: 21 mv to 28 mv extended sources: 15 mv/(arcsec) ² to 22 mv/(arcsec) ²
Photometric Accuracy (When not photo-noise limited)	at least 2%	at least 2%

*References: (1). F. Macchetto and R. J. Lurance, (1977), The Faint Object Camera, ESA SN-126; (2). J. J. Brahm, FOC Scientific and Technical Status Report, ST Science and Operations Project, internal GSFC report - February 12, 1979; (3). F. Macchetto, (1979), "Status of the ST Project in Europe," in ESA/ESO Workshop on the Space Telescope, ed. F. Macchetto, . Pacini, and M. Tarenghi.

The FOC is complementary to the WF/PC. The FOC provides a higher spatial resolution and the WF/PC a larger field of view. The FOC will be faster than the WF/PC (by a factor of between 10 and 50) in the wavelength range between 1200 Å to 4000 Å if the actual noise levels for both cameras are consistent with current expectations. The two systems will be about equal in speed at 5,000 Å. As one goes further into the red, the WF/PC is increasingly more advantageous, being faster than the FOC by a factor ≥ 10 for $\lambda > 6000$ Å.

The FOC contains two independent camera systems, one operating at f/96 and one at f/48. The f/96 relay slightly oversamples the expected point spread function of the OTA at 6328 Å; the focal plane image is magnified by a factor of four in order to minimize the resolution loss resulting from detector spatial sampling. The pixel size is 25 μ which corresponds to 0.022 arcsecs at f/96. The f/48 system magnifies by a factor of two in order to include a wider field with only moderate resolution loss due to detector sampling.

The f/96 mode contains a coronagraphic facility which allows the camera to suppress light from bright objects while observing faint sources in the nearby field. When centered on a stellar image, the occulting disc (0.6 arcsec diameter on the sky) reduces the total measured flux from the image by a factor of 20. It is estimated that imaging of a faint object near (1 arcsec) a bright object will be possible for a difference in magnitudes as large as $\Delta m_V \approx 7$ to 10 (depending on how long one is willing to observe).

The f/48 system provides a long-slit [10×0.1 (arcsec)]² spectrographic capability for observing extended objects. A fixed grating can be used to disperse the light and provide first, second, and third order images covering the wavelength ranges 3600-5400 Å, 1800-2700 Å, and 1200-1800 Å. This spectrographic mode complements the two U.S. spectrographs described below (V C and V D). The spectral resolution is 2×10^3 (a factor of ten less than for the HRS) and the limiting magnitude on point sources is 3.4 magnitudes brighter than that of the FOS. However, the FOC spectrographic mode is unique in that it makes possible spectroscopic profiles of extended objects with an angular resolution of order 0.1 arc second. This option will be useful in, for example, measuring velocity dispersions as well as temperature, density, and composition distributions in galaxies, comets and nebulae.

Independent sets of special purpose filters will be provided for the f/96 and f/48 modes. The f/96 mode will have four filter wheels, each containing 12 positions, that can be inserted in the optical path. The filter wheels will contain a variety of filters, including five neutral density filters ($\Delta m = 1, 2, 4, 6, 8$), two objective prisms ($\lambda/\Delta\lambda=50$ at 1500 Å and $\lambda/\Delta\lambda=100$ at 2500 Å), three polarizers for measuring linear polarization ($0^\circ, 60^\circ, 120^\circ$), and a number of special purpose filters. By suitably combining the neutral density filters a maximum attenuation of $\Delta m = 12$ can be achieved thus allowing the overall dynamic range of the FOC to extend from $m_v = 5$ to $m_v = 29$. The f/48 mode will have fourteen insertable elements including the two objective prisms described above, five order-sorting filters, six broad-band filters, and a Lyman-alpha blocking disc.

The identical detectors for the two f-ratios count individual photons; the conceptual design is similar to the imaging photon detectors developed by A. Boksenberg. The first stage of each detector is an EMI-developed three stage, magnetically-focused, image intensifier tube having a gain of approximately 10^5 . The first-stage photocathodes are "hot bialkalis" on Mg F₂, which have useful sensitivity over the wavelength range 1,150 Å to 7,000 Å. The thermionic dark currents of the photocathodes are expected to be very low at ambient temperatures, of order 10^{-4} counts/pixel/sec. The camera tube that scans the output of the intensifier is a high-gain Westinghouse (WX 32 719) TV tube, which is a high sensitivity, high resolution, electrostatically-focused-image-section EBS/SIT tube.

The basic limitation on the field size at highest resolution is determined by the amount of data that can be stored with a limited but dedicated memory. The memory limitation corresponds, with 16 bit words, to a total number of pixels that can be scanned of 512×512 or equivalent combinations. Each detector consists of 1024×1024 pixels. A variety of imaging formats will be available (currently): 1024×512 (with an 8 bit address), 1024×256 , 512×512 , 256×256 , 128×128 , 64×64 . At f/96, the 512×512 format corresponds to 11.3×11.3 (arcsec)²; a larger field, 22.5×11.3 (arcsec)², can be obtained also at f/96. The largest field that will be available for the f/48 mode is 22×22 (arcsec)², obtained by scanning data read from 2-by-2 pixel areas. It is possible that a time-resolved imaging mode will be available for small fields with a time-resolution of order one second (for use in searching, e.g., for optical counterparts of radio pulsars or variable X-ray sources).

The limiting magnitudes given in Table 3 for the brightest objects that can be observed are determined also by the TV scan rate. If the count rate becomes too high, the detector response is significantly non-linear. Much brighter objects than those listed in Table 3 can be observed with the aid of attenuating filters or by using small-scan formats. The faint limiting magnitudes in the ultraviolet may be one or two magnitudes fainter than the faint visual-magnitude limits shown in Table 3. A cumulative exposure of 10 hours should lead to a signal to noise ratio of at least four for stellar objects as faint as $m_v = 28^m$.

The possible applications of the FOC are very numerous. Some of the studies that have been stressed by the ESA Project Scientist and the Instrument Science Team include observations of RR Lyrae stars, Cepheids, bright supergiants, globular clusters and giant H II regions as distance indicators out to expansion velocities $\geq 10^4$ km s⁻¹; investigation of time-dependent features on planetary surfaces; the resolution of spectroscopic and astrometric binaries to establish stellar masses; detailed studies of shock fronts, condensing gas clouds and the relationship of young stars to the gas around them in regions of star formation, optical identification of faint radio and X-ray sources; and the search for direct evidence that quasars and BL Lac objects are the brightest nuclei of faint galaxies.

C. Faint Object Spectrograph (FOS)

The Faint Object Spectrograph is a versatile instrument that can perform moderate and low resolution spectroscopy on faint (and bright) objects in the ultraviolet and visible, as well as spectropolarimetry and time-resolved spectroscopy. The basic performance characteristics are listed in Table 4.

The FOS provides three modes of varying spectral resolution. The moderate resolution mode has $R \equiv \lambda/\Delta\lambda \sim 10^3$ and provides coverage from 1,150 Å to 9,000 Å in six bandpasses, utilizing concave gratings to obtain a resolution of ≤ 1200 when convolved with the 0.25 arcsecond entrance aperture. A low resolution mode, $R \sim 10^2$, consists of three spectral bandpasses - two low dispersion gratings which provide $R = 10^2$ for $1100 \text{ Å} < \lambda < 2200 \text{ Å}$ and $4000 \text{ Å} < \lambda < 8000 \text{ Å}$ and a prism spanning the range 2700 Å at $R = 3 \times 10^2$ to 8,000 Å at $R = 20$. There is also a nondispersed image that will be used for target acquisition.

The spectrograph contains two identical optical paths

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Table 4. Faint Object Spectrograph (FOS)*

The Faint Object Spectrograph can perform moderate ($R = \lambda/\Delta\lambda \sim 10^3$) or low ($R = 10^2$) resolution spectroscopy over a wide wavelength range as well as spectropolarimetry and time-resolved spectroscopy. Two photon-counting Digicon sensors (512 diodes each) are provided that differ only in their (red-biased or blue-biased) photoemissive cathodes.

<u>Characteristics</u>	<u>Expected Performance</u>
Spectral Resolution	$R = \lambda/\Delta\lambda \sim 10^3, 10^2$
Entrance Apertures	0.1 to 4.3 arcsec
Wavelength Range (FOS system efficiency > 1%)	1,150 Å to 7,000 Å
Limiting Magnitudes (no sky contamination; 10 ⁴ sec exposure; S/N(detector) = 5)	1.2 × 10 ³ Å to 7 × 10 ³ Å
R=10 ³ (flat spectrum)	19 ^m ≤ m _v (faintest) ≤ 22 ^m
R=10 ² (flat spectrum)	22 ^m ≤ m _v (faintest) ≤ 26 ^m
Dynamic Range	5 × 10 ⁷
Photometric Accuracy	at least 1%
Time Resolution	
minimum exposure	50 μ seconds
continuous exposures	100 exposures (10ms) per second
Linear Polarization Measurements (10 ⁴ second exposure)	1.2 × 10 ³ Å to 3 × 10 ³ Å
R=10 ³ (flat spectrum)	11 ^m ≤ m _v (faintest) ≤ 15 ^m
R=10 ² (flat spectrum)	13 ^m ≤ m _v (faintest) ≤ 17 ^m

*References: (1). R. Harms, (1979), Scientific Investigation Studies Report for the FOS, UCSD Report: FOS-UCSD-SC-01 (February 1979). (2). R. Harms, et al. (1977), UC/MNC Faint Object Spectrograph for the Space Telescope, Technical Volume-Instrument Definition Team, submitted by the University of California to NASA (July 1977).

which form a spectral image on a red-biased and a blue-biased detector. Each beam is reflected from a grazing incidence mirror through an order-blocking filter and then onto one of the grating elements selected from a ten-position carousel. The selected grating disperses the light in first order onto the faceplate of the Digicon. The carousel can supply to the Digicon certain filter/grating combinations or a non-dispersed image. The polarizing assembly can be inserted ahead of the grazing mirror assembly.

The FOS uses two magnetically focused, photon-counting Digicon sensor systems that differ only in their photoemissive cathodes and window materials. Digicon detectors are single-stage, photon-counting devices that operate by re-imaging photoelectrons onto a monolithic silicon diode array of 512 diodes. In order to cover the broad wavelength range of the FOS, two independently-operable Digicons are used. The ultraviolet/visual sensor has a magnesium fluoride faceplate and a bialkali photocathode. The visible/near-IR sensor has a silicon oxide faceplate and trialkali photocathode. Each diode has a width of 40μ and a height of 200μ ; the image scale at either Digicon will be 140μ per arc second, corresponding to a magnification of 0.5 of the OTA focal plane.

The FOS will be an accurate and sensitive spectrograph over a wide wavelength range. For both the moderate and low resolution modes, the FOS efficiency is expected to exceed one percent over the entire range from 1200 \AA to H- α , two percent from 1200 \AA to 2000 \AA , seven percent from 2000 \AA to 4000 \AA , and will have a peak efficiency exceeding ten percent. The FOS background noise during inflight conditions is expected to be low: less than 2×10^{-3} counts/sec/diode. The counting rate from a constant source should be constant to a one percent accuracy for 99 percent of the diodes over periods up to four hours for all spectral regions in each mode (holding the spectral region and observing mode fixed over the observing period).

The limiting magnitude₃ that is achievable depends on the resolution mode ($R = 10^3$ or 10^2) and the spectral region. The peak sensitivity occurs in the range 4000 \AA to 5000 \AA . The faintest attainable magnitudes are approximately the same (plus or minus of the order of one magnitude) in the entire range from 2000 \AA to 7000 \AA . The sensitivity falls off rapidly below 2000 \AA or above 7000 \AA ; at 8000 \AA the typical faintest attainable magnitudes are 6 magnitudes brighter than at 4500 \AA . Some range of faintest limiting magnitudes attainable in 10^4 second exposures are given in Table 4.

The indicated limiting magnitudes were computed using the advertised ST performance, the 0.25 arcsec FOS entrance aperture, the FOS efficiencies described above, internal background of 0.002 counts/sec/diode, and a pessimistic sky background. The limiting magnitude is defined to be that which results in 0.01 counts/sec/diode from a stellar target. As another example, note that the FOS will achieve a signal to noise ratio of seven per diode at 4000 Å in the $R = 10^3$ mode for a three-hour integration on an unreddened AOV star of magnitude $V = 23$. Stars as bright as $m_V = 6$ can be observed in the $R = 10^3$ mode.

For spectropolarimetry, the relevant measure is the limiting magnitude for which both of the Stokes parameters describing the state of linear polarization can be obtained with, for example, one-percent accuracy. In a 10^4 second observation, the faintest magnitude for which this accuracy can be achieved in the $R = 10^3$ mode rises monotonically from $m_V = 10.8^m$ at 1200 Å to $m_V = 15^m$ at 3000 Å for a source with a flat spectrum ($F_V = \text{constant}$). For the $R = 10^2$ mode, the faintest magnitudes attainable vary from $m_V = 13^m$ to 17^m over the same spectral range under the conditions specified above.

The FOS can provide exposure times as short as 50 μ seconds duration. A continuous set of exposures, each of duration 50 μ sec to 10 msec, can be made at a rate up to approximately 100 512-channel exposures per second.

The FOS design also incorporates special entrance apertures matched to the ST optics to maximize the signal from a nebula surrounding a stellar source (for example, a quasar that occurs in a galaxy).

The scientific applications of the FOS are numerous and varied in character. The instrument development team and the principal investigator have discussed a number of possible investigations (see references to Table 4). These include: high spatial resolution spectra of quasars, Seyfert and other active galactic nuclei in order to determine physical conditions; observations of H II regions and planetary nebulae in the Local Group Galaxies to measure population abundances; the study of globular clusters in the Virgo Cluster to determine stellar populations and to measure radial velocities; the measurement of the ultraviolet spectra of the central stars of planetary nebulae; time-resolved spectrophotometry of X-ray sources; ultraviolet spectrometry of comets to measure various spectral features and some radial velocity measurements of wave structure in

cometary tails; and ultraviolet spectropolarimetry of stars and reflection nebulae to help determine the origin of interstellar polarization, as well as spectropolarimetry of white dwarfs, quasars, and Seyferts to help delineate the physical processes occurring in these objects.

D. High Resolution Spectrograph (HRS)

The High Resolution Spectrograph is a photon-counting, ultraviolet instrument that will provide a resolving power equal to that of the largest ground-based Coude spectrograph. It can perform moderate and high resolution spectroscopy in the region between 1100 Å and 3200 Å. The basic characteristics of the HRS are shown in Table 5.

The HRS (like the FOS) provides three modes of varying spectral resolution. The primary HRS observing modes are with a resolving power $R = \lambda/\Delta\lambda = 1 \times 10^5$ (by far the highest on ST) and with $R = 2 \times 10^4$, both covering the wavelength 1.1×10^3 Å to 3200 Å. Most of the numerous scientific programs that have been suggested so far (see below) for the HRS refer to these two primary modes. The moderate resolution mode has $R = 2 \times 10^3$, similar to the FOS. However, this HRS moderate resolution mode is limited to the region 1050 Å to 1700 Å. The moderate resolution of the HRS will be used for efficient target acquisition, for estimating exposure times at higher resolution, and to provide valuable sensitivity in the short wavelength region where the OTA efficiency is low and higher resolution spectroscopy is not feasible. The partial redundancy with the FOS is intentional.

The HRS will contain two square entrance apertures of 0.25 and 2.0 arcseconds, designed to accommodate the astigmatic defocussing of the OTA beam. (The HRS will not resolve spatial information within the 0.25 arcsecond slit.) Slit selection is accomplished by orienting the telescope so as to place the image of the target in the slit. Within the spectrograph, the light is reflected by a collimator to one of six plane gratings in a rotatable carousel.

The HRS (like the FOS) contains two independent Digicon detectors, each with 512 diodes. For one of the HRS Digicons, the photocathode/window combination is Cs Te/Mg F₂ while for the other it is Cs I/Li F (peak efficiency at ~ 1250 Å). Three of the gratings (blazed at 1600 Å, 2000 Å, and 2700 Å) diffract the light towards a camera mirror which focuses a first-order, high resolution ($R = 2 \times 10^4$) spectrum on the Digicon having a Cs Te/Mg F₂ combination. A fourth grating (blazed at 1400 Å) produces a similar spectrum on

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Table 5. The High Resolution Spectrograph (HRS)*

The High Resolution Spectrograph can perform high ($R=2 \times 10^4$ and $R=2 \times 10^5$) and moderate ($R=2 \times 10^3$) resolution spectroscopy in the ultraviolet, as well as time-resolved spectroscopy. Two photon-counting Digicon detectors are provided, one with a Cs Te/Mg F₂ photocathode/window combination and the other with Cs I/Li F.

<u>Characteristics</u>	<u>Expected Performance</u>
Spectral Resolution	$R = 1 \times 10^5, 2 \times 10^4, 2 \times 10^3$
Entrance Apertures	0.25×0.25 (arcsecond) ² 2.0×2.0 (arcsecond) ²
Wavelength Range (HRS Efficiency: 0.4% to 4.0%; preliminary estimate)	$(1.1 \text{ to } 3.2) \times 10^3 \text{ \AA}$ ($R=10^5$) $(1.1 \text{ to } 3.2) \times 10^3 \text{ \AA}$ ($R=2 \times 10^4$) $(1.1 \text{ to } 1.7) \times 10^3 \text{ \AA}$ ($R=2 \times 10^3$)
Limiting Magnitude (2×10^3 sec; AOV star near peak HRS efficiency; $S/N \geq 10$)	$m_V = \begin{cases} 11 & (R=10^5) \\ 14 & (R=2 \times 10^4) \\ 17 & (R=1 \times 10^3) \end{cases}$
Photometric Accuracy (count rate $\leq 10^4$ /sec/pixel)	$\sim 1\%$
Minimum Exposure Time (reset time ≤ 0.002 sec)	0.025 sec

*References: (1). J. C. Brandt et al. (1977), A High Resolution Spectrograph for the Space Telescope, Technical Proposal-Instrument Definition Team, submitted by GSFC to NASA Headquarters, HRS-680-77-01; (2). J. C. Brandt, et al. (1979), Proceedings, Society of Photo-Optical Instrumentation Engineers, Vol. 172, in the press.

the Digicon with the Cs I/Li F combination, using a second camera mirror. The moderate-resolution ($R = 2 \times 10^3$) mode is also recorded in first order by this Digicon. The highest resolution observations ($R \geq 10^5$) will be achieved with the aid of a sixth, echelle grating that can be used with either Digicon. A limited range of the spectrum is recorded by the array at one time. In the $R = 2 \times 10^4$ mode, the length of the spectrum on the detector varies from about 30 Å at 1100 Å to about 45 Å at 3200 Å. The spectrum length for the $R = 2 \times 10^3$ mode is about 290 Å. In the echelle, high-resolution mode ($R = 10^5$), the spectrum length varies from 4.5 Å at $\lambda = 1100$ Å to 16 Å at $\lambda = 3200$ Å.

The sensitivity of the HRS in various wavelength ranges depends on the efficiencies of the gratings and Digicons as finally manufactured by the HRS vendors. The sensitivity goals are: for the $R = 2 \times 10^4$ mode, a quantum efficiency in excess of 1% over the interval from 1200 Å to 2800 Å and a maximum of at least 3% within this spectral range; for the $R = 10^5$ mode, a spectrograph efficiency in excess of 0.4% at the blaze wavelengths over the entire interval from 1200 Å to 2800 Å, and a maximum efficiency no less than 1.2% within the 1800 Å to 2800 Å range.

The brightness ratio of signals ($\geq 10^5$ total counts) from any two channels within the image format and within the Digicon dynamic range will remain constant to within 1% (1σ) of the mean ratio value over periods up to 30 days. For count rates randomly distributed in time up to 10^5 counts/sec/channel, the measured rate will be correctable to the true rate to an accuracy better than 4%. For count rates between 1 and 10^4 counts/sec/pixel, the measured rate will be correctable to the true rate to an accuracy of better than 1%.

The HRS will achieve a signal-to-noise ratio of at least 10 in each channel at a flux maximum near the wavelength of maximum HRS efficiency in a 2×10^3 second integration period on an unreddened AOV stellar flux distribution corresponding to approximately $V = 14^m$ at $R = 2 \times 10^4$ and to approximately 11^m at $R = 1 \times 10^5$. (This assumes an OTA throughput of 0.6, a radiation background of 0.001 counts/channels/sec, and a sky background of 10^{-3} photons $\text{cm}^{-2} \text{sec}^{-1} \text{Å}^{-1} \text{arcmin}^{-2}$. At ambient temperature, the photocathode dark current will be less than 0.01 counts/diode/sec.)

The minimum integration period for a single frame of data will be 25 milliseconds when data are transmitted directly and 50 milliseconds when data are stored on-board.

The reset time, that is the time between successive integrations, will be less than 2 milliseconds.

Accurate calibration of wavelengths and system response will be achieved by the use of three types of internal light sources: a Pt-Ne lamp for calibrating the wavelength scale, (accurate to 0.40 pixels, $1-\sigma$), lamps that provide an ultraviolet continuum, and "flat-field" illumination of the Digicons.

The principal investigator and the instrument development team have discussed (see references to Table 5) a number of important observations that are to be made with the HRS. These include: studies of the very local gas, of dense clouds, and of previously undetected molecules all in the interstellar medium; studies of mass loss, mass transfer, and coronal winds in stars using OB supergiants in the Magellanic Clouds, red giants in the Galaxy, close X-ray binaries, and late-type stars; a spectroscopic investigation of the nuclei of Seyfert galaxies and a detailed study of the uv spectrum of 3C 273; a study of the structure of the atmospheres of the Jovian planets, of auroral activity on other planets and satellites, and a measurement of the D/H ratio in Halley's comet.

E. High Speed Photometer (HSP)

The High Speed Photometer is designed to provide accurate, time-resolved photometric observations over a wide wavelength range, as well as linear polarization measurements in the ultraviolet. The basic performance characteristics are listed in Table 6.

The HSP will be capable of resolving two events separated in time by more than 16 microseconds. Observations of rapidly varying sources over time scales this short are difficult or impossible to obtain from the ground because of atmospheric fluctuations. Events measured with the HSP can be related to ground-based time standards with an accuracy of at least 10 milliseconds.

The HSP is designed to be the simplest instrument in the initial group of scientific instruments. It contains no mechanical parts and relies entirely on the fine-pointing of the spacecraft to place an astronomical target onto one of its approximately 100 filter/aperture combinations.

The HSP consists of four magnetically focused image dissectors (two sensitive in the visual and near UV and two

Table 6. The High Speed Photometer (HSP) *

The High Speed Photometer can perform accurate high-time-resolved photometric photometry over a wide wavelength range. Four image dissector devices and one photomultiplier tube are used.

<u>Characteristics</u>	<u>Expected Performance</u>
Wavelength Range (HSP efficiency $\geq 1\%$)	1200 Å - 8000 Å
Spectral Resolution	Defined by Wavelength Filters
Entrance Apertures	0.4, 1.0, and 10 arc sec diameters
Linear Polarization	2100 Å - 3800 Å
Time Resolution	16 μ sec
Dynamic Range	10 ⁸
Photometric Accuracy	~ 0.2%
Limiting Magnitude (S/N=10; integration time $m_V = 24$ 2×10^3 sec)	

*References: (1). R. C. Bless (1977), A High Speed Photometer/ Polarimeter for the Space Telescope, A Proposal to the NASA by the Space Astronomy Laboratory, University of Wisconsin; (2). R. C. Bless, et al. (1978), High Speed Photometer GSFC Preliminary Design Review Package (CM-04).

sensitive in the UV) and one (red-sensitive) photomultiplier tube. (For simplicity, one can think of an image dissector as a photomultiplier tube with spatial resolution.) Two dissectors will have a nominal S-20 spectral response for operation in the 2000 Å to 6500 Å range. Two other image dissectors will utilize a Cs Te Photocathode with a Mg F₂ window for operation in the range 1150 Å to 3000 Å. One of the S-20 dissectors will be used as a polarimeter in the range 2100 Å to 3300 Å. Each dissector will operate as a simple, high-speed beam photometer or polarimeter. In addition, the photomultiplier tube will utilize a Ga As photocathode for operation in the 6000 Å to 9000 Å range.

The choice of entrance-aperture/filter combination will be determined by ST positioning of the optical image within the HSP. This procedure simplifies the instrument design and eliminates the moving parts that occur in a more conventional photometer. Every dissector will be preceded by a focal-plane filter/entrance aperture assembly that will contain about 12 wavelength filters, each with a pair of associated 0.4 arc sec diameter and 1.0 arc sec diameter aperture stops. There will also be, for area photometry without a filter and for target acquisition, a 10 arc sec diameter aperture on each dissector faceplate. Standard filters from various photometric systems will be included. The filter plate assembly for the polarimeter will contain wavelength filter strips each overcoated with a polarizing film transmitting light plane-polarized in four separate orientations, enabling the linear polarization to be measured.

Three operational modes will be used: star-sky photometry with a single filter/aperture combination, requiring no special ST motion; photometry or polarimetry with several filters viewed sequentially by small ST motions with corresponding dissector beam deflection; and area photometry over a 10 arc sec diameter aperture without a filter, requiring no special ST motion.

The photometric accuracy at all wavelengths should be very high, of order 0.2 percent or 1.3 times the combined photon noise alone, whichever is larger. The maximum signal to noise ratio attainable in a single exposure will be at least 4000; the dynamic range will be at least 10⁸ with the photometric accuracy described above for the lowest six decades of the dynamical range. The HSP will have a system efficiency of at least 1% over the entire range from 1200 Å to 8000 Å with a peak efficiency of at least 9% at 4000 Å.

The limiting visual magnitude will be at least 24 with

a signal to noise ratio of at least 10 after a 2000 second integration on the source.

The HSP makes possible a number of important scientific programs. The principal investigator and the instrument development team have discussed some typical interesting observations. These include: determination of the properties of components of binary star systems; searches for optical counterparts to radio pulsars; measurement of the shortest time-scales for variability of compact extragalactic sources; accurate brightness measurements of the zodiacal light and diffuse galactic light; determination of the wavelength and time dependence of polarization in a variety of galactic and extra-galactic sources; and measurements of the diameters of stars and solar system objects, as well as determinations of the profiles of the physical parameters of planetary atmospheres. One class of "service" observation will be of special importance to the general astronomical community, i.e., the establishment of faint stellar calibration standards, magnitude system transformations, and transfers between previously established photometric sequences and ST targets.

F. Astrometry with the Fine Guidance System (FGS)

The Fine Guidance System (FGS) consists of three identical sensors distributed in an annulus centered upon the optical axis of the ST. Each sensor has its own accessible area [69 (arcmin)^2]. In normal operations, two of the sensors will be used for fine pointing with the aid of pre-specified guide stars. The sensor that is not used for telescope pointing, which can be any one of the three FGS sensors, will be available for astrometric measurements. The basic characteristics of the FGS as an astrometric instrument are listed in Table 7.

An FGS sensor consists of a set of rotating mirrors such that any star within its field of view can be placed on an image dissector/interferometer combination. The encoder readings of the rotating mirror axes supply the object position in the field of view; the output of each of the pair of interferometers supplies a fine error signal. The system determines accurate relative positions to ± 0.002 arcseconds (by repeated short measurements) of all pre-designated point sources within the field of view of the FGS astrometric sensor. The spectral range available will be 4670 \AA to 7000 \AA , with appropriate band filters.

Astrometric measurements will be accurate and short.

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Table 7. Astrometry with the Fine Guidance System (FGS)

The Fine Guidance System contains three sensors, two of which are required for guidance while the third can be used for astrometry. The position and magnitude (within broad magnitude limits) can be measured for any pre-designated star within the area of the FGS sensor that is acting as the astrometric sensor.

<u>Characteristics</u>	<u>Expected Performance</u>
Total Area Accessible to each Sensor	69 (arcmin)^2
Relative Positional Accuracy (of any two objects accessible to a given FGS)	0.002 arc seconds
Magnitude Range of Astrometric Targets (with neutral density filters)	$4^m \leq m_V < 20^m$
Spectral Range (with a minimum of three filters)	4670 Å to 7000 Å
Duration of Observation	10 objects in 10 minutes, down to 17^m
Photometric Precision (10 minutes on a $m_V=17^m$ object)	1%
Pointing Stability of the ST (r.m.s.) (10 hours of observing time)	0.007 arc seconds
Field of View of Each Detector	1 (arcmin)^2
Magnitude Discrimination of FGS	$\pm 0.4^m$

References: (1). W. H. Jefferys et al. (1977), Space Telescope Instrument Definition Team - Astrometry; Technical Proposal submitted by the University of Texas (Austin) to the NASA; (2). W. F. van Altena et al. (1977), Space Telescope Instrument Definition Team - Astrometry; Technical Proposal submitted by Yale University Observatory to the NASA; (3). P. J. Shelus and the ST Astrometry Team (1978); Astrometric Observations with the FGS of the ST, technical report, University of Texas (Austin).

With the aid of neutral density filters, stars in the magnitude range of $4^m \leq m_v < 20^m$ should be measurable (the faint limit will lie between 17^m and 20^m). It will be possible to determine the positions of 17th magnitude (visual) stars; and to measure ten stars in ten minutes within the field of one of the fine-guidance sensors. A photometric precision of one percent will be achievable in ten minutes on a 17th-magnitude (visual) star.

The FGS can be used in three astrometric modes: primary astrometric targets stationary with respect to the field of view; primary target moving with respect to the field of view; and a scan to obtain the transfer function for each object in the field of view.

The principal investigator and the instrument development team have identified a number of important astrometric problems for which the FGS can be used. These include: positional information of the natural satellites of the outer planets; parallax information on nearby stars and possible unseen companions; resolution of important binaries and mass determinations of nearby spectroscopic binaries; establishment of an inertial reference frame relative to quasars and selected radio sources; and relationships among radio, optical, and dynamical fundamental reference systems.

VI. OPERATIONS

A. Program Options

Because of its complexity and remote location, Space Telescope will be operated in a more automatic manner than large ground-based optical telescopes. The relatively frequent access provided by the TDRSS allows many of the elements of observing that are traditional and convenient. However, there will be many more constraints in scheduling than are normally encountered in operating ground based telescopes.

Observations will be preprogrammed. This means that a series of time-sequenced spacecraft commands will be generated to carry out an observation automatically using a succession of planning steps that involve some previous knowledge of the object being viewed, as well as the operational constraints and capabilities of the Space Telescope and its Science Instruments. This method of operation will allow observing programs to be combined into an efficient schedule that produces the maximum amount of science.

Some scheduling flexibility will be required in a

certain fraction of the observing programs because of the unusual nature of the astronomical source. In such cases, there will be assignments of "block time", analogous to short observing runs on ground-based telescopes. Observers will do detailed preprogramming of their observations, but can include the possibility of selecting between pre-designated choices during the block time.

B. Guide Star Selection

In section IV, it was explained that guide stars would be selected from the edge of the field of view to provide the error signal for the most precise level of pointing control. There will be three Fine Guidance Sensors, each with a field of view of about $69 \square$. Guide stars as bright as $m_v = 9^m$ are usable and desirable, but are not sufficiently numerous. The system should be sensitive enough to guide on stars down to 14.5^m , a brightness level at which there will be more than enough candidates to satisfy the performance requirements that there be at least an 85% probability of finding two usable guide stars at the Galactic Poles. Close binary stars will not be usable since they would confuse the interferometric pattern of the Fine Guidance Sensor. There will also be constraints imposed by very crowded star fields (confusion in identification), bright background signals (some regions near very high surface brightness nebulae), and azimuthal angle (off-optimum roll of the spacecraft and correspondingly low electrical output of the Solar Array).

The selection of appropriate guide stars will be one of the important problems in the planning of any ST observation. These guide stars will be used by the FGS to acquire and hold a target in an entrance aperture of a science instrument. The choosing of guide stars is a more difficult and crucial task for ST observations than for corresponding ground-based optical observations since the fine guidance sensors are interferometric devices without imaging capabilities (over even a small field). No "picture" is obtained with the FGS. The actual field of view of each detector is only 1 (arcmin)^2 , which implies that reasonably accurate pre-selected guide star positions must be available for all science targets. Moreover, the fields of views of the science instruments are even smaller, requiring in some cases positions accurate to arcseconds. The magnitude discrimination of each detector is 0.4^m (visual); candidate guide stars should not have companions within 0.5 arcmin that differ in brightness by less than 0.4^m . Star catalogues are not available throughout the sky with the required star density and accuracy. The astrometry instrument defini-

tion team, and the ST project in general, are investing a great deal of effort in defining and designing an appropriate guide star selection procedure.

C. Modes of Acquisition

In the Pointing Capability section of part IV, we described the automatic pointing method for Space Telescope, mentioning that guide stars could be acquired with an accuracy of 0.01". Positional information of this accuracy will not be available for most stars and fortunately there will usually not be a requirement for pointing this precisely. Available plate material should give positions accurate to about 0.5", which is adequate for those instruments (Wide Field Camera and Faint Object Camera) with fields of view that are much larger. Small entrance aperture instruments (spectrographs and photometers) will be limited by the lack of astrometric quality data on their objects vis-a-vis the candidate guide stars and possible drifts in position of the entrance slits vis-a-vis the Fine Guidance Sensors.

Two methods of fine acquisition are available for the small-aperture science instruments. The science instrument may provide an internal scan of a small field of view and then send commands to the spacecraft pointing system to center the object. Obviously this method is limited to relatively simple fields. The alternative is for the science instrument to perform some type of image scan and send this information to the ground, where the astronomical observer makes the judgement as to where the Space Telescope should actually be pointed. The latter method demands, if it is to proceed efficiently, a close coupling between ST scheduling and the TDRSS availability.

D. Quick-Look Capabilities

An observer using Space Telescope will want to see his data as soon as possible, not only because of intellectual curiosity, but also to allow consideration of changes in the immediate and near-term observations. Because of the constraints of the ground data handling system, the ideal of "all the data immediately" will not be achieved. However it will be possible to quickly send a slightly noisy version of the data at a rate of at least 56 kilobits per second to the Science Institute via an electronic data link between GSFC and the Sci. This information can be used to assess the observational program being executed and to judge the necessity of changing the observing plan.

VII. THE SCIENCE INSTITUTE

A. Plan for Contracting and Developing

The NASA has developed a plan for science operations that is intended to be as similar as possible to the management of other national laboratories in the United States by other Federal Agencies. The analogy cannot be complete since only the NASA has the technical expertise to develop and maintain the Space Telescope, as well as the control and communications system to generate direct spacecraft commands. The intent of the NASA approach is to place the responsibility for performing science with the ST in the hands of the scientists themselves. A call for proposals to operate a Space Telescope Science Institute (ScI) will be issued in the autumn of 1979 and the successful operating group will be selected in the summer of 1980. This gives the ScI about 3½ years to prepare for launch and operations. During this period, the ScI will establish itself at a permanent location, hire staff (about 70) and scientists (about 30), and develop the hardware and software necessary to carry out the functions that are described below. The intent of NASA is to support the ScI throughout the lifetime of the Space Telescope.

An authoritative account of the detailed plan for the operation of ST and the ScI is contained in the document entitled "Science Operations with the Space Telescope: Current Concepts", January 1979, prepared by the ST Program Office. Copies are available from the ST Project Scientist, C. R. O'Dell.

B. Observer Selection

One of the first and most important functions of the ScI will be the selection of the users of the ST. It is expected that requests will far exceed capability. This means that the wisest possible policy must be followed in the selection, based on both scientific judgement and technical feasibility. Certain conditions must be observed in the selections. The many scientists who are now helping to develop the Space Telescope Observatory and the individual science instruments have been guaranteed by NASA a limited fraction of the observing time. At the end of the initial checkout period, 100% of the observing time will go to these users and their fraction will decrease to zero after 30 months, averaging 30% over this period. The scientists with guaranteed observing time will identify their observing programs prior to the first selection of general

users; their plans will be considered in the selection of other users. In addition, at least 15% of the observing time will go on the average to scientists from member nations of the European Space Agency in recognition of an approximately proportional financial contribution to the Space Telescope program.

The first call for observing proposals will be issued about one year before the initial launch of ST. These proposals will be examined for technical feasibility by the ScI staff and for scientific quality by an external science peer review group. Then a selection committee, convened by the ScI but largely composed of non-ScI personnel, will make the final recommendations to the ScI director. The participation of United States observers will be funded by the ScI; non-United States users will have to provide their own funding. New proposals will be reviewed periodically throughout the lifetime of the Space Telescope Observatory.

C. Scheduling

The user programs that are selected may employ one or several of the science instruments and may involve a single observation or many. This means that there will be a variety of needs to be integrated together into a coherent observing schedule. Moreover, the newly selected users will not understand fully how the science instruments perform and are operated. The necessary education as to science instrument capability and use will come from ScI reading material and interaction with science instrument representatives. As the observing plans are refined, an iterative scheduling cycle begins. The first steps in the planning will probably occur some six months ahead of the actual observations and give little more than total time requirements. The final step will be a detailed 24-hour observing schedule, which may be prepared a week or two in advance.

D. Observations

Since the Space Telescope Observatory is highly automated and the appropriate operations are performed remotely, on board a spacecraft, one may well ask what will be the role of the scientific user during an observation. Many of the observations can be done independent of the scientific user since the pointing of ST is automatic, the sensitivities of the Science Instruments will be calibrated accurately, and many results do not require immediate evaluation. On the other hand, some special observing programs may require extensive real-time interactions by the user in cases in which the object is difficult to acquire or the inherent variability of the source demands a quick (few seconds to

minutes) scientific judgement as to how to proceed.

Clearly, the Space Telescope Observatory and the Sci must be able to accommodate both extremes. This capability is planned, although there will be important constraints upon real time interactions due to the limited command access through the Tracking and Data Relay Satellite System. The most commonly used interactive capability will be "quick-look", in which the scientific data will be available at the Sci in a matter of several minutes. This information could then be used to update the next day's observing plan.

E. Data Handling

The scientific data coming from Space Telescope will be characterized by two, usually contradictory, terms: priceless and abundant. This means that the data must be treated with great care and the data handling system must be able to handle enormous quantities of information.

The involvement of an ST observer with data handling begins while his particular observations are still being planned. The observer must understand the various steps involved in observing and data reduction in order to plan appropriate observations.

After the observations are made, the data are sent to the Goddard Space Flight Center (GSFC) where standard processing operations are performed. This step includes rearranging the data and identifying, then correcting, errors that have occurred in the transmission. This accurate and packaged data is then sent to the Sci for the first steps of data reduction. The Sci will perform a set of standard operations on the data from each science instrument. These standard operations will not require scientific judgement, although the work will be supervised by scientists. The observer may use either calibrated or raw data in subsequent analyses. General programs for data analysis will be available for use at the Sci or for copy and use at a home institution. As users develop their own analytical programs, they can be added to the common store of Sci programs.

This method of data handling should be efficient, since repetitive tasks can be done by the (responsible-to-the community) Sci. Users will have a wide variety of analytical tools available to them.

F. Data Archiving

The NASA policy of open access to its data is compliant with law and must be observed by the SCI. This means that all scientific data must be available to all United States users. The precedent has already been set for establishing proprietary periods in order to allow observers time to have the benefits of "first rights" to the data. This period will be one year for the Space Telescope. For programs in which the intrinsic nature of the subject (e.g., parallaxes and very long period variables) demands a longer proprietary period, special exemptions will be made on a case-by-case basis.

This general policy implies that special attention will be given by the SCI to cataloging and cross referencing the data in the archives, since this increases their value to future users. It is expected that proposals to use archived data will be received and funded.

G. Serendipity Data

Since the wide field of view of the Space Telescope is divided into sectors, more than one science instrument can be operated at a given time. This will be done as often as is desirable scientifically within the constraints imposed by the availability of electrical power and the necessity for thermal dissipation. At the very least, the WF/PC can be operated along with any one of the other four axial instruments. This multiple observing capability makes possible two uses of the Space Telescope Observatory that have not been described thus far.

Shared-time observations will result from observing programs requested by the proposal process and accepted for execution. These programs may be very flexible in terms of when and where observations are made (e.g., photometry of the diffuse radiation arising from Zodiacal, Diffuse Galactic and Intergalactic Light) or they may be tied to other observations (e.g., monitor variable stars whenever another science instrument is looking at the Large Magellanic Cloud). These data will be subject to secondary status in scheduling but will be given to the requester on a proprietary basis.

Serendipity data are those secondary observations made by Space Telescope science instruments on an "as-available" basis under direction of the SCI. SCI personnel will identify scientifically justified opportunities for using a second science instrument to obtain measurements at the same time

as a primary observation. Frequently, these will be exposures with the WF/PC. These secondary data will be subjected to the routine processing done on observations prior to being delivered to the observer and will become available immediately to any scientist who proposes using them in an acceptable program. There is enormous scientific potential in the Serendipity data. This will be one of the important areas of activity of the SCI, both in recognizing opportunities and in cataloging the data.

ACKNOWLEDGEMENT

This report is based on the work of a large number of colleagues including the principal investigators for the science instruments, their science teams and contractors, our other colleagues on the ST Working Group, the members of the ST Project Office at MSFC, the ST Science and Operations Office at GSFC, the ST Program Office at NASA headquarters, and the FOC Science Team within the ESA. We are grateful to all these colleagues for their help and collaboration.

This report is dedicated to our colleague, R. E. Danielson. He spent much of his time and energy helping to create the Space Telescope, knowing that he would not be able to share in its use. His technical work underlies the design of Space Telescope; his example of dedication and courage serves as a guide to those who knew him.

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Appendix A. Space Telescope Science Working Group

J. N. Bahcall	Interdisciplinary Scientist	Inst. for Advanced Study
R. C. Bless	PI - HSP	Univ. of Wisconsin
J. C. Brandt	PI - HRS	GSFC
J. J. Caldwell	Interdisciplinary Scientist	SUNY at Stony Brook
W. G. Fastie	Telescope Scientist	Johns Hopkins Univ.
E. J. Groth	Data & Operations Team Leader	Princeton University
R. J. Harms	PI - FOS	Univ. of Cal., San Diego
R. W. Hobbs	Data & Operations Scientist	GSFC
W. H. Jefferys	Astrometry Team Leader	Univ. of Texas at Austin
D. L. Lambert	Interdisciplinary Scientist	Univ. of Texas at Austin
D. S. Leckrone	Scientific Instruments Scientist	GSFC
M. L. Longair	Interdisciplinary Scientist	Univ. of Cambridge
F. D. Macchetto	FOC Project Scientist	ESA
C. R. O'Dell	Chairman & Project Scientist	MSFC
N. G. Roman	Program Scientist-Ex Officio	NASA Headquarters
D. J. Schroeder	Telescope Scientist	Beloit College
H. C. van de Hulst	FOC Science Team Leader (ESA)	Leiden
J. W. Warner	Assistant Project Scientist	MSFC
J. A. Westphal	PI - WF/PC	Cal. Inst. of Tech.

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PLANETARY ASTRONOMY WITH THE SPACE TELESCOPE

Michael J. S. Belton
Kitt Peak National Observatory*

1. INTRODUCTION

The increases in resolution and sensitivity promised by ST over IUE, Copernicus, and OAO-2 will make it a facility of great significance to planetary astronomy, for each of these latter satellites have convincingly demonstrated the ability of earth-orbiting telescopes to contribute to the subject.

My goals in this paper are: to highlight a few problem areas in planetary astronomy that demonstrate the utility and power of the ST; to emphasize the potential for 'discovery' in solar system observations with ST; to emphasize the need for coherent and long-term scheduling commitments and the value of cooperative observations with orbiter or flyby missions; and finally to emphasize to planetary astronomers *that the time to plan and articulate their observational programs and strategies for use of the telescope is now.*

1.1. Experimental Methods in Planetary Astronomy

Observing with earth-orbiting telescopes is now one of many techniques used in planetary astronomy, and the relative importance of these various methods is often, I think, misunderstood. One often encounters the view, for instance, that, as a result of our ability to directly probe, or orbit, solar system objects, remote sensing by ground-based and earth orbital means is of minor importance.

The primary reason why this is not true is that planetary science is still very much in the 'discovery' stage. Unexpected 'discoveries' that are being made today are as likely to be the result of exploratory observations on the ground (new detectors, better instrumentation, new facilities) or in earth-orbit (OAO-2, Copernicus, IUE) as by flyby and orbiting space probes. There are, of course, many substantial areas

*Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

of the subject (e.g. geology of planetary surfaces) where, I think orbiting or landed spacecraft are absolutely essential for further advances. However, there are yet other problems where cooperative observations made from the ground, earth-orbit, and deep space are essential for their advance.

Table 1 attempts to illustrate some of the interplay between the major experimental techniques currently used in planetary astronomy. It can be seen that telescopic observations from earth-orbit not only compensate for many of the disadvantages of ground-based work, but they also compensate for many of the less often recognized disadvantages of the otherwise essential deep space missions.

All three approaches should be used in a complementary way for the most scientific advantage. The potential of earth-orbital observations from ST, SIRT, and several other probable shuttle based instruments, particularly when used in conjunction with deep space missions, is, I believe, the most significant, as well as the most poorly understood, opportunity in planetary astronomy today.

1.2. Current Problems in Planetary Astronomy

Planetary astronomy today divides into three major areas:

- (i) Reconnaissance and exploration of the outer planets and their satellites.
- (ii) A detailed exploration of the terrestrial planets (Mars, Venus).
- (iii) Reconnaissance of primitive bodies in the solar system (comets, asteroids).

Table 1. Comparison of Experimental Methods in Planetary Astronomy (assumes the existence of ST)

Method	Primary Advantages	Primary Disadvantages
Ground Based	Instrumental sophistication, Lowest cost, Programmatic flexibility, Rapid time response to 'discovery' Large optical throughput	Inadequate spatial resolution, Inadequate spectral coverage, Weather; poor time sampling, Limited observing geometry, High sky background in IR
Earth-Orbit	Excellent time sampling (no weather), Excellent spectral coverage, Reasonable time response to 'discovery', Low sky background, Adequate spatial resolution for some objectives	High cost, Limited observing geometry
Deep-Space Missions	Excellent spatial resolution, in situ measurements Excellent spectral coverage, Dedicated objectives, Extended observing geometry, Sample return	High cost, Limited spatial and temporal sampling, Programmatic inflexibility, Simple instrumentation, Non-refurbishable, Long planning cycle, Poor time response to 'discovery'.

I expect that the ST will lead to major advances in terms of (i) and (iii). However, all three areas demand deep space missions for their advancement and the program currently consists of Pioneer Venus, Voyager, and Galileo with VOIR, Comet Rendezvous and SOP² as potential candidates. The word 'reconnaissance' is carefully chosen for many objects are, as I discussed above, still characterized by the unknown and by the excitement of totally unexpected 'discovery.' A broad, quick, first look is the essence of much of the work being done.

Table 2 gives a few examples of recent important discoveries in this field which serve to emphasize that all three basic experimental methods contribute major advances.

The plain fact is that there is still much to learn about the system of planets among which we live. In Table 3 I have attempted to list what I view as the major problems facing the planetary astronomer today. It underscores the fundamental nature of the questions that are being addressed and the fact that adequate knowledge of some of the most obvious phenomena does not yet exist. It also illustrates areas in which I think ST will help to resolve problems.

In the following sections I shall try to illustrate the possible payoff in utilizing the ST for the following selected problems:

1. Atmospheric dynamics.
2. Stratospheric and upper atmospheric processes.
3. Circumplanetary nebulae.

The work done with the ST would not be expected to resolve these problems alone. We can be assured that data generated by sophisticated instruments on the ground as well as data from *in situ* probes, sample returns, and orbiting spacecraft will also be essential. I expect that the very best scientific use of space telescope in planetary astronomy will require a very careful coordination of these different experimental methods.

Table 2. A Few Examples of Recent Discoveries of Major Importance

to Planetary Astronomy

Discovery	Date	Method
1. Uranus Rings	1977	Photometry: Airborne Observatory
2. Pluto's Moon	1978	Photography: G. B. Telescope
3. Neptune's Internal Heat Source	1978	Radiometry: Balloon Telescope
4. Io's Sodium Cloud	1973	High Resolution Spectroscopy: G. B. Telescope
5. Lyman Band (H ₂) Emission on Jupiter	1973	Rocket Spectrometer
6. C ₂ H ₂ on Saturn	1979	IUE
7. Io Induced H ₂ Aurora	1978	Copernicus
8. Jupiter's Rings	1979	Imagery: Voyager
9. Io Volcanism	1979	Imagery: Voyager
10. Jupiter's Plasma Torus	1979	EUV Spectroscopy: Voyager

Table 1. Some Major Problems* in Present Day

Planetary Astronomy

*I address only problems concerning the planets. D. Morrison in a companion paper addresses other solar system objects. The notation (ST) means that I expect ST to provide information important to the resolution of the problem.

OBJECT	PROBLEM
Jupiter and Saturn	1) What is the origin of their banded appearance? (ST) 2) What is the cause of their atmospheric coloring? (ST) 3) What is the origin of their equatorial jets? (ST) 4) What physical processes govern the Jovian Sulphur Torus and inner magnetosphere? (ST)
Uranus and Neptune	1) What is the chemical composition of their atmospheres? (ST) 2) Why does Neptune show a strong internal heat source and Uranus does not? 3) Why do these two planets have such different stratospheres? (ST) 4) How fast do Uranus and Neptune rotate? (ST)
Venus and Mars	1) Why does Mars have global dust storms? (ST) 2) What is the explanation of the peculiar circulation of the Venus stratosphere? (ST)
Mercury	1) What does the 'other' side of Mercury look like? (ST)
Pluto and its Moon	1) What are their sizes, masses, bulk composition? (ST)

2. SPACE TELESCOPE CAPABILITIES

The capability of ST for solar system observations should become immediately clear by looking at Table 4 which is a list of the solar system science objectives proposed by the principle investigators and their teams. I draw the following conclusions from this table:

- (i) All ST instruments have viable solar system objectives,
- (ii) Many of the objectives are associated with time dependent phenomena, and, in fact, need extended and carefully sampled time series of observations for their fulfillment,
- (iii) Many objectives would be enhanced if done in coordination with a deep-space mission (e.g. circulation studies of Jupiter coordinated with Galileo, or studies of chemistry and structures in Halley's comet coordinated with the Halley/Tempel 2 rendezvous),
- (iv) Some objectives would be enhanced if coordinated with ground-based observations (e.g. comet tail studies, coordinated with wide field photography of tail; UV marking studies of Venus coordinated with Doppler and CO₂ measurements from the ground),
- (v) To pursue all of these studies in depth could easily consume most of the available time, especially in the early years after launch.

Table 4. Scientific Objectives in Planetary Astronomy Proposed
by ST Principle Investigator Teams

Instrument	Science Objectives
WF/PC	<ol style="list-style-type: none"> 1) Studies of atmospheric circulation on Jupiter and Saturn. 2) Determination of gross vertical structure of visible and upper atmospheres of Jupiter, Saturn, and Uranus. 3) Optical oblateness of Uranus and Neptune. 4) Aeolian transport on Mars: origin of dust storms, behavior of condensate clouds, support for future lander missions. 5) Evaluation of UV marking on Venus. 6) Exploration of the appearance of planets below 2900 Å. 7) Surface chemistry of airless bodies. 8) Radius of Pluto. 9) Search for extra solar planets. 10) Structure of cometary atmospheres.
FOC	<ol style="list-style-type: none"> 1) Structure and evolution of cometary phenomena. 2) Time dependent features on planetary surfaces.
FOS	<ol style="list-style-type: none"> 1) Structures and velocities in cometary atmospheres and tails.
HRS	<ol style="list-style-type: none"> 1) Composition, structure, and evolution of circumplanetary nebulae: Io's plasma torus. 2) Isotopic ratios in cometary atmospheres: D/H in Halley. 3) Raman scattering in planetary atmospheres. 4) Center to limb behavior of upper atmospheric emissions. 5) Line profiles of upper atmospheric emissions. 6) Auroral activity/dayglow/aeronomy.
HSP	<ol style="list-style-type: none"> 1) Diameters of solar system objects. 2) Vertical profiles of physical parameters in planetary atmospheres.
FGS	<ol style="list-style-type: none"> 1) Positional information on outer planet satellites.

In light of the latter conclusion it is clearly essential to know what is "do-able" so that returned data will be of essentially guaranteed scientific potential. It is also clear that there are preferred times at which certain objectives should be addressed.

In this section I attempt to evaluate the sensitivity and resolution capabilities of the ST instruments in order to estimate their capability for planetary objectives. I also present a calendar for solar system observations which indicates the preferred timing of some of the proposed studies.

2.1. Sensitivity

The discussion of instrumental sensitivity given in Bahcall and O'Dell (1979) makes use of units (visual magnitudes) which are inconvenient when applied to planetary problems. Units of surface light-

Table 5a. Representative Values* for the Surface Brightness of the Planets
in Reflected Sunlight at Three Wavelengths
(photons $\cdot \text{cm}^{-2} \cdot \text{\AA}^{-1} \cdot \text{ster}^{-1} \cdot \text{sec}^{-1}$)

Planet	2000 \AA	5500 \AA	10000 \AA
Mercury	1.3×10^9	1.8×10^{12}	8.1×10^{11}
Venus	1.0×10^{10}	6.4×10^{12}	3.2×10^{12}
Mars	2.8×10^5	2.8×10^{11}	3.8×10^{11}
Jupiter	1.1×10^8	1.2×10^{11}	1.4×10^{10}
Saturn	3.5×10^7	3.6×10^{10}	4.3×10^9
Uranus	1.2×10^7	1.1×10^{10}	2.8×10^8
Neptune	4.8×10^6	4.0×10^9	7.7×10^7
Pluto	2.1×10^6	1.9×10^9	9.7×10^8

*These values are representative and do not represent any particular area on the planetary disk. These values are not recommended as a basis for precise calculations for specific problems.

Table 5b. Characteristic Brightnesses and Line Widths for Selected
Emission Line Phenomena (Rayleigh units)*

Phenomenon	Surface Brightness	Estimated Line Width (FWHM \AA)
Geocoronal Lyman α	1-10 kR	~ 0.06
Jupiter Lyman α	1-20 kR	~ 0.09
Venus Lyman α	~ 18 kR	~ 0.02
Mars Lyman α	~ 5 kR	~ 0.01
Saturn Lyman α	~ 1 kR	~ 0.09
Uranus Lyman α	~ 300 R (?)	~ 0.05
Neptune Lyman α	~ 150 R (?)	~ 0.05
Io Torus Lyman α	0-300 k	~ 0.01
Io Flux Tube Lyman α	~ 100 kR (?)	~ 0.02
Io Sodium (5889 \AA)	~ 10 kR	0.024-0.068
Io SiI (1256 \AA)	43R**	~ 0.09
Saturn Ring Lyman α	~ 200 R	~ 0.01
Saturn Torus Lyman α	~ 500 R (?)	~ 0.01
Jupiter Lyman Band Lines (1608 \AA)	~ 20 ~ 100 R (?)	~ 0.03

*Values followed by (?) are guesses or, at least, very rough estimates.

**Estimate by D. E. Shemansky (1979).

ness are preferred for most problems, i.e. photons $\text{cm}^{-2} \text{\AA}^{-1} \text{steradian}^{-1} \text{sec}^{-1}$, or in some cases, the Rayleigh. This latter unit is equivalent to a surface brightness of $(10^6/4\pi)$ photons $\text{cm}^{-2} \text{sec}^{-1} \text{ster}^{-1}$ and is used to represent the frequency integrated brightness of emission lines from extended objects.

In Table 5a I give representative values of the surface brightness of the planets at three wavelengths: 2000, 5500, 10000 \AA . In Table 5b I give estimates (guesses) of the brightness and line width for a few important emission line phenomena. The information in these tables help define the performance required of the telescope.

Table 6a. Estimated Counting Rates (per pixel per 100 Å or per spectral element)
for ST Instruments on Planetary Disk (counts $\cdot \text{sec}^{-1}$)⁺

INSTRUMENT	λ (Å)	M*	V	M	J	S	U	N	P ⁺⁺
WF	2000	1.3(2)	9.5(2)	2.8(1)	1.2(1)	3.5(0)	1.2(0)	4.8(-1)	2.1(-1)
	5300	1.8(5)	6.3(5)	2.8(4)	1.2(4)	3.6(3)	1.1(3)	4.0(2)	1.9(2)
	10000	8.1(4)	3.2(5)	3.8(4)	1.4(3)	4.3(2)	2.8(1)	7.6(0)	9.7(1)
PC	2000	2.3(1)	1.8(2)	5.0(0)	2.0(0)	6.2(-1)	2.2(-1)	8.6(-2)	3.7(-2)
	5500	3.2(4)	1.2(5)	5.0(3)	2.1(3)	6.5(2)	2.0(2)	7.2(1)	3.4(1)
	10000	1.4(4)	6.1(4)	6.8(3)	2.5(2)	7.8(1)	5.0(0)	1.4(0)	1.7(1)
FOC (f/96)	2000	6.2(0)	4.5(1)	1.3(0)	5.5(-1)	1.6(-1)	5.8(-2)	2.3(-2)	1 (-2)
	5500	8.6(3)	3.0(4)	1.3(3)	5.7(2)	1.7(2)	5.3(1)	1.9(1)	9 (0)
FOS ^{**} (10 ³)	2000	2.8(0)	2.2(1)	6.1(-1)	2.4(-1)	7.5(-2)	2.7(-2)	1.0(-2)	3.2(-3)
	5500	1.2(4)	4.1(4)	1.8(3)	7.6(2)	2.3(2)	7.0(1)	2.6(1)	8 (0)
HRS (10 ⁵)	2000	6.6(-2)	5.2(-1)	1.4(-2)	5.7(-3)	1.7(-3)	6.3(-4)	2.4(-4)	2.8(-5)
HSP	2000	2.1(3)	1.5(4)	4.4(2)	1.8(2)	5.6(1)	1.9(1)	8.0(0)	3.4(-1)
	5500	2.9(6)	1 (7)	4.4(5)	1.9(5)	5.6(1)	1.8(4)	6.8(3)	3.0(2)

*M = Mercury; V = Venus; etc.

⁺1.8(5) = 1.8×10^5 explains the numerical formalism used in the table. I have assumed an effective quantum efficiency of 10% for the imaging detectors and the HSP.

⁺⁺Angular size relative to FOV taken into account (Pluto radius ~ 0.073)

**Assumed apertures were FOS = 0.15 square; HRS = 0.25 square; effective quantum efficiency = 5%.

Table 6b. Estimated Counting Rates Per Emission Line
for HRS (counts sec^{-1})^{*}

Phenomenon	HRS (1.2×10^5)		HRS (2×10^6)	
	Count Rate	FWHM (Diodes)	Count Rate	FWHM (Diodes)
Geocoronal Lyman α	0.3-3	6	19-190	1
Jupiter Lyman α	0.3-6	9	19-380	1.5
Venus Lyman α	5	2	320	< 1
Mars Lyman α	2	1	130	< 1
Saturn Lyman α	0.3	9	19	1.5
Uranus Lyman α	0.1	5	6	1
Neptune Lyman α	.04	5	3	1
Io Torus Lyman α	0.1	1	6	< 1
Io Flux Tube Lyman α	3	2	190	< 1
Io SII (1256 Å)	.01	9	0.6	1.5
Saturn Ring Lyman α	.05	1	3	< 1
Saturn Torus Lyman α	0.1	1	6	< 1
Jupiter Lyman Band Lines	0.005-0.03	2	0.3-2	< 1

*Assumes 5% effective quantum efficiency.

In Tables 6a and 6b I have estimated, using the information given in Bahcall and O'Dell, the expected 'counting' rates, or alternatively the rate of generation of measurable charge, in each of the instruments.

Evaluation of the information in Table 6a and 6b depends on both the sources of noise and also whether the detector reaches saturation at the minimum exposure time. The noise sources are collected in Table 7. The highest counting rates or brightest scenes that can be handled by the various instruments without the use of neutral density filters appear to be: WF/PC $\approx 4 \times 10^5$ cts. sec⁻¹; FOC $\leq 4 \times 10^7$ photons sec⁻¹ cm⁻² Å⁻¹ ster⁻¹ (neutral density filters are provided with this instrument that give attenuation factors that range from 1 to 1.6×10^5). Data on maximum rates was not available for the other instruments, but 10^5 cts/sec is probably a reasonable limit. Important missing data which will not be available until after launch is the actual level of scattered light in the spectrometers.

In the imaging mode the WF/PC should have no problems with the brighter planets providing the spectral bandwidths are ≤ 100 Å. For the faintest planet, Pluto, it should be possible to obtain spacially resolved images at S/N ≈ 10 in less than two hours through a 100 Å filter centered near 2000 Å.

By making use of its attenuating filters, the FOC should also be able to operate on all of the planets, except perhaps Venus in the visual; however, this is probably not scientifically important. This instrument should be able to acquire spacially resolved images of Pluto near 2000 Å (the hardest case) with a S/N ≈ 10 in less than three hours through a 100 Å filter. With suitable filters imaging of emission line phenomena down to the 1 kilorayleigh level seems achievable.

In the spectrographic mode, the FOS will be able to operate on all the planets with 10^3 resolution. Even Pluto can be reached by the FOS at 2000 Å in about 14 hours for a S/N per spectral element of ≈ 10 . The HRS should be able to use its full resolving power out to Jupiter where I estimate a S/N of 10 per spectral element can be achieved in approximately

Table 7. Estimates of Noise Sources in ST Instruments
(Count sec⁻¹ per pixel as per spectral element)

Instrument	Dark	Readout Noise	Sky ⁺	Instrumental Scattering
WF	0.01	± 15	2.7(-3)	-
PC	0.01	± 15	4.9(-3)	-
FOC	0.0001		1.3(-4)	-
FOS	0.002		1.7(-3)	?
HRS	≈ 0.01		8.4(-6)	?
HSP	?	-	1 (-1)	-

*Readout noise is RMS electrons per read.

+ Assume flat spectrum.

13 hours at 2000 Å. At longer wavelengths, e.g. 3000 Å, the counting rates will be up by a factor of 50-100 which may make it even possible to obtain high resolution spectra at S/N ~10 of Neptune at this wavelength in about an hour.

For emission line sources the HRS will be able to reach sources ~1 R/spectral element with a S/N ~10 in six minutes in its highest resolution mode. The FOS with its smallest entrance aperture will reach ~1.0 kR/spectral element in ~15 minutes but with higher spacial resolution than the HRS. At the lower resolution of 2×10^4 with a 2.0 arc sec aperture the HRS should be able to reach emission features of ~2 R/spectral element in one hour at a S/N ~10.

In summary, a comparison of these performance figures with expected brightness levels shows that the instruments on ST have adequate sensitivity to explore the disks of all of the planets in the UV down to 2000 Å with unprecedented spectral and spacial resolution. Also, most known planetary emission line phenomena are available to the HRS at resolutions of 2×10^4 or greater within short observing times again implying a substantial 'discovery' capability.

2.2. Spacial Resolution

I use the following conventions for estimating the resolutions: When the imaging performance is limited at the detector, *experience* shows that the smallest details that can be recognized correspond to about 2.2 pixels; when the performance is limited by the telescope, I have used the Rayleigh criterion. For instruments with single apertures I take the effective linear resolution to be 2.2 times their FOV. The stability of the telescope system should not appreciably affect the effective resolution capability.

While the above conventions may seem arbitrary, their utility is based on the experience that resulting estimates of resolution can be reliably compared with linear scales of physical interest on planetary surfaces or atmospheres.

The planets can be observed from ST over a range of distances; in Table 8 I have collected values of the range of linear resolutions that should be possible for each planet. For the purposes of comparison I also include estimates of what I think can be done under various ground-based seeing conditions.

To assess these capabilities I use the following rules of thumb, which are again based on experience:

- (i) For exploration and 'discovery' any resolution up to and better than the best ground-based resolution. This rule also covers all emission line studies as well as imaging.
- (ii) For detailed atmospheric circulation studies experience with Venus indicates that a resolution of between 1 to 5 scale heights is desirable.

Table 8. Range of Possible Linear Resolution Achieved by
 ST Instruments on the Planets (kilometers)*
 *The two figures in each box represent the resolution at the closest and furthest distance that ST can observe the planet.

Planet	Radius	Atmospheric Scale Height	WF	PC	FOC	FOS	HRS	HSP	Ground Based	
									Best	Average
Mercury	2420	-	152	62	34	227	379	606	342	1368
Venus	6120	5	48	20	11	72	120	191	106	132
Mars	3380	11	84	34	19	125	209	334	108	432
Jupiter	71600	20	672	273	151	1004	1680	2681	1513	6052
Saturn	60000	33	1366	555	307	2041	3407	5449	3074	12297
Uranus	25900	25	2909	1182	654	4345	7254	11599	6545	26179
Neptune	24100	15	4651	1890	1046	6948	11600	18574	10465	41861
Pluto	1600	?	4688	1904	1054	7003	11690	18693	10548	42192
			4992	2028	1123	7456	12448	19905	11232	44928

- (iii) For photogeology resolutions of $\lesssim 1$ km are required for useful work.
- (iv) For examining the chemistry of planetary surfaces, resolution of $\lesssim 2$ km are desired.
- (v) For useful estimates of global properties resolutions of $\sim 5\%$ of the radius or better are required.

The linear resolution capabilities of all the instruments (except perhaps the HSP) coupled with the potential for observations over extended times emphasized the considerable discovery and exploration potential on all of the planets. This will be particularly true for imaging of Pluto, Uranus, Neptune, Mercury, and for emission line studies.

For atmospheric circulation studies Venus and Mars are excellent candidates with the PC as the preferred instrument. The FOC has better resolution characteristics but suffers from its small field of view. Jupiter is also a strong candidate for extended atmospheric studies even though the linear resolution at 273 km is some 13 scale heights. Voyager data has shown that the main features of the global circulations associated within the zone-belt structure can be reliably followed at this resolution. Thus, extended PC studies of global scale atmosphere dynamics on Jupiter when coupled with higher resolution studies (~ 15 km) of limited regions from an orbiting spacecraft (Galileo) can be expected to have considerable payoff (see Section 3).

The ST does not seem to have a lot to offer to photogeologists for detailed morphological studies. However, in the related area of the surface chemistry, the new spectral range of ST combined with resolutions of a few tens of kilometers seems to have considerable potential (Loffler, 1974).

Finally, ST will provide us with our first clearly resolved views of the Pluto system and provide knowledge on masses, density, and bulk composition. ST observations can also considerably refine our knowledge of the oblateness and rotation of Uranus and Neptune.

2.3. Spectral Resolution and Range

The spectral resolution of 1.2×10^5 will allow radial velocities to be determined to about ± 150 m/sec which should be valuable in work on the Io torus. From the data in Table 6b we can see that details of the Lyman α profile will be available for giant planets for the first time. This will say much about mixing processes in these atmospheres. Also the high temperatures in the Io plasma torus can be probed. It may turn out that the most important benefit of the combination of high spectral resolution and sensitivity on the ST is its potential for the discovery of faint emission or absorption lines diagnostic of excitation processes, chemistry, and temperature. Relative intensities of individual H_2 Lyman band lines on Jupiter would be an example of this.

2.4. Time Table for Planetary Observations

I have stressed in the introduction that some planetary observations will have preferred times for their execution. For example, observations of Mercury at aphelion will have greatest interest when the illuminated hemisphere is the one not previously examined by Mariner 10. Similarly Martian dust storms would be best observed when the planet is approaching perihelion. Mission time tables should also be taken into account; extended atmospheric studies of Jupiter might be best done during the 20 months of the Galileo mission, etc.

Figure 1 gives an overview of the timing of planetary phenomena and NASA's program for solar system exploration from which we can assess the impact on ST. A number of obvious things leap to the eye. First, all planets will be available for immediate investigation by the ST, and I would expect the basic parameters of the Pluto system to be worked out within a month. Preliminary exploration of planetary disks in the UV will be done. Within the year we could have our best look at the other side of Mercury. (Note the limited chances to do this.) Halley will also be in the sky at a distance of 8.2 AU from the sun with a nuclear magnitude of ~ 21 and a study of its nucleus and evolving atmosphere would be started immediately in conjunction with ground-based work.

Mars will also be approaching opposition, but probably the best apparition for following the development of a global dust storm is likely

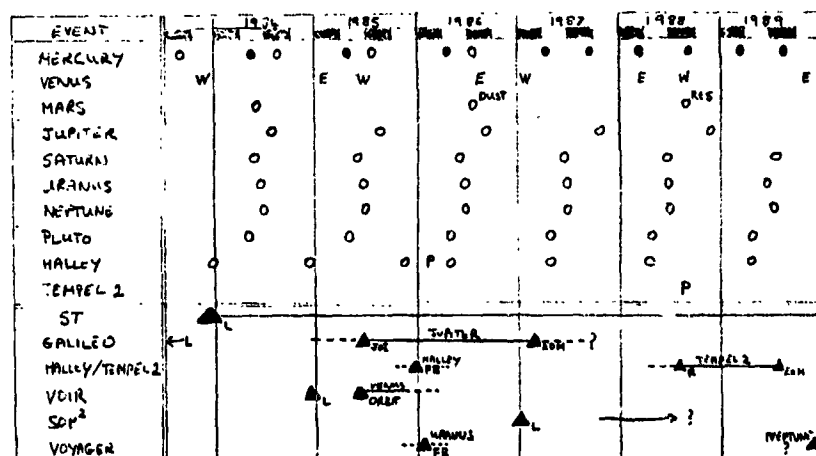


Fig. 1. Mercury: O denotes times when the hemisphere not seen by Mariner 10 is illuminated. Venus: E,W denote maximum elongation East/West. Mars: Dust refers to preperihelion opposition, RES refers to opposition with best surface resolution. Jupiter and Other Planets: O denotes opposition. Halley and Tempel 2: P denotes perihelion passage.

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OF POOR QUALITY

to be in 1986 when opposition occurs just prior to perihelion. The best spacial resolution on the surface of Mars within this time period will be in 1988.

1985/86 is clearly a very important period for planetary astronomy not only because of the Galileo and comet mission, but also because of a potential flyby of Uranus by Voyager 2.

2.5. Capabilities for Selected Problems

2.5.1. Atmospheric Dynamics. The understanding of motions in planetary atmospheres is of interest for at least two obvious reasons: (i) as Stone (1972) points out, the whole question of understanding the vertical structure and local energy balance in an atmosphere usually requires knowledge of the large scale circulation. He points out that a simple radiative-convective calculation for the earth's atmosphere would predict the lapse near the ground to be adiabatic ($9.8^{\circ}\text{K km}^{-1}$), i.e. that the troposphere was unstable; in fact, this is not the case and energy transport due to large scale motions reduces the lapse rate to about two-thirds of this value, i.e. a static stability of $\sim 3.3^{\circ}\text{K km}^{-1}$. (ii) The second reason is more qualitative: We *observe* many long-lived, large scale phenomena, for which we are unable to give a convincing physical (or chemical) explanation. The great red spot on Jupiter is the obvious example.

To make headway in this field it is believed, on the basis of experience in fluid dynamics and meteorology, to be necessary to have measurements of dynamical phenomena over wide range of time and length scale. Figure 2 (provided by P. Gierasch) illustrates this for various fluid dynamical phenomena that might exist in planetary atmospheres. The subject is new and has had most development for the Martian troposphere and the Venus stratosphere. For Mars information on global scale drives for motions has been derived from thermal IR measurements made from Mariner 9 (Pirraglia and Conrath, 1974), and wind fields from surface markings and local sampling at the Viking lander sites. For Mars, theory and observation generally seem to agree. For Venus the information is from apparent motions of UV markings, sporadic information on the horizontal drift of descent probes, and a growing body of Doppler measurements made spectroscopically from the ground (Traub and Carleton, 1979). In this case there are many theories and a poor factual base.

For the outer planets, and Jupiter in particular, the basis of information so far has been imaging of apparent motions by tracing the motion of atmospheric markings at various latitudes. Unfortunately, as can be seen from examining Figure 2, there seems to be little hope for adequately pursuing the problem with ground-based telescopes - even if the weather allowed adequate time sampling. It is still too early to say what the spectacular Voyager sequences can tell us in physical terms except that our factual base will be enormously expanded by virtue of the extended observing time. What contributions can Space Telescope make to this growing field? From a reconnaissance point of view Uranus

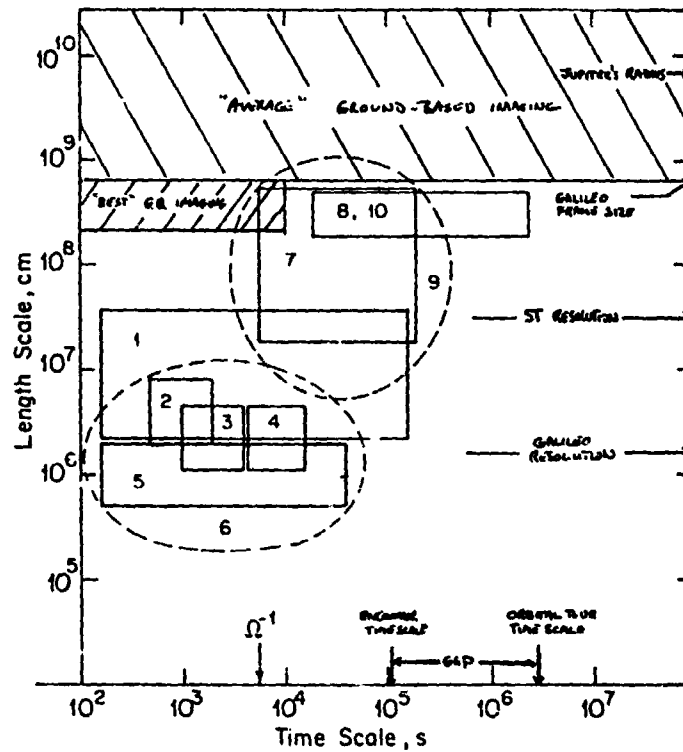


Fig. 2. Time and Spatial Scales Associated with Atmospheric Dynamics at Jupiter; based on a Diagram by P. J. Gierasch (1978). 1) Vertical shear measurement. 2) H_2O moist convection. 3) NH_3 moist convection. 4) Mixing-length convection. 5) Vertical shear instability. 6) Inertia-gravity waves. 7) Inertial-baroclinic instability. 9) Rossby planetary waves. 10) Horizontal shear measurement, spot flows.

and Neptune are natural objectives for the imaging cameras. We would like to know what kind of organization, if any, exists in their atmospheres. The imaging should be done in near IR CH_4 bands and in the far ultraviolet where there is a chance to see markings.

From a more detailed point of view we know from experience that if the available spatial resolution is in the range of 1-5 scale heights and the image format is big enough, then much can be said about global motions provided the time sampling is dense enough or extended over a sufficient length of time. For the planetary camera on ST, these conditions can be met for Mars, Venus, and almost for Jupiter, providing the time can be made available. My reservation about Jupiter is mar-

ginal and disappears if the space telescope is utilized to tackle these problems in the same time frame of the Galileo mission (cf. Section 3).

In order to be more specific about particular observing programs that I would expect to be proposed for ST, I offer the following list:

- Origin and evolution of global dust storms on Mars.
- Individual Martian cloud dynamics.
- Nature of the bow-wave and circumequatorial jets in the Venus stratosphere.
- Nature of the Venus UV patterns (global UV imaging done in conjunction with Doppler measurements from the ground).
- Nature and stability of the equatorial jets on other high speed streams in the Jovian and Saturnian atmospheres.
- Interaction of classes of spots on Jupiter (further tests of the soliton hypothesis).
- Jovian equatorial plumes: Are they instabilities or evidence for waves?
- Development of the Jovian global circulation during the Galileo mission.
- etc.

2.5.2. Stratospheric and Upper Atmospheric Processes. The chemical and physical processes that occur in the upper atmospheres of the planets (and some satellites) are exceedingly complex and in many cases poorly understood. Aeronomical theories are very good at explaining what is observed but have a very poor record of predicting what might be observed (e.g. the non-prediction of the hot Jovian thermosphere (Atreya and Donahue, 1976); and the surprise at finding such a weakly developed ionosphere on Mars (McElroy, 1973).

Furthering our understanding is of interest since these phenomena have a bearing, not only on the course of our every day lives (for example, the stability of the O₃ layer in the earth's atmosphere), but on such atmospheric properties as overall chemical stability and evolution, large scale vertical mixing and interactions with the surrounding space environment.

The observations of these phenomena are, in general, exceedingly difficult to make and involve just about every conceivable observing technique including the use of earth-orbiting telescopes. Both OAO-2 and Copernicus have been used successfully (Hayes et al., 1972; Riegler, 1976) to probe the topside of the O₃ layer and Copernicus has been used to probe thermospheric H₂ and O₂ distributions (Atreya et al., 1976). IUE and Copernicus are also providing important results for other planetary atmospheres; e.g. the possible detection of a powerful source of Lyman α emission at the foot of Io's flux tube in the Jovian ionosphere (Atreya et al., 1977); and a convincing spectrum showing C₂H₂ in Saturn's stratosphere (Moos et al., 1979). The primary observational methods that concern us as far as Space Telescope seem to be the following:

- (i) direct detection through remote spectroscopy of upper atmospheric emissions,
- (ii) observing the occultation of stars by a planet's (or satellite's) atmosphere.

We can best understand the utility of ST for exploring the details of planetary airglow through considerations of Figures 3a and 3b which show the best published spectra of Jupiter in the far UV (Giles et al., 1976; Anderson et al., 1969). Both of these are rocket spectra. In the region 1100 Å - 1500 Å the low albedo is dominated by strong CH₄ absorption near the $n(\text{H}_2) \sim 10^{15} \text{ cm}^{-3}$ density level; longward of 1500 Å the low albedo is a result of Rayleigh scattering from H₂ over a presently unknown combination of absorption due to at least C₂H₆, C₂H₂, NH₃, and photochemically produced aerosols. The two most prominent features in the spectrum are Lyman α and the NH₃ dip between 1700 - 2000 Å. The far UV spectrum also shows a measurable albedo between 1250 and 1520 Å for which Giles et al. make a convincing identification with the Lyman band of H₂, although at the resolution of 25 Å these are far from resolved. The only higher resolution spectra in this range are resolved spectra of Lyman α obtained by Atreya et al., 1977; and by Bertaux et al., 1979) with Copernicus. The Voyager UVS spectrometer clearly, but briefly, showed strong Lyman band emissions in the polar regions of the planet and was able to get special information across the disc in Lyman α but only at low spectral resolution ($\sim 10 \text{ Å}$). The Galileo spectrometer will cover this entire spectral region with good spatial resolution and high sensitivity but again with low spectral resolution. Both Copernicus and IUE have moderate spatial resolution and high spectral resolution capability but generally lack the sensitivity to adequately make use of it on planets.

ST provides what is missing and what is required to complement the work already done and also the investigations to be done by Galileo: high spectral resolution combined with good spatial resolution and adequate sensitivity. Perhaps even more importantly ST allows us to pursue these problems deeper into the solar system - to Saturn, Uranus, and Neptune.

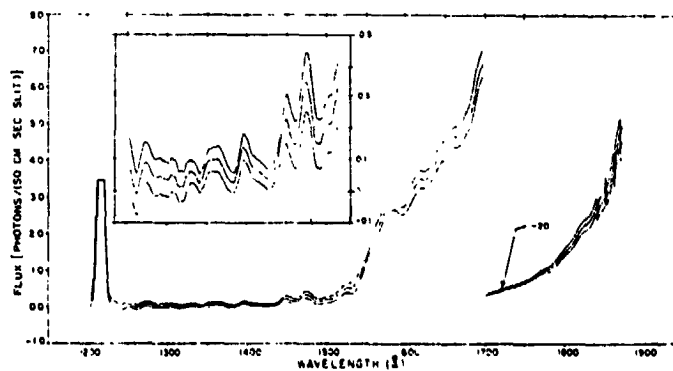


Fig. 3a. Jupiter Ultraviolet Spectrum (Giles et al., 1976)

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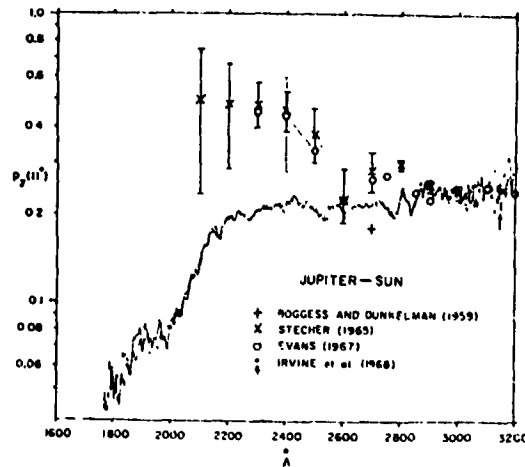


Fig. 3b. Jupiter Ultraviolet Spectrum (Anderson et al., 1969)

Let me outline some of the more obvious problems I expect ST to address in this field:

- (a) Examination of the profile of Lyman α and its spacial dependence across Jupiter and Saturn. The current explanation of Jupiter Lyman α intensities (Wallace and Hunten, 1973) limits scattering to the column of H above the homopause. This is because the more massive CH_4 molecules which are the primary sink for solar photons at this wavelength, diffusively separates out at this level in the atmosphere. The theory shows that the Ly α albedo, the shape of the line, and its distribution over the disk is therefore governed by the extent of dynamical mixing processes in the lower atmosphere; i.e. the eddy diffusion coefficient, which in turn governs the chemical equilibrium of the upper stratosphere (Strobel, 1975). To date, the sporadic measurements of the Lyman α albedo have all given very different results ranging from 1-20 kR and provide little confirmation of theory and generate considerable confusion. ST has the capability to attack these problems in detail.
- (b) Examination of the albedo and profile of Lyman α and the distribution of lines in the Lyman bands of H_2 in Jupiter's *auroral* regions and the foot of Io's flux should give new knowledge on the location and nature of the excitation processes involved. Auroral Ly α may reach ~ 100 kR (Shemansky, private communication) and should present little problem to ST. The Lyman bands should have individual lines whose intensities reach ~ 100 R which are also within reach of ST. Auroral activity associated with H should also be looked for on Saturn, Uranus, and Neptune since the results of Brown (1975) indicate that all of these planets may have magnetospheres.
- (c) Unknown emissions. The probable fact that the atmosphere of each of the major planets sits in an active magnetosphere, plus the

possibility, at least in Jupiter's case, that metallic atoms are entering the atmosphere from the outside, suggest that there may be many unknown features to their airglow spectra. ST should be involved in a reconnaissance for such emissions to the limit of its sensitivity.

Observations of the occultation of stars by planetary atmospheres from ST also have much to commend them. This technique, which has produced many significant results, is limited by (a) the rarity of events with bright enough stars, (b) atmospheric seeing, and (c) the speed of the occultation event. The combination of pointing stability, small effective aperture (to discriminate against background light from the occulting object), and the sensitivity of the HSP over a wide spectral range would make it the best available instrument for future planetary occultation studies. Further gains might accrue from making occultation studies. Further gains might accrue from making occultation measurements in the UV, and also by using the spacecraft motion to slow the occultation event down. Elliott (private communication) estimates that as a result of the potential improvement in data quality, the frequency of useful occultations by the outer planets could increase by a factor of 5 to 20 for ST over ground-based. Currently, for example, Neptune offers a single worthwhile opportunity every 5-10 years while from ST Elliott expects this to rise to 1-2 occultations per year.

One of the primary objectives of these experiments should be to acquire enough independent occultations events (hopefully in cooperation with ground-based observers) to settle the question of the origin of occultation 'flashes.' At present it seems impossible to reasonably decide whether these are the result of incoherent turbulence in the stratosphere (Young, 1976; Jokipii and Hubbard, 1977) or due to large amplitude wave propagation (French and Gierasch, 1974) or to stable layers. A lot is at stake here for the most widely entertained explanation for the 1000° K Jovian thermosphere is the wave phenomenon (Atreya and Donahue, 1976).

Finally, it has been pointed out to me by S. Atreya that the pointing stability of the ST combined with its ability to obtain high spectral resolution in the UV over reasonable spectral bandwidth make it a very important instrument for probing the abundance and distribution of minor constituents in the upper stratosphere, particularly during the night. He finds that it should be possible to sound many constituents important to the chemistry of the O₃ layer; he notes that ClO, NO, HNO₃, NO₂, CCl₄, and O₃ itself should all be observable from ST if the programmatic complexities of performing stellar occultations can be overcome.

2.5.3. Circumplanetary Nebulae. The phenomenon which I call circumplanetary nebulae was first recognized when McDonough and Brice (1973) pointed out that hydrogen atoms escaping from Titan's upper atmosphere would not be able to escape the gravitation attraction of Saturn and would probably form a 'hydrogen torus' encircling the planet. They suggested that such hydrogen tori might be commonplace in the outer solar

system and called for a Lyman α search for them. In the same year Brown (1974) discovered the neutral sodium cloud (a partial torus) emanating from Io, Blamont (1974) calculated that Saturn's rings should retain a measurable OH/H atmosphere, and finally in December of the same year, Pioneer 10 arrived at Jupiter to discover a neutral hydrogen torus associated with Io (Carlson and Judge, 1974).

Since that time Weiser, Vitz and Moos (1977) may have discovered, using a rocket borne spectrometer, the hydrogen atmosphere associated with Saturn's ring (200 R); Wu, Judge and Carlson (1978) may have found clouds of O and H associated with Europa, and finally, a host of neutral and ionized atoms (K, SII, SIII, OII, OIII) have been found by ground-based, earth-orbital, and Voyager observations in the vicinity of Io with the ionized component in a torus locked to Jupiter's magnetic equator. The subject is an excellent example of the primary theme of this article, which is the synergism of observations made from the ground, earth-orbit, and deep space.

The physical mechanisms that govern the Io related plasma and neutral tori are far from clear: Source mechanisms that have been suggested include sporadic eruptive ejection from Io volcanos, sputtering from the surface, and thermal escape from a tenuous atmosphere. Loss and excitation of observable species appears to be due to electron collisions, charge transfer, and to diffusion out of the region of the torus.

The stability of the system is also in question. The sodium cloud appears to be relatively stable; while the neutral hydrogen cloud seen by Pioneer had disappeared at the Voyager encounter. The hot ($\sim 10^5$ K) sulphur and oxygen plasma torus found by Voyager on the other hand, was not present when Pioneer flew by. There are now indications of major changes between Voyager 1 and Voyager 2. There is evidence in both the ground-based data and Voyager data that strong compositional and temperature gradients occur in the region. A strong acceleration mechanism is also apparently at work for O, Na, and S nuclei with energies in excess of 7 Mev have been found in the immediate vicinity of Io (Vogt et al., 1979). Neutral sodium (a small fraction of the total) has been seen flowing out from Io at velocities up to 18 km sec^{-1} as the satellite passes through Jupiter's magnetic equator (Trafton, 1975).

The capabilities of ST for pursuing these problems is substantial. In the 'discovery' mode the evolutionary behavior and temperature of the now missing, neutral hydrogen torus at Jupiter is a natural objective. For example, is it possible that the hydrogen and plasma tori are mutually exclusive, the latter being sporadic and dependent on intermittent volcanic activity? The brightness of the H torus during the Pioneer flyby was $\sim 300 \text{ R}$ and is within easy reach of the HRS in the 2×10^4 resolution mode. Similarly a search for emission (H and OH) originating from Europa may be possible to a few tens of Rayleighs given enough observing time. This emission might also be sporadic and related to upwelling of slush through Europa's cracked crust. At Saturn it is unclear what will be important for much will depend on the results from the Pioneer 10 and

subsequent spacecraft; however, if Blamont's estimate of 100-500 R for the Titan torus is roughly correct, then it should be within easy reach of ST as should the ring atmosphere. A look at Neptune might also be worthwhile extrapolating Blamont's Titan estimate to the distance of Triton we might be surprised to find as much as 50 R of Ly α . This would have implications for Triton's atmosphere and for the environment within which it orbits Neptune. Finally Uranus is so peculiar in so many unexpected ways we had better have a look there also!

In a more detailed mode an examination of the plasma torus is an obvious objective. ST can contribute knowledge regarding its composition, stability, the sources that feed it, and its interaction with Jupiter (if any). The ST may also find signs of D, Ca, C, Si, N, Mg, S, O as well as emissions in the torus due to SIII (1194, 1201), SII (1256). Shemansky (1979) predicts 60 and 43 R for these latter emissions. This work could again be done in conjunction with observations of Na, K, SII, OII, SIII from the ground and should reveal detailed information regarding the source mechanisms at work, temperatures, and compositional homogeneity as the nebula evolves. The high spectral resolution capability should allow secure identification of emitting species to be made.

The special spatial resolution capabilities of the ST spectrometer, when used to probe neutral species very close to the satellite, may also be able to distinguish in a definite way just where on the satellite the source locations are located. The interpretive study of Murcray and Goody's (1978) sodium cloud pictures by Smyth and McElroy (1978) seem to indicate that examining D line intensity contours perhaps as close as ~ 2 arc sec from the satellite would give secure knowledge of the location of source on its surface. Finally, another obvious problem is to characterize the emission at the foot of Io's flux tube and its relation to torus activity and to radio bursts.

3. THE GALILEO IMAGING PROBLEM: AN EXAMPLE OF THE USE OF THE SPACE TELESCOPE IN CONJUNCTION WITH A DEEP SPACE MISSION.

The Galileo spacecraft will drop a probe into the Jovian atmosphere in June 1985 and then will itself be injected into orbit around the planet. The orbiter will operate for 20 months negotiating some 11 encounters with the Galilean satellites. One of the main objectives of the mission is to investigate the chemical composition and physical state of Jupiter's atmosphere. It is in attaining this objective that an extended sequence of observations from ST, particularly with the planetary camera, would be of tremendous value.

3.1 What Galileo Can Do and Some of Its Limitations

The Galileo spacecraft is of the dual-spinner type; it is also an exceedingly massive spacecraft. As a result of the latter factor and also because of the finite booster power of the shuttle/IUS combination, the spacecraft must arrive at Jupiter on a trajectory that approaches the

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planet at a high phase angle ($\sim 120^\circ$); also the initial orbit is characterized by long looping orbits extending to the night side. The situation is illustrated in Figure 4.

Because of the long nightside orbits only a small fraction of time (20-30%) will be available for viewing the lighted hemisphere; also, on approach to the planet (or receding from it), the imaging, and other remote sensing instruments on the stabilized part of the spacecraft, must look past the spinning section which is characterized by several extremely long booms. The remote sensing instruments are therefore in a 'shoot-through-the-booms' mode for a substantial period - including the entire initial approach trajectory! The three booms rotate at 3.3 rpm and periodically obstruct the view. The problems of approach and recessional imagery are made worse by a recent Voygaer finding that at phase angle of 120 degrees and greater, planetary features lose much of their contrast. The final component of this problem is that because of severe weight limitations the imaging system on this spacecraft is limited to a single camera, and for reasons that are not germane to this discussion, the camera has a very high resolution capability and, consequently, a small FOV (~ 8 mrad square). The result is that when the camera can see Jupiter adequately, the images are usually limited to very small areas of the planet.

The Galileo imaging system is superlative in its capability to deal with surfaces of the satellites, and detailed studies of special features in Jupiter's atmosphere. However, as a result of the above problem, it

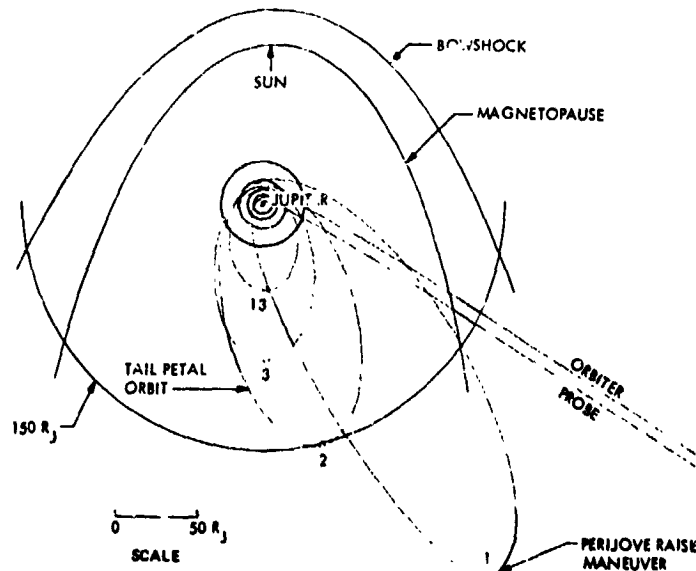


Fig. 4. Galileo Reference Tour 79-1

lacks the ability to obtain high quality information on the global state of Jupiter's atmosphere *on a continuing basis*. As a result, it will not be possible for Galileo to adequately inform itself on the general state of Jupiter's atmosphere during the initial approach, or during probe entry, or of its subsequent changes. It will not be possible, at least in any simple way, to accurately target on particular atmospheric phenomena that we wish to examine in detail during each perijove pass. Finally, it will be difficult to properly characterize the global context of the probe descent region.

3.2 The Role of the Space Telescope in the Galileo Mission

The role of ST in Galileo as far as the problems I have posed above are concerned is to provide continuing global coverage of the state of Jupiter's atmosphere over the duration of the Galileo mission. The ideal observing program would call for about two image every 1/4 rotation ($\sim 2\ 1/2$ hours) throughout the approach to the end of the mission, i.e. ~ 650 days! This is roughly 12,000 images. This can be compared with the roughly 50,000 images that will be taken from Galileo itself. Such an observing effort is what the Galileo imaging team would like to get. Some compromise is presumably inevitable. The scientific value of this coverage would not only be to substantially enhance our understanding of dynamical processes that are occurring in Jupiter's atmosphere, but allow us to extend out detailed knowledge of the probe descent region to a global context. It would increase our confidence in the relevance of much of the probe data to the discussion of Jupiter's atmosphere as a whole.

4. OTHER ISSUES AFFECTING THE SCIENTIFIC USE OF THE SPACE TELESCOPE IN PLANETARY ASTRONOMY

4.1. The Space Telescope Institute

Many of the future professional staff of the Institute are probably sitting in this room at this instant, and, without doubt, it is essential that the majority of them should have their scientific interests firmly rooted in modern astrophysics and cosmology. The reason is, of course, very straightforward for the performance of this staff will be crucial, in my view, to the efficient scientific operation of the telescope and ultimate scientific success of the project as judged by the community.

However, as I have tried to outline above, the space telescope and its initial instrumentation has considerable potential in planetary astronomy. Also, many of the observations that planetary people will want to make will be technically difficult: sometimes these observations will push the stability and guidance capabilities of the system to their limit, sometimes they may clash with safety limits for telescope operations, and sometimes they may involve complex maneuvers. W. L. Upson II informs me that in the case of Copernicus it is his experience that observations of solar system objects are by far the most demanding to plan and execute.

In addition considerable thought and advice will have to be given on the scheduling problem so that the maximum benefit of cooperative observations with orbital, rendezvous and flyby spacecraft can be obtained.

It seems to me, and I speak both to any potential institute director that might be sitting here as well as the larger community of planetary astronomers, that as a result of these complications, it seems to me to be essential that some of the professional staff of the forthcoming institute should be planetary astronomers if the best scientific use of the ST for solar system problems is to be achieved.

4.2. Refurbishment

The initial instrumental capabilities on ST are extremely powerful and will certainly provide a major leap in our knowledge of solar system objects. However, there are some obvious problem areas that the telescope system will not at first, be able to address; for example, high spatial resolution imaging capability of the telescope could be put to excellent use in the visible and near infrared if it could be coupled with directly high spectral resolution. Center-to-limb observations in the H₂ quadrupole lines on the outer planets for probing the vertical structure and location of cloud layers in their atmospheres is an example which cannot be done with the present complement of instruments and for which instruments are currently being developed on the ground.

I bring this topic up because I believe the ST will continue to have great potential for solar system studies well after the initial instrument complement has yielded its share of new knowledge, *and that it is not too early, particularly in the case of complex instrumentation to start thinking about the first refurbishment cycle now.*

5. ACKNOWLEDGMENTS

I would like to thank the following persons for generosity in providing inputs, advice, and discussion: S. Atreya, J. L. Bertaux, J. C. Brandt, J. Caldwell, J. Elliott, N. Evans, P. Gierasch, S. Hayes, W. Moos, S. Ridgway, B. Smith, L. Trafton, W. Van Altena, L. Wallace, C. Wu, and D. York.

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DISCUSSION

Smith (Discussion leader): ST can provide crucial knowledge of the Uranus and Neptune systems which will assist Voyager Project in making a 1985 decision of whether or not to send Voyager 2 past Uranus at the appropriate point in space to carry it onward to Neptune. Since a trajectory through the aiming point could compromise the scientific yield at Uranus, such a decision should be made with the greatest possible understanding of both planetary systems.

There can be little doubt that complex organic chemistry, similar to that which occurred on Earth prior to the formation of life, is still going on in the atmospheres of the giant planets. Production and destruction rates are not known, but complex organic molecules are likely to be locally concentrated. Many of these prebiotic molecules have diagnostic or quasi-diagnostic absorptions in the spectral range 2300-2700 Å. High dispersion, high resolution spectroscopy of selected regions on Jupiter and perhaps Saturn should be included in the observing program.

Many studies of interest to planetary scientists can be accomplished with a single or a few observations. Others, relating to time-dependent phenomena, may require extensive observing programs which will have to be judged in competition with other scientific objectives.

Time-lapse sequences of global circulation of Jupiter's atmosphere obtained by Voyager have spatial resolutions from 5 to 3 times poorer than those attainable by ST. The Voyager observations cover only two brief epochs in Jupiter's changing "weather" patterns. A much more detailed and temporally complete study could be accomplished by ST.

Caldwell: I have two comments to make on the subject of planetary astronomy with Space Telescope. They concern priorities for planetary study, and practical considerations for making such observations.

First, it is apparent that planetary science by itself could oversubscribe the available time on ST. Furthermore, this saturation would include uniformly good science. Therefore, there seems to be no viable alternative to the painful necessity for the planetary community to discipline itself and make priority judgements about the various programs. I therefore propose a criterion for rating ST Solar System research.

Currently, the quality of knowledge about the planets is excessively heterogeneous, with some planets known in intimate detail (Venus, Mars, Jupiter) and some are only poorly known (Mercury, Neptune, Pluto). Moreover, those planets that are well known are such because of their location, not their intrinsic interest. In fact, no one knows which planets are most interesting.

The basic aim of our research is to provide an understanding of the origin and evolution of the Solar System. It seems to me that a necessary basis for this work is to establish data of more nearly uniform quality about the extremes of the system. To some extent, any comprehensive theory must be limited by the least precise data in it.

My suggestion, therefore, is to weight planetary proposals somewhat according to the current ignorance of the target. This would not imply any quota or ceiling on the absolute number of successful planetary proposals. It should not absolutely exclude programs of extraordinary merit (Galileo support, for example) for any planet. But it would discourage people from doing just "more of the same". And if the remote objects should unexpectedly prove to be relatively uninteresting, the policy could quickly be changed.

My second point is that planets have their own peculiar observing problems. Venus, for example, never gets more than about 47 degrees from the Sun. To observe this planet, one must slew the ST a large distance to a pointing that is more favorable with respect to thermal ar power considerations on every orbit. Thus the brightness of the planet is more than counteracted by the excessive slewing time in the total accounting for time.

Recently, the ST project considered an engineering exercise in which Venus was hypothetically imaged once per day for cloud dynamics studies. However, because of the limited fraction of the disk observable, and the speeds of the features, such a sampling would produce no overlapping of images, and would be useless for their stated purpose. It would be necessary to increase the sampling rate by a factor of two or more to make the scheme viable.

We must therefore address the hard question of whether such a project, meritorious though it may be, is worth the cost in time. If it requires one hundred hours of slewing to achieve one hour of cumulative exposure, it is just as costly as one that requires one hour of slewing for one hundred hours of exposure.

Atreya: I have two comments on Mike Belton's presentation: first, I would like to emphasize the importance of planetary line shape measurements. A good example is Jovian Lyman- α . So far, there are only three spectral doppler line profile measurements of this emission, all on Copernicus. Mike has already discussed how the significant atmospheric parameter, the eddy diffusion coefficient, may be determined from Jovian Lyman- α . Actually, one needs only the total intensity for doing that. The line profile however can provide the temperature of the upper atmosphere. The only two temperature measurements are: Pioneer epoch at the solar minimum, and Voyager at the solar maximum. The upper atmospheric temperature has increased dramatically by more than

60% during this period. It is extremely important that the Jovian Lyman- α spectral profiles be monitored continuously to understand the physical processes leading to the heating of the exosphere of Jupiter. It has become apparent that Jupiter sustains a corona. What remains to be known is how this energy is supplied to its upper atmosphere, what causes its temporal variation, and whether or not the variation is sporadic. The ST is perfectly suited for accomplishing this task. The above arguments are equally applicable to the emission lines of the Io plasma torus.

Secondly, ST is the most powerful instrument yet to come along for detecting trace pollutants in the earth's stratosphere. The technique used will be similar to the limb "grazing" stellar occultation demonstrated to be highly successful on Copernicus. Although atmospheric refraction, instrumental scattering and guidance problems limited the Copernicus observations down to about 44 km (about one scale height below the stratopause) it is precisely the region between 50 and 100 km which is in need of most help. This is due to the fact that the influence of trace pollutants on the atmosphere, particularly ozone, is predicted by theoretical models applied to the stratosphere ($z < 50$ km). In order to have confidence in these models, they must be capable of successfully predicting the distribution, diurnal, temporal and latitudinal variations of the "natural or unperturbed" atmosphere between 50 and 100 km. This region is not accessible by conventional techniques such as balloons, rockets or other earth orbiting vehicles. The ST with its excellent stability, guidance capability and sensitivity is ideally suited to carrying out stellar occultation exercises to determine parts per billion (even tenths of ppb) pollutants in the height range greater than 40 km.

Noos: The combination of spatial and spectral resolution can provide significant information about the interaction of the magnetosphere and the atmosphere of a planet, and hence about the nature of the plasma trapped in the magnetic field. On Jupiter, for example, ultraviolet emissions are expected where magnetic field lines from the magnetotail, the Ioian torus and Io itself enter the atmosphere. Since the field lines from each of these sources enter the atmosphere at different latitudes and longitudes, each source will have a different spatial signature. At present, we do not know how these sources change with solar activity and with planetary parameters. Using the IUE instrument with a resolution of ~ 6 arcsec it is possible to observe the auroral zones on Jupiter. With much improved spatial resolution, it will be possible not only to differentiate between the plasma sources but to discover unsuspected kinds of magnetospheric plasma sources.

Belton: While on the subject of plasma tori and magnetospheres, it should be noted that both Saturn and Uranus have been detected as radio emitters indicating they probably have magnetospheres similar to Jupiter. Magnetospheric studies and related observations should not be restricted to Jupiter.

Filcher: You have just heard a number of reasons for studying the Jovian magnetosphere. I'd like to point out another, perhaps broader, reason. The Jovian magnetosphere contains a unique example of an astrophysical plasma that we can study both by means of conventional astronomical techniques and by means of *in situ* observations. This capability of sending spacecraft to a plasma that emits several of the lines that have been observed for decades in the study of planetary nebulae and other astrophysical plasmas may afford us an unparalleled opportunity to further our understanding of the relationship between the plasma conditions in these distant astronomical objects and the radiation they emit.

I can best illustrate the capabilities of the Space Telescope for studies of the Jovian magnetospheric plasma by showing you the results of some recent ground-based observations. These data are images of the Jovian sulfur ring in the λ 6731 Å forbidden line of S II. This transition from a meta-stable level, being excited predominantly by electron collisions, is diagnostic of the characteristics of the ambient thermal plasma as well as those of the sulfur plasma itself. The spatial structure and temporal variability in these data, acquired on two successive nights in April 1979, make it clear that the Space Telescope can be used to great advantage in the study of this system. I propose that at least three ST instruments may be used extremely profitably for these observations.

1. Wide Field Camera - Images of the circum-Jovian ring of heavy ion plasma may be obtained in a variety of lines of sulfur, oxygen, sodium, potassium, etc. in a variety of ionization states (e.g., SI-IV, OI-IV). These images may be used to deduce the nature of the source of the heavy ion plasma as well as some aspects of the plasma characteristics.
2. Faint Object Camera Spectrographic Mode - The high degree of spatial structure (see, for instance, the "fan" observed in the sulfur ring) combined with the diagnostic nature of line ratios (these may be used to determine n_e , T_e) makes this a powerful technique for examining the small-scale spatial non-uniformities in the plasma.
3. High Resolution Spectrograph - This instrument will allow us to measure precise emission wavelengths and line shapes, providing unique information on the plasma dynamics.

Elliot: I would like to describe briefly the study of planetary upper atmospheres using the technique of stellar occultations and describe the new results that we would hope to obtain with the Space Telescope. The main reason for using the Space Telescope for occultations is that a much higher signal-to-noise ratio can be achieved for most events, due to the rejection of background light from the occulting planet that is possible with a small focal plane aperture, and the absence of

scintillation noise from the earth's atmosphere. For example, only about six stellar occultations appropriate for the study of planetary atmospheres, have been observed in the last twenty-five years. With the high speed photometer on the ST, we expect the capability to increase to a few per year per planet.

From a stellar occultation we obtain a variety of information about the occulting planet and its ring system, if it has one. From the occultation by ring material we learn the detailed optical depth structure of the rings and their precise relative positions - the positional accuracy is about 10^{-4} arc-seconds at the distance of Uranus, for example. From the occultation by the planet itself, we obtain the temperature, pressure and number density profiles of its upper atmosphere at the 10^{-2} millibar pressure level. The only other method to obtain the structure of the atmosphere at this level is by spacecraft probes that directly enter the atmosphere. For planets beyond Jupiter, no missions involving entry probes are currently funded.

Several questions come to mind, which we could hope to answer with occultation observations with the ST: Do Triton and Pluto have atmospheres? What are the temperatures and dynamical properties of the upper atmospheres of Saturn and Titan? Why is the upper atmosphere of Uranus about 40 K cooler than that of Neptune, and what are the origins of the "wavelike" temperature variations observed in the occultation profiles obtained for these planets? Further information on this topic can be obtained from my review article in this year's issue of the Annual Reviews of Astronomy and Astrophysics.

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N80-22133

INVESTIGATION OF SMALL SOLAR SYSTEM OBJECTS WITH THE SPACE TELESCOPE

David Morrison
Institute for Astronomy
University of Hawaii
Honolulu, Hawaii 96822

One of the prime motivations behind astronomical research in general, and utilization of the Space Telescope in particular, is our desire to understand our ultimate origins. With the ST we expect to find answers to fundamental questions concerning the birth and death of the universe. But another fundamental question of comparable significance deals with more local beginnings. The Sun and its planetary system were formed long after the initial creation, accreting in an obscure corner of our galaxy by processes perhaps less well understood than those of the universal Big Bang. In this paper, I consider ways in which the Space Telescope can contribute to studies of the birth and early evolution of the solar system, through studies of its smaller members.

It is generally believed that the solar system was formed about 4.5×10^9 years ago when a local collapse of a cloud of interstellar material developed a hot central mass, the proto-sun, surrounded by a more tenuous disk of orbiting debris, the solar nebula. The nebula was presumably mostly gas, but it may have included interstellar dust grains which were never vaporized by the proto-sun before general cooling of the nebula permitted widespread condensation of refractory solids. For some period the condensing solids remained in approximate chemical equilibrium with the gas, with composition controlled primarily by temperature. The degree to which chemical equilibrium was reached, or maintained as the grains accreted into larger masses, is a major area of uncertainty. Apparently the growth of solids proceeded rapidly once condensation began, with planetesimals of up to several hundred kilometers diameter formed; these in turn accreted to form the planets and satellites, in the process being mixed and scattered by gravitational interactions. Each planet presumably contains materials from a variety of locations in the nebula, and the record has been further blurred by subsequent heating and differentiation to the point where large bodies retain at best a faint memory

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of the conditions of their birth. In contrast, some of the primitive planetesimals escaped both incorporation into larger bodies and gravitational ejection from the solar system. These remain today as asteroids, small planetary satellites, rings, and comets.

Most of what we know about the formation of the solar system has been derived from these objects, particularly those whose fragments reach the Earth as meteors, meteorites, and interplanetary dust. Detailed chemical and isotopic analysis of these samples in terrestrial laboratories remains the primary tool for this research. But astronomy also plays a vital role in relating the samples to their parent bodies, and in exploring the classes of small solar system objects that are presumably not represented in our randomly acquired collection of fragments that have reached the Earth. The Space Telescope also has an important place. Since the number of basic questions about the small bodies that can be answered by ST is relatively small, these investigations will make modest demands of observing time. However, it is vital that this instrument be used where it has a major capability, since the alternatives are sometimes extremely expensive planetary deep-space missions. In solar system research, we must combine carefully the strengths of laboratory studies, of ground-based astronomy, of observations from Earth orbit, and of dedicated planetary missions in order to achieve our goal of exploration and understanding in an efficient and cost-effective manner.

In the above I have sketched a motivation for studying small objects in terms of their chemically primitive nature, as the least-altered survivors of the original conditions from the solar nebula. But, of course, many small bodies have undergone subsequent chemical evolution of differing degrees, up to the case of Io, which is surely the most thoroughly heated, processed, and volatile-depleted object in the solar system. In the following, I will include studies of the evolved, as well as the primitive, small bodies. The upper size limit for a "small" body is ~5000 km, so as to include the largest satellites, except for Titan, which is considered a planet for purposes of this discussion.

High-resolution imaging is one of the important tools provided by ST for study of small solar-system objects. In the following, I will assume that resolutions of ~0.05 arcsec, or equivalently ~40 km at 1 AU, can be achieved. This resolution corresponds to the pixel size of the Planetary Camera. To achieve it, special image processing will be required; without this effort, the nominal resolution will be about a factor of two worse. The Target Object Camera has a pixel size a factor of two smaller yet, corresponding to about 0.002 arcsec. For the nominal resolution of the ST optics, this represents oversampling of the point-spread-function, and it is unlikely to yield realizable resolutions this high. However, if the optics perform better than now

expected, the FOC is likely to provide higher-resolution images than those assumed in this discussion. The actual resolution of any of these instruments, of course, will not be known until ST is actually performing in orbit.

PLANETARY SATELLITES

The 34 known natural satellites in the solar system encompass a remarkable variety of worlds, from Titan with its cloudy atmosphere and Io with its gigantic volcanic eruptions and complex magnetospheric interactions, to thousand-kilometer-diameter ice-balls such as Phebe or Dione, to small objects such as Elara or Phobos that may be genetically related to the primitive asteroids. The study of these objects has grown over the past decade into a major branch of solar system astronomy, and with the Voyager exploration of the Galilean satellites (and unimagined wonders yet to come at Saturn), their continued prominence is assured. Each of the major satellite systems - of Jupiter, Saturn, and Uranus - is a kind of miniature solar system, and we already know for the Galilean satellites that these objects are as varied, and as interesting, as the terrestrial planets themselves.

The most spectacular advances in our knowledge of planetary satellites have come from direct exploration, of Phobos and Deimos from Viking and of the Galilean satellites from Voyager. Generally speaking, these objects are now the province of the geo-scientist, not the astronomer. Where a Mariner-class spacecraft has already explored, there is not a great deal remaining for Earth-based astronomy, except in the study of time-variable phenomena. In the preceding paper Belton has discussed these areas, including the exciting cases of Titan and Io. In this paper, I restrict myself to satellites without atmospheres or extended plasma clouds.

From the geological point of view, images with resolution of about 10-20 km are required for a first-order global perspective, and resolution near 1 km is required to reveal the details of geological processes. The ST cannot approach these resolutions for any outer solar system satellite. For the Galilean satellites, resolutions of ~200 km are possible, but such images could contribute little after Voyager, with the one exception noted below. At Saturn, the resolution is ~400 km; even today, such images would be of only limited interest, and after Voyager they too would be obsolete. There is only one major area in which ST imagery of satellites might be useful, and that is in extending the search for faint inner satellites of Saturn, Uranus, and Neptune. The high spatial resolution, freedom from atmospheric scattered light, and faint limiting magnitude of ST should produce much more complete surveys than have been possible from the ground. The discovery of such inner satellites would have important implications

for the origin and dynamical structure of planetary rings. In contrast, the ST will not be used to search for faint outer satellites, which are best located with ground-based, wide-field surveys.

Although the prospects for carrying out geological studies of satellites from ST are weak, there exists a special opportunity to study time-variable phenomena in the case of Io. The largest volcanic fountains or plumes seen by Voyager are 200-300 km high and perhaps 600 km across at the base. At a nominal 200-km resolution, such features might be detectable, with appropriate image processing. If so, ST could make a major contribution to understanding the time-scale for volcanic activity on Io, as well as monitoring the presumed sources of ions to the Io plasma torus and to the auroral zones on Jupiter. Also near the resolution limit, but of comparable significance, would be measurements of albedo and color changes on Io. A major eruption could easily deposit an optically thick layer of pyroclastics and condensed volatiles over an area hundreds of kilometers in dimension in a period of a few weeks. If the new surface contrasted strongly in albedo or color with the old, the change could be seen in ST images.

Both Pluto and its satellite are "small bodies" within the definition of this paper, and both can be investigated profitably with the ST. The planet, with a diameter of only about 3000 km, is barely resolvable. However, its satellite, with a magnitude of about 17 and a maximum separation of about 0.7 arcsec, should be easily separated. A small number of images will yield much improved values for the semi-major axis of the orbit and hence the mass of Pluto, as well as yielding colors and magnitudes for the satellite. Accurate photometry of both planet and satellite can also be obtained with the high speed photometer. Astrometric measurements may allow the mass of the satellite itself to be calculated. Without the ST, there is very little we can do to learn more about the physical nature of this extraordinary planet/satellite pair.

One additional area remains in which I expect the ST to contribute to satellite research. Low-resolution reflection spectroscopy has proved itself as the technique best able to determine the mineralogy of a solid surface, including the identification of both ices and silicates. Most of this work has been done in the infrared, from about 0.7 to 4.5 μm ; unfortunately, ST will not be able to contribute much in this area with its initial instrumentation. However, there have been several recent suggestions of the capability of ultraviolet spectra to reveal features diagnostic of surface composition. In the UV, the energy of a photon is of the same order as the valence-conduction band gap in a number of solids of geologic interest, including olivine, ilmanite, calcium-feldspar, and augite. Observations are now being made of some small solar system bodies using IUE; depending on their outcome, there might be observing proposals for ST to extend UV spec-

troscopy to much fainter satellites, asteroids, and cometary nuclei.

PLANETARY RINGS

Three of the four Jovian planets are known to have ring systems consisting of particles orbiting in the equatorial plane of the planet inside the Roche limit. The Saturn system, first seen by Galileo and identified as rings more than 300 years ago, consists of several concentric planar rings composed primarily of small (tens of centimeters), high-albedo ice particles. The densest part (ring B) has optical depth near unity, and the relatively narrow gaps, corresponding to simple resonances with the inner satellites, are not swept entirely free of particles. The characteristic ring width is tens of thousands of kilometers. The Uranus rings, discovered by stellar occultation in 1977 and since observed as well by reflected light (visible and infrared), are entirely different. The ring particles are of low albedo (~3%) suggesting carbonaceous chondritic composition. The rings themselves, of which about ten have been identified, are more ribbon-like than planar, with widths of tens of kilometers at most, and maximum optical depths somewhat less than unity. The major (ϵ) ring is apparently non-circular and precesses rapidly. The ring positions do not coincide with simple satellite resonances. Finally, a third ring system was discovered this year during the Voyager encounters with Jupiter. This system consists of a main ring several thousand kilometers wide with a sharp outer edge, and a second continuous ring about a tenth as bright extending inward to the planet. The surface brightnesses of these rings are very low, suggesting optical depths less than 0.01; nothing is known about the albedo or composition of the particles, except that they seem unlikely to be ice and they have a reddish color. The edges of the main ring also do not correspond to simple resonances with Amalthea or the Galilean satellites.

Perhaps the most immediate question concerning planetary ring systems is whether each of the four Jovian planets possesses one. It is within the capability of ST to answer this question by carrying out a search for a Neptune ring system. Direct imaging in a methane band is likely to detect any but the faintest ring. The rings of Uranus have been detected marginally in this way with a CCD on the University of Arizona 1.5-meter telescope, and the advantages of ST resolution should far outweigh the greater distance of Neptune. Alternatively, the Neptune system might be detected by stellar occultations with the ST High Speed Photometer, although it should be remembered that the cross section for occultations is substantially less than in the case of the high-inclination Uranus rings. Clearly, measurements by both occultation techniques and reflected light are required to begin to characterize the nature of this ring system if it exists.

The rings of Jupiter should be within the imaging capabilities of the Planetary Camera; they have already been detected in their reflected light at $2.2 \mu\text{m}$ from the ground. The resolution of the camera is $\sim 200 \text{ km}$ at Jupiter, possibly permitting measurement of radial structure in the main ring when the system is near its maximum inclination with respect to Earth ($\sim 3^\circ$). Occultation observations are highly desirable but extremely difficult; without them it is difficult to estimate the optical depth of the rings or the albedos of the individual particles.

The rings of Saturn will be a glorious sight in Planetary Camera images; with a resolution of about 400 km , it will be possible to trace the radial photometric structure in detail and to establish the radial dependence of the large-scale photometric asymmetries between quadrants seen in ground-based photometry. Optical depth profiles can also be traced from stellar occultations, an extremely difficult task from the ground, requiring a rare occultation of a very bright star. Ultraviolet spectra will also be of interest in establishing the nature of the contaminants in the ice that produces the well-known drop in albedo toward short visible wavelengths. However, it is difficult to predict the degree to which all of these studies will still seem relevant after the Voyager flybys in 1980 and 1981. The Voyager resolution and range of viewing geometry will far exceed that of ST. Important questions may be raised that will require ST data for their resolution, or it might turn out that ST has little to contribute after Voyager.

One area of study of the rings of Saturn in which ST has unquestioned superiority is that which concerns the long-term variations associated with the 15-year cycle of ring tilt. Voyager will obtain two snapshots near the time of minimum ring tilt; ST will, however, be able to view the planet year after year as the rings become fully open in about 1988 and then close again toward the 1995 ring plane crossing. In particular, it appears that photometric imagery in 1995 is likely to provide the best data on the physical thickness of the rings and on possible out-of-plane warping that we will obtain in this century.

The rings of Uranus can be studied with the Planetary Camera at much higher resolutions than are available from the ground. Additional occultation profiles of optical depth can also be obtained, although these may not represent a great improvement over occultations observed at $2.2 \mu\text{m}$ with large infrared telescopes. The acquisition of color data, and perhaps ultraviolet spectra, could help establish the composition of the ring material. And finally, the bizarre nature of the ϵ -ring is a continuing puzzle, and ST data may play a role in unraveling its dynamical behavior. Occultation measurements of precession rates can also provide data on the gravitational moments of Uranus.

The recent discoveries of rings around Uranus and Jupiter have

introduced many confusing elements; in general, I would say we understand planetary rings much less well today than we thought we did a decade ago. Both improved data on radial structure and new insights into the dynamical interactions of rings and satellites are badly needed. In such a period of flux, it is especially difficult to predict the effect of a major new instrument such as Space Telescope.

ASTEROIDS

The asteroids or minor planets have become, within less than a decade, one of the most active areas of planetary astronomy. The application of a wide variety of observational techniques to hundreds of these objects has permitted the identification of a variety of compositional types and of their distribution in space, and has established for the first time such basic parameters as the sizes of these objects. Many mineralogical analogs have been found for common meteorite classes, and many of the advances of the past few years have come about through close contact between astronomers and meteoriticists. We now know that the majority (~75%) of the asteroids are chemically primitive (similar to the carbonaceous chondrites), but that mixed among them, particularly in the inner belt, are many objects that appear to be fragments of heated and differentiated parent bodies. An outstanding question, however, remains the identification of the parents of the most common type of meteorite, the ordinary chondrites, for which no link to main belt asteroids has been reliably established.

The main problems in asteroid research today concern geology and geochemistry. We have never "seen" an asteroid in the geological sense; these bodies remain unresolved point sources rather than true planetary bodies or, perhaps even more exciting, fragments of planetesimals that reveal their interior structure. Geochemical relationships also remain more tantalizing than secure, with no clearly established connections between individual meteorites, which reveal such a wealth of data in modern laboratories, and their asteroidal parents. Unfortunately, neither of these areas is likely to be advanced in a major way by ST observations.

The Planetary Camera will have a resolution for a typical main-belt asteroid of about 100 km, not high enough to reveal geological structure. This is sufficient resolution to yield good diameters for the larger objects, but it is not competitive with stellar occultation measurements, and it may be no better than indirect techniques of diameter measurement, such as by infrared radiometry. This resolution is clearly great enough, however, to search for albedo or color variations on the largest asteroids. For 1 Ceres, an image would include about a hundred pixels, for 4 Vesta and 2 Pallas, about 30. Clearly, these three objects should be imaged in several colors, as a first step

toward revealing the global structure of a previously unresolved class of objects.

There is an additional area of current concern in which ST can make a major contribution. Based on some recent occultation photometry, it has been suggested that several asteroids, most convincingly 432 Herculina, may be double or multiple. The Planetary Camera can easily resolve this question; the suggested companion of Herculina would be separated from it by more than 10 pixels, and the 3.6-mag brightness difference is well within the range of the detector. One or two ST frames will either lay this problem to rest or else open a fertile new field of research into multiple asteroids.

COMETS

The comets are the most primitive small bodies in the solar system, with the highest ratio of volatiles to solids. Presumably, they condensed early from the solar nebula, and it is probable that even some interstellar grains are incorporated within them. Preserved billions of years in the deep freeze of space, the comets are fed at a slow but steady rate back into the inner solar system. While a single comet may survive only a few hundred perihelion passages before its volatiles are exhausted, the comets as a class are a renewable resource, providing a supply of pristine material from which we can infer the conditions of origin of the solar system.

In spite of their great potential, the comets are in fact poorly understood. We have never measured the nucleus of a comet without its obscuring halo of atmosphere; we do not even know with any precision how big a cometary nucleus is. Most of the volatile materials that are emitted from the nucleus as it is heated by the Sun are also unobserved; instead, we see the molecular fragments of photodissociation and other less well-understood chemical processes. The intricate dynamics of comet tails are controlled by complex plasma processes, as the cometary atmosphere interacts with the solar wind. And even the ultimate fate of comets is unknown; they may evolve into Apollo/Amor asteroids, or perhaps they dissipate into unobservable fragments as their volatiles are exhausted.

A number of important investigations of comets can be carried out with the ST. Some of these involve short-period comets, especially observations of the nuclei at large distances from the Sun when they are not shrouded in gas and dust. These can be scheduled long in advance. However, it is also important that the ST be available to investigate any large, bright comets that may be discovered. Only about one such comet appears per decade, but often there is little warning; ability to reschedule on as short as a week's notice for a

really spectacular comet could yield important dividends. Finally, there is the special case of Comet Halley, which is the only bright, active periodic comet available for study during the rest of this century. The 1985/86 apparition of Halley will not be well placed for ground-based observations, but the ST will be in an excellent position for study of this object. (It is interesting to note that the last Halley apparition, in 1910, took place before the advent of large reflecting telescopes or even simple photoelectric detectors, in one orbit of Halley, we have gone from the Lick and Yerkes refractors and rather slow photographic emulsions to the construction of a large astronomical observatory in space!) It seems almost certain that the public, as well as the scientific, perception of Halley in 1986 will be based in large part on ST data.

A comet includes phenomena in a wide range of spatial scales, from the nucleus (~1 km) to the tail (~ 10^8 km). Unfortunately, the nucleus itself will not be resolvable by ST; at a distance of 0.2 AU, the limit of about 10 km is larger than the anticipated size of any but the very largest cometary nuclei. However, fine structure in the coma and the tail should be extremely interesting, especially if some reasonable time resolution is possible. Comets are dynamic objects, and it is important to sample time domains of minutes to days if we are to understand the phenomena.

Ultraviolet spectroscopy with both the High Resolution Spectrograph and the Faint Object Spectrograph will provide the area in which the primary contribution to cometary research can be made with ST. Most of the resonance transitions of the anticipated parent molecules in the inner coma lie in the vacuum UV. The combination of UV sensitivity with high spatial resolution raises the promise for the first time of understanding the composition and chemical processes of the neutral coma. Special spectroscopic studies will also be of interest, including the precision measurement of the ratio D/h for this sample of primitive solar-system material.

Although the nucleus cannot be resolved directly, the ST can contribute uniquely to the study of cometary nuclei by carrying out observations when the nucleus is inactive. The comet could be followed to 6 AU or farther from the Sun, and studied by the photometric and spectroscopic techniques used to determine the surface compositions of asteroids. As an example of the power of ST, I note that it will be possible to observe the nucleus of Comet Halley throughout its orbit, even at aphelion.

A special opportunity for ST observations of comets will become available if there is a NASA solar-space mission to one or more comets in the late 1980's. The most promising such mission opportunity involves a launch in July 1986 and a fast-flyby of Halley near its perihelion, including deployment of a dedicated probe toward the

nucleus. The primary spacecraft then continues, slowly modifying its orbit with an ion drive low-thrust propulsion system. In July 1988, it achieves rendezvous with the short-period comet Tempel 2. For the next twelve months, it remains close to the nucleus, making detailed observations of the nucleus and the inner coma. During both the Halley and the Tempel 2 phases of the mission, the large-scale perspective provided by ST observations will be needed to complement the detailed, small-scale observations made from the spacecraft. In turn, the in situ data will provide a unique calibration of remote sensing by ST and ground-based telescopes, thus greatly increasing their power to study other comets for which there will be no direct exploration by a deep-space probe.

ACKNOWLEDGEMENTS

I am grateful to J.-L. Bertaux, Jack Brandt, James Elliot, Bradford Smith, and James Westphal for useful conversations. Attendance at this Colloquium and preparation of this paper were supported in part by NASA Grant NGL 12-001-057.

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DISCUSSION

Owen (Discussion leader): Dr. Bradford Smith has already referred to the general goal of understanding the origin and evolution of the solar system as an underlying motivation for many of the investigations we are discussing this morning. Another such goal is the understanding of the origin and cosmic distribution of life. Studies of primitive bodies in the solar system have a direct bearing on both of these questions.

I must disagree with Dr. Morrison's suggestion that only small bodies are primitive. While it is true that the giant planets have not retained the memory of their origin, Jupiter and Saturn may actually represent trapped samples of the original solar nebula itself. If they do, we may also regard them as separated fragments of the interstellar medium that have been preserved for 4.6×10^9 years at temperatures well below the threshold for nuclear reactions, conveniently available for our investigation. We may then have the opportunity to study elemental abundances in great detail, thereby at last obtaining a rigorous calibration for theories of nucleosynthesis and mixing within the galaxy. The high resolution spectrograph on the Space Telescope is bound to make important contributions to these studies.

The lack of original memory to which Dr. Morrison referred pertains to the chemical evolution that is taking place within the atmospheres of these objects. But this evolution is limited by the ability of all four giant planets to retain hydrogen. Thus the chemical processes we observe on these planets today are probably very similar to those that took place at various locations in the original solar nebula. What are the products of these reactions?

Dr. Smith has already alluded to the probability that these products include organic compounds of interest to us in our attempts to unravel the chemistry that took place prior to the origin of life on Earth. The most obvious evidence we have that such chemistry is actually occurring on Jupiter is the presence of colored regions in the Jovian clouds. Yet we still do not know the identity of the chromophores that produce the colors we see. Organic polymers, polysulfides, and red phosphorous are all likely possibilities.

Perhaps the most famous colored area on Jupiter is the Great Red Spot and we now know from both ground-based and Voyager observations that the atmospheric disturbance responsible for this feature propagates to altitudes that are accessible to UV observations. We do not know what the red material is - Voyager has been unable to tell us and it seems unlikely that the Galileo Project or further ground-based studies will be of much help. With its high spatial and spectral resolution, Space Telescope may at last solve this enigma.

But that is only the most obvious of many possible studies of the chemistry of the upper atmospheres of the giant planets and their satellites. We already know that a rich variety of photochemical reactions is taking place, but we need much more information on the products of these reactions and their global distribution.

Moving now to a consideration of smaller bodies, I would like to emphasize the special importance of Titan, the largest satellite of Saturn. The atmosphere of this satellite is at least three times as dense as that of Mars, but its composition is still poorly understood. We know it contains a large amount of methane, perhaps over 95%, with small traces of higher hydrocarbons. There is a possibility that a large fraction of the atmosphere is made of a mixture of nitrogen, and neon, with perhaps a detectable amount of carbon monoxide. The latter was a suggestion made by Dr. Robert Danielson, who was the first person to understand that the peculiar thermal emission Titan produces is caused by an inversion in its upper atmosphere.

What makes Titan so interesting is its unusual characteristic of having an evolved, reducing atmosphere. It can lose hydrogen, yet the atmosphere has retained a hydrogen-rich character. This is totally different from the oxidized atmospheres we find on small bodies in the inner solar system. And here again chemical evolution is occurring. We see evidence of this in the photochemical products (C_2H_2 , C_2H_4) detected in the upper atmosphere and in the presence of a reddish haze that seems to envelope the entire satellite.

Dr. Caldwell and I have been studying Titan in the UV with the help of the IUE. We find no evidence for a brightness increase with decreasing wavelength consistent with Rayleigh scattering, even at 2200 Å, and we cannot even detect Titan below 2000 Å. With the Space Telescope, we could improve both the wavelength coverage and the spectral resolution, perhaps at last identifying some of the other atmospheric constituents and better characterizing the red aerosol. Once again we want to know what the chemistry taking place in this natural laboratory can tell us about pre-biological chemistry on the primitive Earth.

Our interest in Titan should not distract us from other satellites we presently know much less about. First on the list here is Triton, the large satellite of Neptune. Triton did not appear on Dr. Morrison's illustration of bodies intermediate in size to the moon and Mars, because we don't yet know how big this object is! Space Telescope will give us that answer with one or two images, and will also permit us to substantiate the intriguing possibility that this satellite too has an atmosphere.

In the case of comets, I would only like to emphasize Dr. Morrison's observations concerning the primitive state of these bodies. It seems

quite likely that they were the first objects to condense out of the solar nebula. As such, we may expect them to contain frozen remnants of the interstellar medium, in which virtually no chemical processing has taken place. While we cannot expect Space Telescope to tell us much about the interstellar grains that comets may contain, we can expect to learn more about the molecules frozen in comet nuclei, which may be the same molecules that form the ever-growing list compiled by radio astronomers studying dense interstellar clouds. The organic compounds in comets have a special relevance to our larger goals, since they may have given a head start to organic synthesis on the primitive Earth. Even if the compounds themselves did not survive entry into our planet's early atmosphere, cometary impacts may have been an important source of the volatile elements that are essential for the origin of life. We must know much more about the composition of these objects before we can sensibly attempt to recreate our planet's early history. Space Telescope is bound to provide new information through high-resolution studies of cometary spectra at spatial resolutions heretofore unobtainable.

Perhaps the greatest adventure we can take with the ST in our efforts to establish our origins is to look for other solar systems. Science often makes its greatest leaps when it has a number of different examples to classify and compare. It would be wonderful to be able to do that with solar systems - to know which stars have planets and which do not, whether there are systematic differences in the types of planetary systems associated with stars of differing spectral type, etc. But the fact is that while we have some good observational hints and some persuasive theoretical arguments, we presently know of only one solar system in the universe: our own.

Many of us have played the game of trying to calculate the number of advanced civilizations in the galaxy, N , following a straightforward equation established by Frank Drake nearly twenty years ago $N = R_* f_p n_e f_i f_c L$. In this expression, R_* is the rate of star formation, f_p is the fraction of stars that have planets, n_e is the number of earth-like planets in each system, f_i is the fraction of such planets on which life develops, f_c is the fraction of such inhabited planets on which intelligent life develops, f_c is the fraction of planets with intelligent life on which a civilization capable of interstellar communication emerges and L is the lifetime of such civilizations.

At the present time, astronomy can only evaluate the first term in the Drake equation. The value of the other factors must be guessed, and the numbers become progressively more speculative as we move to the right. But there is no rule against playing this game with real knowledge, and Space Telescope appears to have the ability to give us our first good estimate of f_p . Two basic techniques are available: astrometric studies of the motions of nearby stars, and direct inspection of

stellar images, in which light from the star is blocked internally or by a distant occulting disk (the moon?). If we are very lucky, and find planets in the α Centauri system, we may even be able to estimate n_e . We shall still be forced to extrapolate to other stars in the galaxy, but we should be twice as confident in doing so as we are today.

Brandt: Comet research with the Space Telescope should be profitable in the following areas.

1. Spatial Resolution - The molecular plasma is organized by the magnetic field into rays. Their diameter is presently thought to be $\approx 10^3$ km. The ST should resolve the rays or reduce the upper limit to $\approx 10^2$ km.

Synoptic coverage of ray evolution will be most important for ST because ground-based observing conditions make obtaining proper photographic time sequences nearly impossible. The most notable exception in this century was comet Morehouse in 1908. Most photographs provide only snapshots and the situation makes the understanding of cometary morphology, particularly of the plasma, very difficult. A small number of concentrated sequences with the WF/PC should be fundamental. An obvious time for this would be during the 1985-86 apparition of Halley's comet. Coordination of the ST sequences with the prime observing times of the proposed Halley/Tempel 2 Comet Mission would enhance the scientific return.

2. Motions - Patterns with speeds in the range 10 to 200 km s⁻¹ have been observed in comet tails. However, their physical origin - waves versus bulk motions - has not been settled. Measurements of doppler shifts from the ST could resolve this issue.

3. Spectroscopic Diagnostics - The spectra of comets, particularly in the ultraviolet, hold great promise. For example, a rocket spectrogram of comet West on March 11, 1976 (obtained by the Laboratory for Astronomy and Solar Physics, NASA/GSFC) shows many species of interest in the range 1600 to 4000 Å. These include CO⁺, CN⁺, CS, OH, CO₂⁺, NH, and CN. High resolution spectra in this range and at shorter wavelengths on new comets should probe physical conditions in the cometary atmosphere through the construction of synthetic spectra. There are also some interesting isotope ratios that can be measured in the ultraviolet (including D/H).

Baum: The search for planets around stars seems destined to be an exciting adventure with high potential for public interest and important implications for the future of space exploration. There are several possible methods for the detection of extra-solar planets. The radial velocity variation of parent stars due to their planets can be pursued fairly well from observatories on the ground. Interferometric methods are also being explored on the ground and may have future potential

in space. Direct imaging detection may be barely possible from space, but it puts formidable demands on optical and detector performance. Astrometric detection of the positional variation of parent stars is the method on which I want to focus attention because that is the method of planetary-system detection for which the Space Telescope can play a key role.

Astrometry also has an advantage over the radial velocity approach in that the likelihood of detection is not dependent on the spatial orientation of a planetary system. No matter how a planetary system is oriented, the resulting positional wobble of the star will have roughly the same amplitude, whereas the amplitude of the star's radial velocity variation has a first-order dependence on the orientation of its planetary system.

Astrometry of planetary-system candidates will probably be attempted with the Wide-Field/Planetary Camera, with the Fine Guidance System, and possibly with the Faint Object Camera. At the present state of instrument development, the Wide-Field/Planetary Camera seems to offer the greatest promise. The Fine-Guidance System, which operates astrometrically down to 17th magnitude, utilizes the positional readout of moving parts and would need to preserve long-term reproducibility equivalent to 0.5 micron in the focal plane to achieve the claimed accuracy of 2 milliarcseconds. The Faint Object Camera has a rather small field for finding enough reference stars, and its astrometric reproducibility depends on the stability of electrooptical components.

The Wide-Field/Planetary Camera (WF/PC) can work astrometrically much fainter (22nd mag.) than the Fine-Guidance System but covers a smaller field. The field is imaged either at $f/12.9$ or at $f/30$ on to four CCDs. Milliarcsecond astrometry will probably be limited to the quarter field covered by a single CCD, where astrometric reproducibility will depend only on long-term stability of the thermostated silicon membrane of the CCD.

Reaching faint magnitudes with high S/N ratios means that there will usually be an abundance of reference stars within a small angular distance of each program star. Even more important, the irregular motions of faint reference stars (due to their companions) will typically be smaller than the irregular motions of the program star we seek to detect. In the jargon of astrometry, the "cosmic errors" will be acceptably small. For the detection of planetary systems, where milliarcsecond accuracy is needed, this suppression of "cosmic errors" is important.

Each star image produces a mound of charge carriers a few pixels wide on the CCD. Therefore, the determination of the centroid of a star image will be precise if there are enough charge carriers in the

image for the statistical uncertainty ($n^{-1/2}$) to be small, if there are enough pixels within the star image to sample its profile adequately, and if the sensitivity profiles of individual pixels are not radically non-uniform.

There is in fact an optimum relationship between the size of a star image and the size of a pixel. If the effective focal length is too short so that the optical image is excessively compressed, the star image profile will occupy too few pixels for its centroid to be well determined. On the other hand, if the effective focal length is too long so that the optical image is excessively magnified, the star image profile will occupy more pixels than necessary for precise centroid determination, while the CCD will cover too small a field in the sky to provide enough reference stars for astrometry. The WF/PC f/30 and f/12.9 systems fall in an optimum range between those two situations.

Figure 1 shows the expected accuracy of astrometry with the CCD cameras as a function of star magnitude for ST exposure times of 1000 seconds. This plot indicates that an accuracy of about 1 milliarc-second should be achieved down to 22nd magnitude with the f/30 camera, whereas the f/12.9 camera has a 2-milliarcsecond error at that magnitude. However, the f/12.9 camera covers a field five times larger in sky area, so more reference stars would be available. Bars at the left-hand ends of the curves in Figure 1 indicate approximate saturation magnitudes for 1000-second exposures. For shorter exposures, these curves (and the saturation magnitudes) march toward the left.

Many of the nearby stars that are astrometrically desirable to test for the presence of planetary systems are bright compared with saturation magnitudes for any reasonable exposure times that provide enough reference stars. These brighter candidates therefore have to be separately attenuated without introducing variable astrometric errors. A suitable attenuation factor (6 or 7 magnitudes) can be produced rather easily at the f/24 focal plane by providing a tiny bare spot (non-aluminized spot) on one face of the pyramid mirror and putting an antireflection coating on it.

How much positional wobble of a candidate star are we looking for, and therefore how many candidates are in reach of the ST instruments? If one plots the actual wobble of the Sun due to the planets of our own Solar System, it is not a simple sine wave with a 12-year period due to Jupiter. It is a surprisingly complex curve in which all the major planets play significant roles. Using solar wobble distant alien observers might detect the existence of a planetary system around our Sun within a few years, but the specific contents of our Solar System would take them many decades to figure out.

Nevertheless, the contribution of Jupiter is a good yardstick for

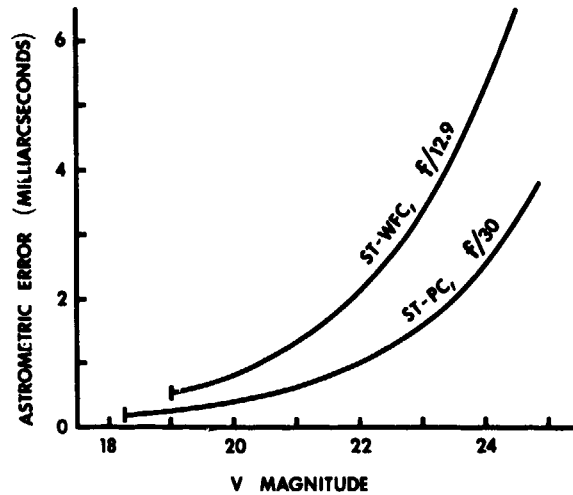


Fig. 1. Theoretical error in the location of the centroid of a star image, plotted as a function of star magnitude, for a single 1000-second ST exposure through a photovisual filter. Bars at the left-hand ends of the curves represent saturation magnitudes (in 1000 seconds) for the f/12.9 and f/30 CCD cameras, respectively.

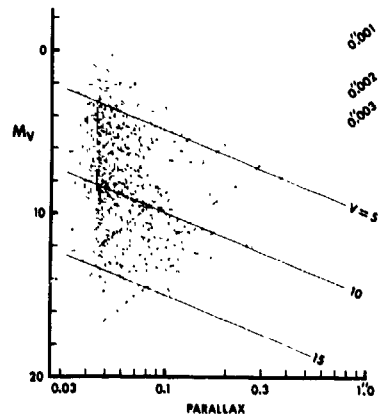


Fig. 2. The absolute magnitude-parallax distribution of nearby stars from Gliese's catalog. Upper and lower limits for the detection of hypothetical "Jupiters" are indicated by the sloping lines, representing possible values for the astrometric accuracy (arcseconds) and V magnitude threshold of an instrument.

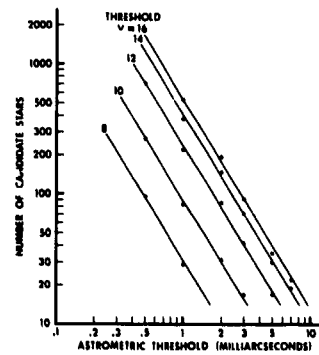


Fig. 3. The number of planetary-system candidates that can be investigated with an instrument of given astrometric accuracy and magnitude threshold. These data are taken from Figure 2 and are based on supposing each star to possess a hypothetical "Jupiter".

the typical amplitude of variation within any decade-long interval. So, as a criterion for the astrometric detectability of other planetary systems, I have imagined each nearby star to possess a hypothetical "Jupiter" (a planet of Jupiter's mass and orbital size) and have calculated the resulting amplitude of positional oscillation that would be expected. Since about 90% of nearby stars are main-sequence dwarfs, I have used a simple linear mass-luminosity relation to translate absolute magnitudes into approximate masses for the purpose of this statistical exercise.

The fact that existing catalogs of nearby stars are incomplete near their limits should not greatly concern us, because we can draw the desired information mainly from candidates that are not near catalog limits. The question of catalog completeness is of no practical interest anyway, because an actual ST observing program will have to be based on the targeting of individual stars we know well. I chose Gliese's 1969 catalog, updated with some Naval Observatory data, because it was conveniently at hand in machine-readable form. I thank Dr. Westphal and his colleagues at Cal Tech for providing me with a magnetic tape suitable to the present exercise.

The amplitudes of positional oscillation of nearby stars that would be produced by hypothetical Jupiters is represented by the family of upward sloping lines in Figure 2, which is a plot of M_v versus π for stars in Gliese's catalog. These lines represent half-amplitudes of 1, 2, and 3 milliarcseconds, and one may think of them as upper limits for the selection of planetary-system search candidates. The downward sloping lines represent loci of stars having the indicated values of apparent magnitude V and are therefore lower limits for detection. For any particular choice of upper and lower limits, the stars falling in the wedge-shaped area at the right of those limits are the planetary-system candidates of interest.

Based on that, Figure 3 shows how the number of "Jupiter" detection candidates will depend on the astrometric threshold. We see that each factor 2 improvement in astrometric performance should result in having three times as many candidate stars. Reaching fainter also helps, though not equally at all threshold magnitude levels; however, down to about $V = 12$, the number of candidates increases roughly 1.7-fold per magnitude.

It is evident from Figure 3 that the Space Telescope CCD cameras could choose from among more than 500 candidate stars if they reach a threshold of 1 milliarcsecond. For a more conservative selection, there are about 100 candidates at the 3-milliarcsecond level. And that list might wisely be reduced to about 10 prime cases for early Space Telescope imaging, excluding cases with close stellar companions, with unfavorable distributions of reference stars, or with excessively long

expected periods. For those prime cases, the probability of detecting any planetary systems similar to our own should be excellent.

Elliot: The problem of directly imaging an extra-solar planet is extremely difficult, because one must detect a faint object in the presence of the scattered light from the nearby bright star. For example, if the Sun and Jupiter were at a distance of 10 pc, Jupiter would be a 27th magnitude object having a maximum separation of 0.5 arc-sec from the Sun, which would appear as a 5th magnitude star. To overcome this great disparity in brightness, Spitzer suggested that an occulting edge at a large distance from a telescope in space be used to attenuate the light from the star. For the space telescope, a practical realization of Spitzer's scheme would be to use the black limb of the moon as an occulting edge. I have worked out the details of this plan in a paper (*Icarus*, 35, 156), so will just describe the main results. The signal-to-noise ratio would be sufficient to detect a Jupiter at 10 pc, but the alignment between the telescope and the lunar limb must be maintained for about 20 minutes. This would be possible for specialized orbits, but not the one presently planned for the Space Telescope. However, twice during each orbit of the Space Telescope, the moon will appear nearly stationary relative to the star fields, so that any object occulted precisely at the stationary point would remain within 0.05 arcsec of the lunar limb for about 9 seconds. There will be some motion of the occulted object parallel to the lunar limb, because of the relative inclination between the orbit of the moon and the orbit of the space telescope.

Although the alignment time is not long enough, and the nearby stars of interest will certainly not fall at the stationary occultation points, we should observe a few stationary occultations to find out if the occulting edge approach would be feasible for imaging extra-solar planets. Incidentally, lunar occultations occurring near the stationary points will have a much greater signal-to-noise ratio than can be achieved from the ground. Coupled with the possibility of using a small focal plane aperture to reject scattered moonlight, we can obtain accurate angular diameters of faint red stars, the brighter quasars and other objects of astrophysical interest.

Macchetto: You mentioned the possibility of using the Moon as an occulting disc. In the FOC, we have a built-in occulting disc which we call a "coronagraphic" mask. With this disc, we can attenuate $\Delta m \approx 19 m_v$, depending on the angular distance and on the final quality of the optics.

Fastie: I would recommend the investigation of a small number of nearby stars for planetary systems by direct imaging. It looks as though the optics will be very good with wavefront errors less than $\lambda/50$. There is a good chance that the telescope will be diffraction limited at

3000 Å and correspondingly the Airy disc moves in reducing the A. continuum which limits the detection of very faint companions.

Hemenway: The Fine Guidance Sensors should not be discounted for the purpose of detecting extra-solar systems planetary systems via astrometric measurements.

Elliot: If the faint object camera has an effective occulting spot and the telescope optics are good, then it might be possible to detect a Jupiter type planet near α Centauri A. Although this star is part of a multiple system, stable planetary orbits would probably be possible close enough to the star. A "Jupiter" orbiting at 5 a.u. from α Centauri A would reach a maximum separation of 4 arcsec from the star and would be 23rd magnitude. This observation should be attempted.

van de Hulst: Some participants have suggested that the Planetary Camera is the best instrument to be used in the search for extra-solar system planets. You will see from the article by Bahcall and O'Dell that the highest angular resolution is obtained with the f/96 mode of the Faint Object Camera which is a factor of two better than the Planetary Camera.

Elliot: As with the study of upper atmospheres, the advantage of using the Space Telescope for observing occultations by rings is the better signal-to-noise ratio. For the Uranus rings we need a high signal-to-noise event to resolve the controversy of whether or not there is material of low optical depth between the nine known rings and to search for new rings. Another goal would be to obtain precise optical depth profiles of the rings. Already, the two most advanced models for the rings - one by Dermott, Gold and Sinclair and the other by Goldreich and Tremaine - are attempting to explain the structure of the ϵ ring. More accurate data for these structures would further constrain their attempts, and perhaps determine which - if either - of these two models is correct. Since both of these models invoke small satellites to explain the sharp edges of the rings, it would be important to use one of the cameras to search for a possible reservoir of such satellites just outside the ring system. These satellites could be as bright as 17th magnitude, but probably several magnitudes fainter.

We should also use the high angular resolution potential of occultations to probe the rings of Jupiter and Saturn to see if they have narrow structures, akin to the Uranian rings. No photoelectric occultation data for these rings has yet been obtained. Because of its ability to reject background light, the Space Telescope would be the perfect instrument for this work.

Baum: Although I am somewhat more pessimistic than Dr. Fastie about the probable amount of scattered light in the wings of star images

recorded with Space Telescope cameras, any images of stars that are planetary-system candidates should certainly be scrutinized very closely for any direct evidence of low-mass companions (not necessarily substellar). But in my opinion, the inspection of star images would not alone be a sufficient test for planetary companions, so an organized ST search should instead be based on astrometric detection.

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PHYSICAL CHARACTERISTICS OF IONIZED GASEOUS NEBULAE*

Donald E. Osterbrock
Lick Observatory, Board of Studies in Astronomy & Astrophysics
University of California, Santa Cruz

INTRODUCTION

The chief advantages of the Space Telescope over conventional ground-based telescopes, namely, ability to observe ultraviolet radiation and high angular resolution, make it particularly valuable for research on gaseous nebulae. These objects are interesting not only in themselves, but also because they provide an opportunity to measure the abundances of the common light elements in the first two rows of the periodic table. H II regions are samples of interstellar matter from which stars are now forming in our galaxy, and in other galaxies. Planetary nebulae are objects approaching the end of their evolution as luminous stars, in which an outer shell has been thrown off and is returning to interstellar space. They represent one of the most prolific sources of mass return to interstellar matter at the present time in our galaxy. Thus both these classes of nebulae provide important and different information on abundances. Supernova remnants, although considerably rarer, in general contain a mixture of highly processed material being returned to interstellar space and interstellar gas being swept up by it. Physical conditions in them are considerably more complicated than in photoionized planetary nebulae and H II regions, and it is therefore not so straightforward to go from the observed strengths of the lines to the deduced abundances of the ions that emit them. However, the potentiality of understanding some of the extreme products of nucleogenesis lies in these remnants.

The great advantage of gaseous nebulae for abundance determinations is that the strengths of emission lines are directly related to the abundances of the ions that emit them. Thus complications due to radiative transfer effects, such as the continuous opacity, and the resulting relationship between the strength of an absorption line and the abundance of the ion responsible for it, are much smaller in gaseous nebulae than in stellar atmospheres. The difficulty in the past has been that only a limited number of the stages of ionization of common elements in gaseous nebulae has been observable. Many common ions such

*Contributions from the Lick Observatory, No. 420

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as C^+ , C^{++} , C^{+++} , N^{++} , N^{+++} , O^{+++} , O^{++++} , etc., do not have strong emission lines in the optical spectral region. Therefore, the abundances of such ions have been deduced from ionization-equilibrium calculations, or from simplified interpolation schemes based on such calibrations. The models are invariably simplified for practical computational reasons; in addition some of the rates of physical processes important in the ionization equilibrium are only poorly known. As a result, comparisons of these models with observable quantities always show discrepancies. Therefore the calculations or estimates of the abundances of the unseen stages of ionization contain a considerable amount of uncertainty. However, nearly all ions have lines somewhere in the observable region, from the satellite ultraviolet through the optical to the infrared. Numerous ions are observable only in the ultraviolet, and the Space Telescope thus is a very important tool in these abundances studies.

All gaseous nebulae that have been observed carefully have turned out to contain very many density fluctuations or density inhomogeneities. The better the angular resolution of the observing system used, the smaller the angular size of the inhomogeneities that have been observed. Clearly the physical conditions in a small volume of space, such as a "clump", "knot", "front", or low-density minimum between these structures are more informative than the average physical conditions over the nebula. The power of the Space Telescope to measure very small areas in the sky will be of great benefit in nebular studies.

Supernova remnants are different from planetary nebulae and H II regions in that the primary excitation mechanism in most supernova remnants is "collisional" or "shock-wave heating", that is, the conversion of kinetic energy into thermal energy, rather than photoionization the conversion of photon energy into thermal energy. As a result, supernova remnants have different spectra from photoionized nebulae, with a wide range of temperature and ionization occurring in a relatively small volume in space. Again, the wide range of ultraviolet spectrum, detectable only from above the earth's atmosphere, will greatly increase our ability to analyze these objects. The high angular resolution also will make it possible to study in much more detail the physical processes going on in supernova remnants, and thus in the end to determine the abundances of the elements in them more accurately.

In the following sections I will discuss planetary nebulae in some detail, and then those aspects of H II regions and supernova remnants that differ from planetary nebulae, outlining the main opportunities for nebular research with the Space Telescope. A vast amount of work has been done on these objects and I will not attempt to summarize it here, but simply refer to books such as Osterbrock (1974) and Spitzer (1978) and review articles such as Miller (1974), Salpeter (1977) and Chevalier (1977).

PLANETARY NEBULAE

Planetary nebulae are well understood as photoionized nebulae with very hot central stars. They range in angular size from below the limit of resolution of ground-based telescopes to several minutes of arc. Many planetary nebulae have fairly high symmetry, usually of a kind that can be interpreted as symmetry about an axis. They have emission-line spectra ranging up to high ionization, such as [Ne V] and [Fe VII] in some cases and [O III] and [Ne III] in nearly all cases. The electron densities and temperatures are of order $N \approx 10^{3 \pm 2} \text{ cm}^{-3}$ and $T \approx 10^{4 \pm 0.3} \text{ K}$. Collisionally excited lines (in the optical region nearly all of them forbidden lines) from abundant ions with excited levels within a few volts of the ground level dominate the spectrum, along with recombination lines of H I, He I and He II. The energy input to the gas occurs through photoionization, which thus fixes both the ionization equilibrium and the thermal equilibrium at each point in the nebula. The planetary shells are expanding with velocities that increase more or less linearly from zero at the center, to approximately 25 km/s in the main part of the [O III] emitting regions. Infrared measurements show that many planetary nebulae contain heated dust. Furthermore, observations of [O I], [N I] and even CO (Mufson *et al.* 1975) and H_2 (Treffers *et al.* 1976) molecules show they also contain, or have very close to them, heated clumps of neutral gas.

From an evolutionary standpoint, planetary nebulae represent a relatively short-lived stage of a highly evolved star, which has exhausted its central H and He nuclear fuels and is losing its outer envelope as the remnant stellar core contracts toward the terminal white-dwarf stage. The luminosity of the star, which photoionizes the gas in the shell it threw off, is probably derived from H burning in a shell source just outside the C and He zones containing most of the mass of the star, gravitational contraction of the outer parts of this core, and cooling of the degenerate inner part of the core. The whole lifetime of a particular object as an observed planetary nebula is of the order of a few times 10^4 yr.

The basic simplicity of nebular astrophysics results from the fact that the density is very low. Nevertheless, Coulomb collisions quickly thermalize electrons produced by photoionization. Two-body collisions of these electrons with positive ions produce ions or atoms in excited states which in most cases emit a line photon before suffering a collision. The specific intensity, or surface brightness, in a given emission line can thus be written in a form

$$I(\lambda) = \int N_e N_i \epsilon(\lambda, T) \cdot b(\lambda) \cdot h\nu dV. \quad (1)$$

Here N_i is the density of the ion responsible for emission of the line, ϵ is the rate coefficient for the two-body process responsible for populating the upper level of the line, and b is a factor giving the fraction of these population processes that are followed by emission of a photon in the line in question. At low densities, b depends almost

entirely on transition probabilities; if the density is high enough so that collisional deexcitation becomes important it also depends on the collisional rates. The integral is over the volume of the projected area of the entrance aperture extended along the line of sight through the nebula. In the very simplified situation in which the nebula has uniform density and temperature, the ratio of strengths of two lines gives directly the ratio of abundances of the responsible ions:

$$\frac{I(\lambda_1)}{I(\lambda_2)} = \frac{N(i_1)}{N(i_2)} \frac{\epsilon(\lambda_1, T)}{\epsilon(\lambda_2, T)} \frac{b(\lambda_1)}{b(\lambda_2)} \quad (2)$$

In general, for recombination lines the temperature dependence of ϵ is weak, approximately $\propto T^{-1}$, and does not differ greatly from one line to another. Hence equation (2) serves well for calculating the ratio of two recombination lines, such as H α /H β , or for determining the relative abundances of H $^+$, He $^+$ and He $^{++}$ from their recombination lines, even if the temperature varies and its average value is roughly known. On the other hand, for collisionally excited lines,

$$\epsilon = \frac{8.629 \times 10^{-6}}{T^{1/2}} \frac{\Omega(i, j; T)}{\omega_j} \exp(-\chi_{ij}/T), \quad (3)$$

where Ω is the mean value of the collisional strength (a dimensionless form representing the main dependence of the collision rate) between the two levels, ω_j is the statistical weight of the upper level, and χ_{ij} is the excitation energy of the upper level with respect to the lower level. It can be seen that a small error in the temperature causes a large error in the local excitation rate, and hence in the derived relative abundances.

A very large amount of data on relative line intensities in planetary nebulae has been obtained in the ground-based optical region, and much of it has been collected and made available by Kaler (1976). The amount of extinction along the path and within a given nebula can be calculated by comparing observed and calculated H I recombination line ratios, using a standard interstellar extinction curve derived from measurements of stars. Ratios involving optical, infrared and radio-frequency (free-free) measurements generally give concordant ratios except in cases where the extinction varies radically across the face of the nebula, such as in NGC 7027 (Scott 1973, Seaton 1979). The extinction derived in this way can then be applied to all the observed relative line strengths, to determine the intrinsic relative intensities emitted by the gas in the nebula.

In principle, the best way to derive abundances from the observational data is by using calculated models of the planetary nebula to which they refer. The assumed geometry, density distribution, properties of the central star and abundances should all be varied, and agreement of all observed line strengths (as well as spectrum and

magnitude of the central star, if they are observed) with one of these models determines all these quantities. A recent example is the series of models of NGC 7027 calculated by Shields (1978). In every case known to me, the agreement between observed data and model predictions is less than perfect, no doubt because the actual physical structure of the nebula is more complicated than any models yet computed, and because the rates of some of the physical processes are not yet known to sufficient accuracy. Usually the best overall agreement of observed data with quantities believed to be most accurately calculated is taken as the test of a model.

Since models are difficult, time consuming, and expensive to compute, empirical methods, based on interpolations among models or among observed nebulae, are often used to derive abundances. First of all, mean values of the temperature can be calculated using equation (2) for any ion in which two levels with different excitation potentials give rise to lines in the observable spectral region. The best example is [O III], for which the main dependence of the intensity ratio $[I(\lambda 5007) + I(\lambda 4959)]/I(\lambda 4363)$ is exponential on the temperature, with also a weak density dependence for $N_e \geq 10^5 \text{ cm}^{-3}$. Other ions with energy-level structure permitting temperature determinations of this type are [N II] $(\lambda 6583 + \lambda 6548)/\lambda 5755$, [S III] $(\lambda 9532 + \lambda 9069)/\lambda 6312$ and [Ne III] $(\lambda 3697 + \lambda 3869)/\lambda 3342$, although the last line is so far into the ultraviolet that accurate ground-based spectrophotometric measurements of it are exceedingly difficult.

Instead of simply adopting a mean temperature, a better approximation is to use a power-series expansion about the mean, keeping the first few terms. This method is described by Torres-Peimbert and Peimbert (1977). It has not been widely used, partly because the determination of the coefficient representing the second-order expansion term requires more observational information than is usually available, and partly because it is not obvious that a second-order expansion is sufficient to represent the exponential temperature dependence of ϵ for collisionally excited lines.

Mean values of the density can be estimated, again from equation (2), from collisional deexcitation effects in ions which have observable lines from two upper levels with nearly the same excitation energy. The best examples are [O II] $\lambda 3726/\lambda 3729$, [S II] $\lambda 6731/\lambda 6716$, [Cl III] $\lambda 5538/\lambda 5518$ and [Ar IV] $\lambda 4740/\lambda 4711$. Using these mean densities and mean temperatures, relative abundances of all ions giving rise to observable lines can then be calculated from equation (2) or from the second-order power series form of equation (1).

The largest uncertainty in deriving abundances is in the correction for unseen stages of ionization. For instance, from observations of [N I], [N II], [O I], [O II], and [O III], all of which have lines in the optical region, the abundances of N^0 , N^+ , O^0 , O^+ and O^{++} relative to H^+ can be determined. To determine the abundances of N and O relative to H also requires knowledge of the abundances of N^{++} , N^{+++} ,

N^{++++} , O^{+++} and O^{++++} , all of which can exist in planetary nebulae. In the empirical method, the relative abundances of these stages of ionization are estimated from insights gained from photoionization theory and models. For example, since the ionization potential of O^{++} is 54.9 eV, which is very close to that of He^+ , 54.4 eV, and because He^+ is so efficient in absorbing photons with energy ≥ 54.4 eV, the outer edge of the O^{+++} zone coincides with the outer edge of the He^{++} region. Consequently, the correction to the oxygen abundance for the unobserved stages of ionization O^{+++} and O^{++++} can be taken from the abundance of He^{++} (both summed over entire nebulae) in the form

$$\frac{N(O)}{N(H)} = \frac{N(O^+) + N(O^{++})}{N(H^+)} \cdot \frac{N(He^+) + N(He^{++})}{N(He^+)} \quad (4)$$

Similar but more complicated expressions are used to derive the abundance of N from the abundance of its one observed stage of ionization N^+ , and the abundance of Ne from the abundance of Ne^{++} , if infrared observations of $[Ne II] \lambda 12.8\mu$ are not available to give the abundance of Ne^+ . These expressions are based on the similarity of the first and second ionization potentials of O, N and Ne, and hence the expected coincidence of the O^+ , N^+ and Ne^+ zones, as well as of the O^{++} , N^{++} and Ne^{++} zones (Torres-Peimbert and Peimbert 1977).

Probably the best collections of spectrophotometric data and resulting abundances for planetary nebulae are the papers of Torres-Peimbert and Peimbert (1977) and Barker (1978a, b). The accurate measurements by these authors show that in the lower-ionization planetaries, a correction for He^0 within the H^+ zone is necessary to get high precision He abundances. Although a correction formula based on the approximate equality of the ionization potentials of He^0 and S^+ has been used, there are observational reasons for questioning it (Barker 1978b). Consequently the best relative helium abundances are those derived from the nebulae with hot central stars and strong $He II \lambda 4686$. The general conclusions from these papers are that planetaries of widely varying kinematic properties have nearly identical (approximately solar) relative abundances of H, He, Ne and O, and less reliably, N and S. This differs from stars, in which the heavier-element abundances (metals such as Fe, Ti and V) are correlated with kinematic properties. There is some weak evidence for a galactic gradient of the relative abundances of He, O and N with respect to H, in the sense that they all decrease outward, but there is considerable scatter about the mean relationship. Accurate spectrophotometry of more ions, such as the Space Telescope can make in the ultraviolet spectral region, are clearly desirable.

Some ultraviolet measurements already exist. Although attempts to observe planetary nebulae were made with the University of Wisconsin OAO-2 satellite, no positive detections of individual emission lines were made (Code and Savage 1972). Ultraviolet spectra have been obtained with a 33-cm telescope in an Aerobee rocket of the planetary nebulae NGC 7027 (Bohlin *et al.* 1975) and NGC 7662 (Bohlin *et al.* 1978). Both

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these objects showed intense emission lines of C IV $\lambda 1549$, He II $\lambda 1640$ and C III] $\lambda 1908$, and NGC 7662 also showed strong [Ne IV] $\lambda 2440$. Several other lines were possibly detected. Although the spectrophotometric accuracy of these measurements is naturally not nearly as high as the best ground-based measurements, they give very valuable information. The high dust extinction of NGC 7027 is well confirmed by the He II $\lambda 1640$ /He II $\lambda 4686$ ratio, and for NGC 7662 an abundance ratio $N(C)/N(O) = 1.0$, considerably higher than expected, was derived from a model calculation. Also, a 22-cm Cassegrain telescope in the ANS satellite has been used to detect and measure C IV $\lambda 1549$ in about 10 bright planetary nebulae (Pottasch et al. 1978a). Two interference filters centered at $\lambda 1550$ were used, one approximately 50 Å wide and the other 150 Å wide, together with other interference-filter measurements at wavelengths away from strong lines. These observations, though relatively crude (the entrance aperture is a 2.5 square), agree with the rocket spectra in giving a considerably lower relative abundance of C than the optical determinations of Torres-Peimbert and Peimbert, which are based on weak high-level recombination lines. The difficulty with measurements of very weak lines is that if the line is not detected, it is ignored, but any noise or blending with other weak lines that may occur tends to strengthen the line and thus may introduce a positive bias. The ANS satellite measurements also produced some information on the continuous spectra of the central stars of planetary nebulae. They all showed that the indirect methods of determining stellar temperatures and ultraviolet luminosities, based on longer wavelength optical measurements, give incorrect results in some cases (Pottasch et al. 1978b).

Very recently the IUE 45-cm Cassegrain telescope has begun to provide ultraviolet spectra of planetary nebulae. In NGC 7027 a total of 20 emission lines were measured in the wavelength range $\lambda \lambda 1406-3000$, including one or more lines of the ions C III], C IV, N III], N IV, Mg II and Mg V, all of which are unobservable in the optical and infrared spectral regions (Grewing et al. 1978). In NGC 7662, Lutz and Seaton (1979) have measured accurately the wavelengths of [Ne IV] $\lambda \lambda 2421.84, 2424.47$ and from the intensity ratio of these two lines found $N_e = 1.1 \times 10^4 \text{ cm}^{-3}$, in close agreement with the value determined from the corresponding [Ar IV] doublet in the optical region. Flower et al. (1979) have identified ultraviolet lines of C III], C IV, N III], N IV], N V, O IV], Mg II and Si III] in the "young planetary nebula" V 1016 Cyg.

The few available rocket and satellite observations of planetary nebulae clearly show that the Space Telescope will be able to detect and make accurate measurements of planetary-nebula spectra. Using figures given by Longair (1979) and Bahcall and O'Dell (1979), it appears that the Faint Object Spectrograph with a resolution $\lambda/\delta\lambda = 10^3$ and a diaphragm 0".25 in diameter would require 1 sec exposure time to achieve a signal-to-noise ratio of 10 at H β surface brightness $S(H\beta) = 4.3 \times 10^{12} \text{ ergs cm}^{-2} \text{ sec}^{-1} (\text{arcsec})^{-2}$. A complete list of observed H β surface brightnesses (averaged over the face of the nebula) is available (O'Dell 1962), and shows that the nonstellar planetary

nebula with the brightest surface brightness, IC 418, has $S(H\beta) = 2.4 \times 10^{12} \text{ erg cm}^{-2} \text{ sec}^{-1} (\text{arcsec})^{-2}$. This would require only 2 sec observing to obtain the signal-to-noise ratio quoted above. Several of the strongest lines in the ultraviolet are expected to be of comparable strength to $H\beta$ and, since the sensitivity of the Faint Object Spectrograph is fairly uniform, would be observable in approximately the same exposure time. Put another way, with a limiting exposure of 10^4 sec, emission lines in IC 418 should be measureable down to about 0.002 the strength of $H\beta$. This will include a very large number of ultraviolet lines. There are approximately 10 northern planetary nebulae with average surface brightness comparable with that of IC 418. For a fainter nebula such as NGC 6720 with an average surface brightness approximately 100 times smaller than IC 418, a 10^4 sec exposure should detect and measure to the quoted accuracy lines down to about 0.2 the intensity of $H\beta$. According to available estimates, there should only be 4 or 5 lines at this strength in the satellite ultraviolet region ($\lambda\lambda 1000-3000$), but they include C III] $\lambda 1909$ and C IV $\lambda 1549$, which should provide important information on the C abundance. NGC 6853, another well known planetary, is down in surface brightness by another factor of 8 below NGC 6720, but C III] and C IV should still be measureable in it.

To gain additional photons on faint nebulae, the full 200 μ height of the Digicon array can be used with a slit $0''.25 \times 1''.4$; this has seven times the area of the $0''.25$ diameter circular aperture and therefore a sensitivity correspondingly larger. This aperture is still considerably smaller than the apertures used for nearly all ground-based work on planetary nebulae to date. There is no doubt that many emission lines can be observed in the ultraviolet spectra of the brighter planetaries, and at least a few lines in many planetaries.

The great advantage of the ultraviolet spectral region is that in it many ions that do not have strong collisionally excited lines in the visible region are observable. A list of expected ultraviolet emission lines prepared some years ago shows that of the ten most abundant elements, the ions with previous ionization potential up to 90 eV that have lines in the satellite ultraviolet are C II, C III, C IV, N II*, N III, N IV, N V, O III*, O IV, O V, Ne III, Ne IV*, Mg II, Si II, Si III, Si IV, S II*, S III*, S IV, S V, Ar IV*, Ar V (Osterbrock 1963). Only the ions marked with asterisks have strong lines in the visible or near infrared.

The ultraviolet spectral region is especially valuable because there are many discrepancies between the predictions of theoretical photo-ionization models of planetary nebulae and the observations. In general, the calculations always indicate sharp edges to the various ionization regions so that for instance O^+ , Ne^+ and N^+ all occur together in the H^+ , He^0 zone in low-ionization planetary nebulae, and there is practically no O^{++} , Ne^{++} or N^{++} in this zone. Yet the best observational data show clearly that there is considerable penetration of O^{++} and Ne^{++}

into the O^+ , N^+ zone in IC 418, (e.g. Reay and Worswick 1979). This must be due to the complicated density fluctuations, often described as filamentary structure, that are not taken into account in the models. The careful measurements of Hawley and Miller (1977) show that in the outer part of NGC 6720 [Ne III] and [O II] are both strong in the same region, a result which contradicts the available photoionization models and the conventional procedure for correcting the Ne abundance for unobserved Ne. Here it seems likely that the highly efficient charge-transfer process between O^{++} and H^0 (Butler et al. 1979) significantly reduces the equilibrium fraction of $N(O^{++})/N(O^+)$ in the outer part of the region where photons that can ionize O^+ are available. The ultraviolet measurements of other ions can be used in place of other perhaps equally invalid corrections for unseen stages of ionization.

The ultraviolet spectral region contains significant additional information on the temperature within nebulae, because it extends the range of excitation energy that can be observed. Thus the temperature-sensitive [O III] ratio $[I(\lambda 5007) + I(\lambda 4959)]/I(\lambda 4363)$ can be supplemented by [O III] $I(\lambda 1661) + I(\lambda 1666)$ which arise from the 3S level at an excitation potential of 7.45 eV. Similarly the [N II] ratio can be supplemented by $I(\lambda 2140) + I(\lambda 2143)$ arising from the corresponding 3S level at 5.79 eV. Other ions with temperature-sensitive ratio in or including the ultraviolet are [Ne III] $[I(\lambda 3967) + I(\lambda 3869)]/I(\lambda 3342)$ (much better observed from space than from the ground), Si II $I(\lambda 2335)/I(\lambda 1817)$, and [Mg V] $[I(\lambda 2786) + I(\lambda 2931)]/I(\lambda 2415)$. Ratios that are sensitive to both temperature and density include Si III] $\lambda 1892/\lambda 1205$ and C III] $\lambda 1907/\lambda 1909$. In all cases the best way of using the observational data is to compare with a model, but if this is impossible the mean temperatures and densities derived from these ratios can be used to estimate the abundances of all observed ions.

Bright planetary nebulae such as IC 418 typically have sizes of order $10''$, while lower surface brightness nebulae such as NGC 6720 and NGC 6853 are several minutes of arc in diameter. With either a $0''.25$ circular aperture or a $0''.25 \times 1''.4$ slit it will be possible to sample over the face of the nebula in a systematic way, rather than observing the whole nebula, or a slice through it, as has often been done in the past with ground-based telescopes. The importance of adequate finding and guiding systems cannot be overemphasized.

Besides the Faint Object Spectrograph, the Faint Object Camera can be used in the spectroscopic mode with a long slit, $10'' \times 0''.1$, with $0''.1$ resolution along the slit. Operated in this way, it has to have a resolution $\lambda/\delta\lambda = 2 \times 10^3$ but a limiting magnitude on point sources 3.4 magnitudes brighter than the FOS. This presumably means that for the same exposure time it will only detect lines in nebulae that are about 20 times brighter than the faintest detectable with the FOS used with an $0''.25$ aperture. This still permits measurement of many of the brighter planetaries. Compared with the FOS used with a $0''.25 \times 1''.4$ slit, the FOC spectrograph is slower by a factor of about 140, but provides seven different $0''.1 \times 1''.4$ areas along the slit. The fact that the

wavelength regions $\lambda 2700 < \lambda < \lambda 3600$ and $\lambda > \lambda 5400$ are unobservable with the FOC spectrograph is a severe limitation.

All observed planetary nebulae contain inhomogeneities in density on a small scale: filaments, condensations, bright knots, and the like. As Aller (1976) has particularly emphasized, they must be taken into account in any complete model. With the Space Telescope's very good angular resolution, it will be possible in many cases to get spectra of individual knots or fronts, contaminated only by the foreground and background emission in the nebulae. In these as in all other spectroscopic measurements of planetary nebulae with the Space Telescope, not only the ultraviolet emission lines, but the optical and near infrared lines out to the limit of sensitivity at $\lambda 9000$ should be measured. Attempting to combine them with ground-based optical data, which inevitably have been or will be taken with lower spatial resolution and different guiding, would seriously degrade the results.

In this connection, the direct camera, operated in the Wide-Field mode at $f/13$, will be particularly valuable for investigating the ionization structure of planetary nebulae. Several of the special line filters that "may be available" will be especially suited for this program: [O I] $\lambda 6300$, H α , [O II] $\lambda 3727$, [O III] $\lambda 5007$, [Ne III] $\lambda 3870$, and in the ultraviolet C IV $\lambda 1549$ and La. Exposure times used by Minkowski (1968) with the Hale telescope at $f/3.7$ ensure that the first five of these filters will certainly provide data for some of the brighter planetaries in reasonable exposure times, and the two ultraviolet lines are expected to be of comparable brightness. These line-filter direct images will be useful not only for studying the overall ionization structure of a nebula, but particularly to see how the ionization varies in, around, and behind small dense condensations. Comparison of the [O III] and [Ne III] images will be especially valuable in studying the effects of the $O^{+} + H$ charge-transfer reaction on the $O^{+} + O^{++}$ ionization equilibrium. The He I $\lambda 10830$ filter will be useful in assessing the effects of collisional excitation from the He I 2^3S metastable level. It is a strong line and images of the bright nebulae will be obtainable with it if the CCD sensitivity holds up to 1.08μ , as it should.

Finally, the High Resolution Spectrometer on the Space Telescope will be extremely useful for studying the line profile of La in planetary nebulae. Forbidden lines and recombination lines to excited upper levels (except He 2^3S) are not subject to radiative transfer effects because of the very small optical depths in all these lines. However, La is the opposite extreme with an estimated optical depth up to 10^4 at line center in an object with small expansion velocity. The problem of the transfer and escape of resonance-line photons in a gaseous nebula has been theoretically investigated in great detail. Each treatment makes highly specific predictions, about the emergent line profile at each point on the surface of the nebula. The resolution $\lambda/\delta\lambda = 2 \times 10^4$ or $\delta\lambda = 0.06 \text{ \AA}$ corresponding to 15 km s^{-1} should be ideal for testing these predictions observationally. Since

$\text{L}\alpha$ is expected to be of order 10 times stronger than $\text{H}\alpha$ in slightly reddened planetaries, there should be no problem observing the brighter planetaries with a 1" x 1" or 2" x 2" entrance aperture.

H II REGIONS

H II regions are spectroscopically similar to planetary nebulae, since both are photoionized, low-density gas clouds. However, H II regions represent samples of interstellar matter from which stars have recently formed, and thus provide the opportunity for measuring abundances in material quite different from planetary nebulae. In general, H II regions are less regular in form than typical planetary nebulae. The gas in H II regions is usually not symmetrically distributed around one central star, but more often is chaotically distributed about several O stars which contribute to the ionization. Hence, realistic models are more difficult to calculate, and the results on the ionization structure calculated from necessarily simplified models must be regarded more as a guide than as a standard that can be directly compared with observations. The importance of using the Space Telescope to observe all relevant stages of ionization is again obvious.

A large amount of optical spectrophotometric data exists in published form and has been summarized by Kaler (1976) and Alloin *et al.* (1978). The Orion Nebula, NGC 1976, has been studied in most detail (Peimbert and Torres-Peimbert 1977), and shows essentially solar abundances of the light observable elements. Several other more distant H II regions have been carefully observed and appear to show a galactic abundance gradient in which the relative abundances of N and O decrease outward, N having the steeper and better determined gradient (Peimbert *et al.* 1978, Hawley 1978). The ionization is lower in typical H II regions than in typical planetaries, but close to the O6 star θ Ori A in NGC 1976 the level of ionization is comparable to that in many planetaries.

The Faint Object Spectrograph, with a slit 0".25 x 1".4, will be most useful for measuring emission lines in H II regions. The brightest areas near the center of NGC 1976 have $\text{H}\beta$ surface brightness only about a factor of 2 lower than IC 418, while the outer parts are down by a factor of 10^2 or more from this value (Dopita *et al.* 1975). Of the northern H II regions, only M 8 has a surface brightness even comparable with NGC 1976, and in general the exposure times will be long, even with the large slit.

Density fluctuations are very important in H II regions, and spectra of some of the fronts and knots in NGC 1976 should yield good comparisons with theoretical predictions of the structure and ionization stratification of ionization fronts and globules. Very small condensations recently identified by Laques and Vidal (1979) will be particularly interesting to study in the ultraviolet spectral region. Line-filter direct images with the very good angular resolution of the Faint Object

Table I

Ion	i, j	$\langle \Omega(i, j; T) \rangle$				Reference
		5000	10000	15000	20000	
C II]	$2p^2 2P^0, 2p^2 4P$	3.24	3.17	3.09	2.97	Jackson 1973
C III]	$2s^2 1S, 2p^3 3P^0$	1.45	1.44	1.42	1.41	Flower and Launay 1973
C III	$2s^2 1S, 2p^1 1P^0$	2.80	2.86	2.92	2.92	Flower and Launay 1973
C IV	$2s^2 2S, 2p^2 2P^0$	8.50	8.66	8.73	8.80	Bely 1966*
N II]	$2p^2 3P, 2p^3 5S^0$	1.27	1.28	1.29	1.27	Jackson 1973
N III]	$2p^2 2P^0, 2p^2 4P$	1.86	1.91	1.89	1.83	Jackson 1973
N IV]	$2s^2 1S, 2p^3 3P^0$	0.83	0.82	0.82	0.81	Osterbrock 1970*
N V	$2s^2 2S, 2p^2 2P^0$	6.61	6.65	6.69	6.72	VanWyngaarden and Henry 1976
O III]	$2p^2 3P, 2p^3 5S^0$	1.23	1.34	1.36	1.35	Jackson 1973
O IV]	$2p^2 2P^0, 2p^2 4P$	1.33	1.37	1.42	1.44	Extrapolated*
O V]	$2s^2 1S, 2p^3 3P^0$	0.52	0.51	0.51	0.51	Malinovsky 1975*
O VI	$2s^2 2S, 2p^2 2P^0$	4.98	5.00	5.03	5.05	Bely 1966*
[Ne II]	$2p^5 2P^0, 2p^5 2P^0$ $\frac{3}{2} \quad \frac{1}{2}$	0.36	0.37	0.37	0.38	Seaton 1975
[Ne III]	$2p^4 3P, 2p^4 1D$	1.35	1.34	1.33	1.32	Pradhan 1974
[Ne III]	$2p^4 3P, 2p^4 1S$	0.15	0.15	0.15	0.16	Pradhan 1974
[Ne IV]	$2p^3 4S^0, 2p^3 2D^0$	1.12	1.13	1.14	1.15	Lutz and Seaton 1979
[Ne V]	$2p^2 3P, 2p^2 1D$	2.16	2.12	2.08	2.05	Giles 1979
[Ne V]	$2p^2 3P, 2p^2 1S$	0.32	0.28	0.27	0.27	Giles 1979
Mg II	$2s^2 2S, 2p^2 2P^0$	17.2	18.5	19.6	20.5	Burke and Moore 1968
Si III]	$3s^2 1S, 3p^3 3P^0$	2.8	2.8	2.8	2.7	Osterbrock and Wallace 1977
Si IV	$3s^2 2S, 3p^2 2P^0$	16.9	17.0	17.0	17.1	Flower and Nussbaumer
S VI	$3s^2 2S, 3p^2 2P^0$	11.8	11.9	11.9	11.9	Flower and Nussbaumer 1975

*See Osterbrock and Wallace 1977

Camera, particularly in H α , [O II], [O III], [Ne III], and La will undoubtedly reveal previously unknown, even smaller condensations. Though a long exposure will be required, it will be extremely informative to get profiles of La in the brightest parts of NGC 1976 with the High Resolution Spectrograph. The optical depth there is probably higher than in most bright planetaries so that the resonance-line radiative transfer theories will be more severely tested.

The Space Telescope observational data will be valuable in understanding the structure and content of H II regions and planetary nebula. Large amounts of money, time and effort will go into obtaining the data. Comparable amounts of money, time and effort should go into interpreting it. Realistic models must be calculated and their physical parameters must be adjusted until they agree with all the observational data. Atomic data, particularly the collision strengths for all likely lines of all stages of ionization, should be calculated and available. In Table I some of the best values of the most important collision strengths, chiefly for ultraviolet lines but including some optical and even one far infrared line, are collected. With modern techniques, it is possible to calculate collision strengths to an accuracy better than ten percent (Giles 1979). It will be important to invest the necessary computing resources to obtain collision strengths for the many important lines of the third row of the periodic table before the Space Telescope data begin coming down.

The properties of the photoionizing star or stars are important for any model. The best possible stellar models must be calculated and used in the nebular models (Balick and Sneden 1976, Hawley and Grandi 1977, Shields 1978). The effects of dust on the ionizing radiation and on the emitted lines must be correctly taken into account, including not only true absorption but also scattering, and the assumed properties of the dust must be systematically varied. Also, the line-transfer problem must be treated correctly, for not only La but also the resonance lines of C IV, N V, O VI and many other ions have large optical depths in a typical planetary nebula or H II region. In the gas itself, density inhomogeneities and internal velocities must be taken into account, as emphasized above. A reasonably correct description of the true physical situation, although complicated and expensive, will be necessary to extract the full value of the Space Telescope nebular data.

SUPERNOVA REMNANTS

In old supernova remnants, such as the Cygnus Loop, mechanical energy is converted into heat in a shock wave running out through the surrounding interstellar gas and is radiated, partly in the form of emission lines. In some young remnants, such as Cas A, fast moving gas clouds with very anomalous abundances, evidently ejected by the supernova itself, can be observed. The Crab Nebula, approximately 10^3 yr old, is a case in which we observe gas enriched in He but not significantly in heavier elements, photoionized by the optical synchrotron radiation from the central part of the remnant. In these and in all supernova

remnants, observations of more ions in the ultraviolet spectral region will clearly help delineate the physical conditions and abundances better than the presently available optical data alone can do. They are faint objects, but available optical data suggest that the brighter ultraviolet lines will be measurable in several of them with the Faint Object Spectrograph, although interstellar reddening will be a severe problem in Cas A. The high angular resolution of the space telescope will be very useful because of the many small knots, condensations and filaments, and the generally highly irregular structure of supernova remnants.

In the shock-wave remnants, high temperatures are reached, up to approximately 2×10^6 K in Cygnus Loop, for example. X-rays have been detected from several remnants, and optical [Fe XIV] $\lambda 5303$ emission from at least two (Danziger and Dennefield 1976, Woodgate et al. 1977). The ionization is collisional, and decays as the temperature falls, as a consequence of radiative cooling behind the shock. Some of the temperature-sensitive lines mentioned above and others from even higher excitation levels will be useful to test these calculations. Shemansky et al. (1979) have detected several ultraviolet lines in the Cygnus Loop, including C II $\lambda 1037$ and C III $\lambda 977$, using a spectrometer in Voyager 2.

Large numbers of simplified models have been calculated by Dopita (1977) and Raymond (1979); they discuss in detail which lines are most useful for abundance determinations, and which for determinations of the physical parameters such as density and shock velocity. Observed deviations from the symmetric plane-parallel shocks of these theoretical treatments clearly are large, no doubt because of the inhomogeneous structure of the ambient interstellar gas clouds. More realistic models and interpolation schemes based on them are needed; probably observations on as small a linear scale as possible will most closely match the uniform conditions of existing models.

I am very grateful to B. F. Hatfield for his assistance in collecting material for this paper, and to J. S. Miller for many discussions on the subjects treated here. I am also grateful to the National Science Foundation for partial support of this research under grant AST 76-18440.

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DISCUSSION

Collin-Souffrain (Discussion leader): I want only to mention briefly some particular points concerning the observations of Planetary nebulae and H II regions that can be made with the ST. There are many other possibilities and I am sure that some of them will be raised in the following discussion.

Dr. Osterbrock has emphasized the importance of knowledge of the ionization structure and of the detailed morphology of ionized regions, in order to obtain a better understanding of their physics. He mentioned in particular that the presence of density inhomogeneities may be important for the whole nebular spectrum. These studies are also important from the standpoint of their formation and evolution.

With regard first to the planetary nebulae, small condensations have been observed in the nearest example, the Helix nebula. They are about one arcsec in diameter and are of high surface brightness. Their detailed study is particularly well suited for observation using the FOC with interference filters. It is most probable that such globules are present in many planetary nebulae and it will be important to detect them and measure their line intensities - even with no spatial resolution.

The study of young or proto-planetary nebulae should also be a goal for the ST. Such objects have already been studied in the UV range by Flower and coworkers and have revealed a very rich spectrum. They have typical dimensions of a few arcsec. The ST will enable their density distribution to be determined, which, at the present time, is a very controversial problem: does it increase or decrease towards the edge of the nebulae? Are the shells single or multiple? Clearly answers to these questions will lead to a considerable improvement of our knowledge of the formation processes of planetary nebulae, of their duration, of their stellar winds, etc.

Dust in planetary nebulae is also a very important problem both for its great influence on the overall nebular spectrum and from the point of view of its physics: how does it form, how is it destroyed? These problems can be attacked successfully with the ST because of its capability of measuring directly the intensity of the UV band at λ 2200 Å. On the other hand recent UV observations of the MgII (λ 2800 Å) lines have shown that they are more than an order of magnitude fainter than the predictions of photoionization models while the MgV line, which is produced in the inner part of the nebula, is normal. Is this due to a deficiency of magnesium which at the edge of the nebula is locked in dust grains? Or is it due to destruction of the resonant photons by dust? Whatever the right explanation it will give important clues to the problem of the presence and of the geometry of dust inside NGC 7027. One can even imagine a possible test for the absorption of photons, by

looking at monochromatic images in the MgII lines: if the photons diffuse and are absorbed in a peripheral $Mg^+ - H^0$ region, the Mg II image should be slightly larger than, for instance, the [OII] image.

Finally an improvement of our knowledge of the physical processes in general can be obtained by a systematic confrontation between the most elaborate models and the finest observations. In this respect, I would like to mention the work of Pequignot and coworkers, who from detailed photoionization models of NGC 7027, have shown that the only way to explain the discrepancy between the computed and observed intensities of some low excitation lines, was to assume high rates of charge exchange processes. In particular, they found that the reaction $O^{++} + H^0 \rightarrow O^+ + H^+$ was very fast. At that time, atomic physicists considered this reaction was of negligible importance. But recently, as mentioned by Dr. Osterbrock, Butler et al. re-evaluated this rate and found a value which is in agreement with the earlier empirical estimate of Pequignot et al. One should note that this kind of work was only possible because very detailed spectroscopic observations, in particular by Kaler et al. were available. It is thus quite probable that new UV observations will lead to the empirical discovery of new physical processes. Of course, all previous models of planetary nebulae as well as models of active galactic nuclei have now to be reconsidered.

Concerning H II regions, Dr. Osterbrock has clearly shown how complex a picture is now emerging with globules, ionization fronts, and even dense shocked shells. H II regions are often located at the edge of molecular clouds, forming a kind of "blister", as Israel called them. Dynamical models have been developed for these structures by Tenorio Tagle called "champagne models". Dyson, on the other hand, has studied the interaction of stellar winds with interstellar matter - these two theories account for the presence of thin dense shells of material, and in some H II regions, shell structures, with thickness less than 1 pc, have been observed in the [OIII] lines and are probably common features in H II regions. The high spatial resolution of the ST will help detect new examples of such structures and give better understanding of their dynamics, although unfortunately the spectral resolution is not sufficient to give directly a picture of their velocity structure.

As mentioned by Dr. Osterbrock, high excitation globules, not spatially resolved from the ground, have been observed by Vidal and Laques in the Orion nebula, and their nature is as yet completely unknown: are they clumps in the process of condensation by thermal or gravitational instability or relics of the primordial H^+ region? And, above all, are such globules common features in HII regions? These questions could be answered with the ST.

Stasinska has shown that large uncertainties in the interpretation of line intensities can result from an absence of knowledge of the

structure of H II regions and of their inhomogeneity. For instance, the empirical methods of determining the ionization correction factors are not accurate when the distribution is inhomogeneous, and large errors in the deduced abundance of sulphur and even of oxygen can be made. Helium abundances could also be wrong by 10 or 20%, which is an important uncertainty for this element. On the other hand, the method based on temperature fluctuations developed by Peimbert and Costero (1969) fails in the case of a large abundance of oxygen (2 or 3 times the solar value) which leads through radiative losses in the infrared OIII line to very large temperature variations within the HII region. Even with elaborate models, it is impossible to deduce the oxygen and nitrogen abundances (as soon as they are greater than the solar values), with an accuracy better than a factor 3, if the structure of the H II region is not known!

In this context, studies of bright extragalactic H II regions should be an important goal of the ST. Indeed, our knowledge of H II regions in the galaxy is limited, in the optical and UV range, to the vicinity of the Sun, and to the anticenter direction. There are strong indications however that HII regions near the center of spiral galaxies, have large abundances of C, N and O, and this, of course, is important for galactic chemical evolution, in particular. In order to get better information on these regions, it will be important to get an idea not only of the density distributions of the material in it, but also of the spatial distribution of some strong lines: for instance Stasinska has shown that overabundant regions should be characterized by a very weak ratio $\frac{[\text{O III}] \lambda 5007 + 4959}{\text{He I } \lambda 5876}$ in the center, and a strong increase of this ratio outwards.

Finally, I would like to stress the possibility of using the ST for studies of novae in their nebular stage. As for HII regions and planetary nebulae, the abundances of elements can be obtained through the study of their nebular spectra and very large abundances of CNO have been found in this way. Nitrogen, for instance, is generally overabundant by a factor 100 and since it is generally in the form of highly ionized species (N^{+5} , N^{+4}) which are only observable in the UV range, the ST will be of great significance.

When the nebular shell expands and becomes spatially resolved, it is possible to deduce the distance of the nova by comparing the radial and expansion velocities. Presently this has been performed only for very few nearby novae, since the surface brightness of the shell decreases with time. The ST, allowing spatial resolution at the beginning of the nebular phase, could lead to a considerable increase in the sample of novae having known distances.

On the other hand, when the spatial resolution is not sufficient to

distinguish the nebular shell, the nebular spectrum itself is very difficult to isolate and interpret, since the spectrum is a mixture of several components (the stellar remnant, the accretion disk and the ejected shell), and also because the shell itself is largely inhomogeneous. Recently Williams et al. have obtained for the first time a spectrum of different parts of the old nova Her 34 and they have shown that the shell is composed of 2 "polar" caps and one "equatorial" ring, having different physical conditions and different abundances. Clearly, such studies, which are well suited for the ST, would be of great interest for our understanding of the nova phenomenon.

I would like to end by recalling that all these proposals for the use of the ST are made on the basis of our present state of knowledge of HII regions and planetary nebulae. Because of the large increase in spatial resolution and spectral range that the ST will achieve, it is highly probable that unexpected new problems will be raised and also that we will be obliged to correct misinterpretations of the previous observations.

Burbidge: Which are the elements observed in planetary nebulae that indicate abundance gradients across the disk of the galaxy?

Peimbert: The evidence is reasonably good for a decrease with galactocentric distance of the N/H, O/H and He/H abundance ratios.

Burke: With respect to units, it might be useful to remember that a flux of 4×10^{-12} erg cm⁻² s⁻¹ at wavelength 2500 Å corresponds to a spectral flux density of about half a millijansky.

Gallagher: I will give three examples of how UV observations with ST can provide important information on time-dependent phenomena in galactic novae. First, novae form dust and we are able to observe them from the earliest stages when there is no dust at all to the later stages when a strong infrared excess is observed. Observations throughout that period give direct information about the nucleation process. Novae are often relatively faint during the critical early phase when the dust is forming. ST will enable them to be studied with high spectral and spatial resolution so that we can see where the dust is forming. Second, the emission lines observed in old nova shells differ from those in the shells of planetary nebulae because the source of UV radiation has switched off. The optical emission lines observed come from high levels and might be pumped by various fluorescent mechanisms. Consequently, there are problems in interpreting the optical emission lines to determine relative abundances which are relevant tests of hydrogen flashes and white dwarfs. In the UV, ground state transitions enable some of these difficulties to be avoided to some extent. Third, the energy shift that occurs after a nova goes off is a very sensitive test of the mass of the white dwarf involved

and provides a direct test of the nuclear runaway theory. By understanding how novae evolve in the UV where their evolution tends to be flatter, it may be possible to make better use of them as distance indicators.

Peimbert: HII regions show a very strong continuum due to dust-scattered light in the 1000 to 3000 Å range. IUE observations, in the low dispersion mode, of HII regions in the solar neighbourhood show only a continuous spectrum with the exception of the Orion nebula where $\lambda\lambda$ 1909 CIII, 2326 CII, and 2470 [OII] have been detected. Observations at higher dispersion will increase the emission line to continuum ratio and therefore a faster instrument with higher dispersion will allow the study of a larger number of emission lines in galactic HII regions.

Two effects make the detection of emission lines in giant HII regions with high heavy element abundances more difficult than in giant HII regions with low heavy element abundances: (a) their higher dust content produces, in general, a brighter continuum due to dust-scattered light and (b) their lower electron temperatures make the collisional excitation of UV lines less likely. For galaxies at a few Mpc from us, the ST will enable us to select areas of HII regions without projected O stars and thus suppress the intensity of the UV continuum. The study of these HII regions will increase significantly our knowledge of abundance gradients, particularly that of C/H, in spiral galaxies.

The observation of the planetary nebulae in the Magellanic Clouds with the ST is of great interest for the following reasons: (a) the heavy element content of the interstellar medium in the Clouds is different from that of the solar neighbourhood and therefore abundance determinations from planetary nebulae will provide constraints for evolutionary models of intermediate mass stars with different heavy element content. (b) The expected diameters of the brighter planetary nebulae in the Clouds are several tenths of arcsec, which is well within the resolution range of ST. From the diameters, the known distance and the observed Balmer fluxes it will be possible to derive the root mean square masses for the planetary nebulae in the Magellanic Clouds; in our galaxy with the exception of two or three objects, we do not know the distances and consequently the masses of the shells of planetary nebulae. (c) The masses, fluxes, densities and ionization distribution will enable us to establish a reliable scale for planetary nebulae in our galaxy.

Field: The presence of dust in gaseous nebulae has been mentioned by several speakers. Can we say something more about it?

Peimbert: In addition to dust scattered light in HII regions, the 2175 Å absorption feature is evident in planetary nebulae and HII regions. In particular this feature has been detected, by our group and other groups, in IC 415, the Orion nebula and M8. May I ask

Dr. Bohlin if he thinks that the increase with distance to the Trapezium of the λ 2175 Å feature indicates graphite destruction in the central regions of the Orion nebula?

Bohlin: Bohlin and Stecher (BAAS - Dec. 1975) have a long slit rocket spectrogram in the Orion region from 1200 - 2800 Å. The resolution is \sim 20 arcsec spatially and 15 Å spectrally. θ^2 Ori B is in the slit and the rocket has been calibrated on the IUE scale using the IUE spectra of θ^2 Ori B obtained by Bohlin & Savage. The ratio Ori Neb/ θ^1 Ori C as a function of distance is being interpreted theoretically by Adolf Witt. The θ^1 Ori C spectrum is from IUE, also. Initial results indicate that the dust in Orion is similar to other results by Witt in terms of albedo $a(\lambda)$ and scattering parameter $g(\lambda)$. Because of these complications and that of geometry, it seems unlikely that anything useful can be said about the grain size distribution with distance using the reflection of continuum light from the dust. A more fruitful approach to answering this question is being pursued by Bohlin and Savage, who are producing reddening curves for the 4 Trapezium Stars and θ^2 Ori A and B.

Snow: I can readily think of two aspects of grains that can be explored with the ST:

1. The High Speed Photometer will have the capability of measuring polarization in the ultraviolet, and to date nothing is known about whether or not the interstellar grains create ultraviolet polarization. Hence the ST will provide the first opportunity to explore this and, especially if polarization is found, will produce a wealth of new information about the optical properties of the grains. This will be especially interesting for the extinction bump at 2200Å.

2. There are now specific predictions of structure in the ultraviolet extinction curve due to molecular solids in grain mantles. Any such structure will be best observed in very heavily reddened lines of sight, and ST will allow significant progress in this direction, particularly in the ultraviolet.

Petrosian: I would like to remark on the effects of dust which complicate the simple picture described by Dr. Osterbrock. The dust grains in the nebulae (if any), through absorption and scattering of the ionizing radiation, can modify the ionization structure of nebulae. Only minor modifications are expected if the optical properties of the grains do not vary with frequency. Large effects are expected if the optical properties (such as absorption and scattering opacities and albedo) of the grains vary rapidly with frequency beyond the Lyman limit. This frequency range is not accessible to direct observation so that very little is known about grain properties in this frequency range. Furthermore, calculation of the effects of dust on line intensities is in general complicated because one is normally dealing with dust optical

depths of order unity where simple approximate solutions to the equation of radiative transfer are not possible.

Nevertheless for a given grain model one can calculate their expected line intensities. Hopefully, comparison of this with observations of a sufficient number of UV lines by the ST and IR lines from ground based instruments one can say something about the optical properties of grains in this otherwise inaccessible range of frequencies.

Heidmann: In collaboration with Bottinelli, Gouguenheim, Casini, Tarengi and Benvenuti, we have discovered in some galaxies supergiant HII regions which each are 100 times larger than giant HII regions of the type of NGC 604 in M33 or 30 Doradus in the LMC. This is the case in several respects: they are 100 times more luminous intrinsically, their masses may reach $10^8 \text{ } \odot$, their UV intrinsic luminosity at 1550 \AA is 100 times that of 30 Doradus and they contain as many as 10^4 O or B stars. They are an interesting extension of HII regions towards the gigantic end in the investigation of ionized gaseous nebulae. Their typical sizes are around one arcsec which makes them of particular interest for study with ST. (cf. Casini and Heidmann in ESA/ESO Workshop on the Astronomical Uses of the ST, Geneva, 1979).

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DISTRIBUTION AND COMPOSITION OF INTERSTELLAR MATTER

E. E. Salpeter
Astronomy and Physics Department
Cornell University

1. INTRODUCTION

I am somewhat embarrassed to discuss ST observations of the interstellar medium (ISM) of our own Galaxy for two reasons. First of all it seems, at least at the moment, a less exciting subject for the ST than some others. Secondly, I sadly found, while reading the literature in preparation for this discussion, that I am not sufficiently familiar with optical astronomy to be able to guess where the real advances will come. As a consequence I shall merely summarize (a selection of) observations that have already been proposed, including some for the ISM in external galaxies. Unless otherwise stated, all observations for the high resolution spectograph (HRS) and the faint object spectograph (FOS) are described in more detail by Brandt et al (1977) and by Harms et al (1977), respectively. Observations for the wide field camera (WFC) and faint object camera (FOC), on the other hand, were already discussed at length at the ESA/ESO Workshop on "Astronomical Uses of the Space Telescope" and I shall refer to review papers in the workshop proceedings.

In Sect. 2 I mention some of the current problems about the ISM that interest me personally the most. The remaining sections summarize proposed observations of matter distribution (hopefully, abundances will be discussed by Jura and others). The reader will note a strong emphasis on the HRS over other instruments. This stems in part from the fact that we have learned so much from observations with the Copernicus satellite (Spitzer and Jenkins 1975) and the HRS is "bigger and better" by simultaneously providing better sensitivity and spectral resolution. I cannot guess whether the history of the ST regarding the ISM will indeed stress "bigger and better Copernicus observations" or whether (as often) quite unexpected discoveries will dominate.

2. SOME CURRENT PROBLEMS

My personal views on the various components of (and energy balance in) the interstellar medium (ISM) I stated just a year ago (Salpeter

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1979), so I will list only some current problems. Many of these problems were already described in books and reviews (Dalgarno and McCray 1972, Aannestad and Purcell 1973, Osterbrock 1974, Spitzer and Jenkins 1975, Audouze and Tinsley 1976, Chevalier 1977, Salpeter 1977, Spitzer 1978, McCray and Snow 1979).

For the components of the ISM which contain predominantly neutral, atomic hydrogen one usually talks of "clouds" (or "diffuse clouds") on the one hand and the intercloud medium on the other. It is not clear to what extent the "clouds" are really isolated entities (Heiles 1976) and to what extent the intercloud medium is all-pervasive. More data on correlation between spatial, temperature and velocity structure would be useful. The dense, "molecular clouds" make up an appreciable fraction of the mass of the ISM and are presumably the site of star formation, but quantitatively there is a puzzle: These clouds ought to be in free-fall, free-fall times should be short and the clouds should "turn over" much faster than they seem to. It would be nice to know if something is keeping these clouds in a delicate balance against gravitational collapse (Solomon et al 1979).

The overall fluxing of mass, bulk kinetic energy, thermal energy and ionization through the ISM is understood in broad outline, but questions remain on quantitative details: Is most of the mass loss from stars accounted for by planetary nebulae or is continuous mass outflow at slightly earlier evolutionary stages also important? Is the "coronal gas" (temperatures $\sim 10^5\text{K}$ to 10^6K) in the Galactic Disk mainly due to Supernova Remnants or are "bubbles" blown by the stellar wind from OB-stars also significant? Do central stars of old, low-density planetary nebulae contribute much to ionization and are extended low-density HII regions ionized by O or B stars (Mezger 1976)? Much of the bulk kinetic energy in the motion of clouds comes from supernova remnant blast-waves, but what are the dynamic details when such a blast-wave proceeds through a clumpy medium or encounters a massive cloud-complex, as may be the case with IC443 (see Sect.8)?

Chemical abundances in the ISM now depend on the chemical evolution of the Galaxy at earlier times (Audouze and Tinsley 1976). Some time ago theorists had hoped that the stellar birthrate as a function of time and stellar mass has two simplifying properties: (a) it can be expressed as a simple product of a function of mass alone (the Initial Mass Function) and a function of time alone and (b) it is a smooth monotonically decreasing function of time. From different studies of external galaxies it is clear that both (a) and (b) are wrong: there are large-scale bursts of star formation and long quiescent periods instead of a smooth time-dependence; the mass to light ratio increases strongly in the outermost regions of galactic disks, indicating a preponderance of either very low or very high mass stars, which have long since produced supernova. The possibility of supernova explosions in the outermost regions of galaxies at early times would predict an appreciable iron abundance there (and X-ray spectroscopy has indicated the presence of iron in intergalactic gas). These complexities have led to the realization that one has to

study chemical abundances (and their gradients) in external galaxies even if we wanted to understand only our own interstellar medium.

3. SOME OBVIOUS ADVANCES

The most obvious advance in our knowledge of the ISM would come from simply repeating the Copernicus observations of interstellar absorption lines with the very high resolution mode of the HRS, $\lambda/\Delta\lambda = 1.2 \times 10^5$ instead of 2.2×10^4 . The corresponding increase in velocity resolution from 13.5 km s^{-1} to 2.5 km s^{-1} is of vital importance, especially for the predominantly neutral gas: The purely thermal velocity widths are small compared with 13.5 km s^{-1} and even observed total velocity widths (thermal plus turbulence plus rotation, etc.) of an individual absorption feature are usually $< 10 \text{ km s}^{-1}$, as shown both by observations in the visible of Na, I, say, (Hobbs 1969) and at 21 cm of HI (Dickey, Salpeter and Terzian 1979). On the other hand, the dispersion of velocities of "clouds" (absorption features) is just comparable with the Copernicus resolution - a frustrating coincidence. The resolution of 2.5 km s^{-1} is comparable to that used in modern 21 cm observations and one may wonder if the HRS will really give us new insights into the velocity structure of the ISM? However, the 21 cm absorption studies suffer from the fact that strong extragalactic background sources have to be used, which are sparsely dispersed over the sky. With the great sensitivity of the HRS one could study absorption towards a fairly large number of stars in adjacent regions of the sky (and at different distances). One may then be able to find out, for instance, whether turbulence (and/or rotation) velocities increase towards the spatial periphery of a cloud complex. Furthermore, one may even be able to separate these contributions from the true thermal velocity width and thereby get an estimate of kinetic temperatures (as distinct from excitation temperatures).

The high resolution of the HRS for absorption line studies will also make abundance determinations for ion species and molecules more reliable: The ambiguity between circumstellar and interstellar absorption lines should be lessened and line shapes will be obtained more directly. More important still is the greater sensitivity, which will enable the study of weak (as well as strong) lines for a given ion or molecule so that curve of growth difficulties can be overcome.

Another obvious, although very indirect, advance in our knowledge of the ISM will come from observations of stellar surfaces carried out for quite different purposes. Studies with the WFC and FOC will presumably extend luminosity functions for individual stars down to much fainter magnitudes, well below the main sequence turnoff in many systems. Spectroscopy will presumably lessen the uncertainties in chemical abundances in the surfaces of various stars. All this has no direct bearing on observations of the ISM, but it will put on a much firmer basis theoretical calculations on chemical evolution of galaxies and on the mass balance for the ISM (Tinsley and Larson 1977, Pagel 1979).

4. INTERSTELLAR ABSORPTION FOR HIGHLY REDDENED STARS

Absorption line measurements in the UV with Copernicus were possible for stars with interstellar reddening up to $E(B-V) \sim 0.5$, with $E(B-V) \sim 0.3$ more typical (as for the most famous case so far, Zeta Ophiuchi, Morton 1975, Snow and Meyers 1979). With the HRS, on the other hand, measurements will be possible up to $E(B-V) \sim 2$, with $E(B-V) \sim 1$ still quite economical in observing time. For stars in the galactic plane with the mean reddening law of $\sim 0.6 \text{ mag/kpc}$ in $E(B-V)$ this improvement would only mean extending the range of the instrument from $\sim 500 \text{ pc}$ to $\sim 2 \text{ kpc}$. For a "ubiquitous component" of the ISM, such as the coronal gas characterized by OVI absorption, this extension in range will make the separation between circumstellar and interstellar gas slightly more secure but will probably not have a major impact. However, the situation should be radically altered when the large interstellar reddening is due not to a large total pathlength but due to passage through a molecular cloud.

Typical values of extinction A_{UV} in the UV for $\lambda \sim 2200 \text{ \AA}$ are roughly 2.5 times the visual extinction A_V and roughly 7.5 times $E(B-V)$. Thus a cloud like the one in front of $\zeta \text{ Oph}$ has $A_{UV} \sim 2.5$, whereas the HRS will be easily able to penetrate a cloud with $A_{UV} \sim 7.5$, so that the diffuse field (for photon energies $\sim 10 \text{ eV}$) is attenuated by a factor of order 10^{-3} rather than 10^{-1} . The balance between different ion, atomic and molecular species can be very sensitive to the value of such an attenuation factor since the UV photons mainly control ionization and dissociation. This is already demonstrated dramatically by the balance between atomic and molecular hydrogen (Savage et al 1977, Bohlin et al 1978): The sum N_{tot} of atomic column density $N(\text{HI})$ and of $2N(\text{H}_2)$ is close to $(6 \times 10^{21} \text{ cm}^{-2}) E(B-V)$ both for small and large reddening, but the ratio $N(\text{H}_2)/N(\text{HI})$ changes from very small values for $E(B-V) \leq 0.1$ to large values for $E(B-V)$ appreciably above 0.1. For hydrogen, the rapid change of an abundance ratio occurs at fairly low values of $E(B-V)$ and is expected theoretically (Hollenbach et al 1971, Myers et al 1978); similar, but more complex, changes in other species take place at larger values of $E(B-V)$ which will only be accessible from the ST.

Fortunately there are a number of suitable reddened stars which are quite bright, $V \sim 8$, such as one in the Monoceros Cloud with $E(B-V) \approx 0.8$ and one in the $\rho \text{ Oph}$ cloud with $E(B-V) \approx 1.1$. Four hours of observing time per star with the very high resolution mode of the HRS will give details for about 70 absorption lines and abundances for more than 20 ion, atom and molecule species, mainly from the one dense cloud (or cloud complex) along the line of sight. These abundances will give information on the chemical reaction/ionization equilibrium in the cloud, but hopefully will also measure the gas phase depletion factor for a number of elements. Furthermore, for a few molecular species one should see absorption lines originated from different rotational levels and from different isotopes, which will give information on temperature and density. For many of these clouds, eg. $\rho \text{ Oph}$ (Myers et al 1978), one already has information on many of the same molecular species from microwave emission. It is particularly exciting that a large millimeter-wave

telescope, which can look for three different rotational transitions in CO in emission ($\lambda = 2.6, 1.3$ and 0.87 mm), should come into operation at about the same time as the ST which will see at least two rotational levels in CO in absorption. This will give not merely "one measurement of density and temperature" but enough redundancy to point out any serious discrepancies, which in turn should teach us something about the "real physics" involved.

As discussed in Sect. 3, the velocity structure of a cloud complex can be studied with a velocity resolution of 2.5 km s^{-1} . It will be frustrating that even this excellent resolution is not quite good enough for molecular clouds where the temperature is low ($< 50 \text{ K}$) and the velocity width can be less than the resolution if the cloud is quiescent. However, the real interest lies in non-quiescence: these clouds are at least the forerunners of gravitationally collapsing material which will form stars by fragmentation and the velocity structure might reveal (or at least hint at) shock speeds (Jura 1975) and/or turbulent velocities.

I want to enter my personal plea to observers for redundancy, rather than a broad coverage, when total observing time is limited - i.e. study a few objects thoroughly rather than all of them poorly. This includes using many lines and different observing techniques for one species in one direction in the sky, but also using as many stars as possible in or behind one cloud or cloud complex. As mentioned, this is still difficult to do in 21 cm HI absorption even with as large a telescope as the Arecibo dish; fortunately in this respect the ST mirror is "larger" than the Arecibo dish!

5. INTERSTELLAR DUST GRAINS

The observations discussed in Sects. 3 and 4, although planned for other purposes, will also give information on interstellar dust-grains in three different ways: (i) One indirect but important way is to study the gas-phase depletion of different elements from quantitative abundance measurements of different species, since atoms missing from the gas phase are presumably locked up in grains. It is particularly important to study how the depletion factors depend on (a) the chemical and crystallographic properties of the element (Field 1974, Salpeter 1977), (b) the velocity of the cloud or cloud-component (Shull et al 1977, Snow and Meyers 1979) and (c) the internal density and reddening $E(B-V)$ of the cloud. Much theoretical work (Barlow and Silk 1977, Cowie 1978, Shull 1978, Draine and Salpeter 1979) has been done on this subject, but reliable observational data is badly needed on depletion factors. The increased absolute accuracy in abundance determinations, large number of molecular and ion species per element and the increased range in $E(B-V)$ will help.

(ii) The average extinction curve of interstellar dust grains in the visible and UV is now known fairly well (Aannestad and Purcell 1973, Spitzer and Jenkins 1975), but the variations from case to case are not

yet well understood. In particular, it is important to know how strongly the extinction peak near 2200\AA (supposedly due to graphite) and the extinction rise towards 1300\AA (supposedly due to very small grains) depend on the three parameters discussed under (1). Although the high spectral resolution of the HRS (or even the FOS) are hardly required for this work, extinction curves will become available over a much wider range of $E(B-V)$. Correlation with infrared observations of the same cloud, such as the search for the 3.1μ ice-feature (Harris et al 1978) will also be of interest.

(iii) The ratio of grain scattering to grain absorption as a function of wavelength in the UV is of interest. I have not yet seen detailed plans for studying reflection nebulae in the UV with the WFC and FOC. However, the determination of abundance ratios for different ion stages of one element, or atom/molecule abundance ratios, in the gas phase (Sects.3 and 4) can give some indirect information: Since ionization and dissociation by UV photons has different threshold energies for different cases, one can (in principle) obtain the spectrum of the diffuse radiation field inside a particular cloud from measuring a set of different abundance ratios. Comparison with the diffuse radiation field in unreddened regions then gives estimates for the grain albedo. Some information of this kind has already been obtained (Jenkins and Shaya 1979) from abundance ratios for C, Na and K, but the ST should improve the situation.

So far only a little (Gehrels 1974) is known of the polarizing properties of the interstellar dust. The spectropolarimeter associated with the FOS (Harms 1979) should obtain direct information on this from stars with different amounts of reddening. One question of interest is the polarization of the 2200\AA feature, since models for almost spherical graphite grains predict little polarization.

6. OUR IMMEDIATE NEIGHBORHOOD

The high sensitivity of the ST will mainly be used to increase distances over which observations can be made, but there is also one application to explore the ISM at smaller distances from us than has been possible in the past: For absorption studies in the UV with less sensitive instruments one requires stars which are bright in the UV, i.e. the rare O and B-stars; thus the nearest star observed with Copernicus is about 65pc away. White dwarfs and late-type main sequence stars, on the other hand, are faint in the UV but very common; there are over 20 K-type main sequence stars within 5pc and over 20 white dwarfs within 15pc. Fortunately the late-type main sequence stars emit some chromospheric Ly α and the emission spectrum in the UV of some white dwarfs (especially for type DA) has already been measured with the IUE (Greenstein and Oke 1979).

To be more precise, Copernicus and IUE are sufficiently sensitive to measure the emission spectrum of K-stars and white dwarfs in the UV

and some absorption studies have already been attempted (e.g. for the K2V star ϵ Eri at 3.3pc, McClintock et al 1976). However, the combined sensitivity and high spectral resolution ($\lambda/\Delta\lambda = 1.2 \times 10^5$) of the HRS will be required to disentangle the very faint (but narrow) interstellar absorption lines from the complex spectrum (with broader spectral features) of the star itself. Only a few minutes per white dwarf will be required to look for CI, CII, NI and OI absorption lines at wavelengths between 1200 and 1400Å. Similarly, about 10 minutes per K-star will be required to obtain HI column density and velocity distribution from Ly α absorption.

This study of the nearby ISM is made more interesting and also more difficult by the fact that the HI density in our vicinity is quite low compared with the average density in the galactic disk. Observations of backscattered solar Ly α radiation (Fahr 1974) and some stellar observations (Dupree 1975) had already indicated this, but it is still not clear whether hydrogen densities are typically of order 0.02 cm^{-3} or 0.2 cm^{-3} . A study of a few dozen stars with the HRS will only require a few hours in total and yet should give us a lot of information about the nearby hydrogen distribution. In terms of "value per observing time" I consider this a very high priority project.

7. HIGH VELOCITY CLOUDS; CORONAL GAS IN A GALACTIC HALO

Twenty-one centimeter studies of neutral hydrogen in emission are very extensive; "intermediate-velocity clouds" ($20 \text{ km s}^{-1} < |v| < 60 \text{ km s}^{-1}$) are reasonably common, "high velocity clouds" ($|v| > 60 \text{ km s}^{-1}$) are rather rare but fairly well-mapped. The physical nature of these clouds is mostly a mystery (except for some which are probably connected with very old supernova remnants and others at low galactic latitudes which are probably part of an outer, warped galactic disk). The emission data (Verschuur 1975) can help little on the two important observational questions of temperature and distance for such clouds.

Absorption studies at 21cm can, in principle, measure the temperature of the neutral hydrogen. Some measurements of this kind have been and will be made (Payne et al 1978), but even the Arecibo dish is on the borderline of being too small for this job. In particular, I am not too optimistic for Arecibo absorption data for clouds which are both at very high galactic latitudes and at high velocities, which are the most controversial (furthermore, 21cm studies use extragalactic background sources which are much more distant than these clouds, no matter which model for them is right). Fortunately there are many blue stars at high galactic latitudes with $m_V \sim 7$ to 10, situated in the nearby Galactic halo (1 or 2 kpc away, say). For such stars in the direction of high velocity clouds, the usual HRS absorption line studies will easily show various ion species of C, N, O and Si if the cloud is closer than the star. This is predicted on some models for such clouds, but not on others, and the absence or presence of absorption will provide one clue to the controversy. If present, the absorption lines will also give

chemical abundances and ionization conditions which are also uncertain. Clouds at somewhat lower velocities and latitudes are more plentiful and less spectacular but are not fully understood either and should not be neglected: Some UV absorption results are already available (Shull 1977, Cowie and York 1978), but the HRS can do much more and it would be particularly useful if the same cloud could be studied with the HRS and at Arecibo.

Not only the nature of high-velocity neutral gas is controversial at the moment, but so is the presence in our Galactic halo of coronal gas, which was already predicted by Shklovsky (1952) and Spitzer (1956). Absorption lines in the wavelength region 1200Å to 1600Å of CIV, NV and Si IV should be characteristic of such coronal material. Suitable background sources at high galactic latitudes should be individual O and B supergiants in the Magellanic Clouds, the cores of bright Seyfert galaxies and even 3C273. Some coronal gas in our halo (using stars in the LMC) has already been detected with the IUE (Savage and de Boer 1979), but the sensitivity and spectral resolution ($\lambda/\Delta\lambda = 1.2 \times 10^4$) of the IUE is marginal for this work. Even the lower spectral resolution of HRS is (slightly) better than the highest resolution on IUE (and the sensitivity enormously greater), so these observations should become relatively simple.

8. PLANETARY NEBULAE AND SUPERNOVA REMNANTS; STATISTICS AND ABUNDANCES

The physics of emission nebulae, including planetary nebulae (PN), has been discussed by Osterbrock. Besides being of interest in their own right, planetary nebulae are important for returning mass into the ISM and their central stars may be important for providing ionizing photons. Recent estimates (Pottash et al 1978) of the ionizing flux from a central star are low and these stars may not compete effectively with OB-stars, but more data are needed. Although the ST does not observe photons beyond 13.6 eV directly, observing the emission spectrum of a star in the UV almost up to the Lyman edge will lead to more reliable stellar atmosphere models which in turn can predict the flux of ionizing photons. These measurements can be done most systematically for PN in the Magellanic Clouds where distances are known accurately; the FOS will be suitable for these central stars with $m_V \sim 16$ to 22. About 20 PN in our own Galaxy have central stars with $m_V < 12$; these can be observed with the HRS to obtain absorption lines from each star's own nebula.

For establishing the overall rate of occurrence of PN reliable distances are important and for that purpose PN in the Magellanic Clouds (or other external galaxies) are useful. In order to draw reliable conclusions about the PN distance scale in our own Galaxy from external data one has to understand the variation of PN statistics with Hubble type and therefore one also needs data on the more distant members of the Local Group, such as Andromeda and its companions. Identification of extragalactic PN from groundbased telescopes has already been

achieved (Ford 1978, Jacoby 1978, Webster 1978), especially using onband/off-band filter photography on nebular emission lines such as [OIII] λ 5007. However, most PN even in the Magellanic Clouds have an angular size less than 2" and cannot be resolved reliably from groundbased photographs. The FOC and WFC, on the other hand (D'Odorico et al 1979) will be able to resolve all PN in the Magellanic Clouds (and even display some fine-structure), which should pin down individual ages and overall occurrence rates fairly well. For the more distant members of the Local Group the PN sizes should range up to about 0.2", so that only some can be resolved but many can be detected. H β observations of internal fine structure (at least for the nearer PN) should provide filling factors and, hopefully, masses (as well as ages) of individual nebulae will be obtained more reliably.

With supernova remnants (SNR) one also will be striving for statistics from external galaxies with known distances, on the one hand, and more physical details for Galactic SNR on the other hand. There are already some groundbased observations of SNR in the Local Group (Danziger et al 1979, Dopita 1979), but one is limited by sensitivity or resolution. Searches with the WFC (using H α or [SII] filters) should do much better and the FOC could reveal internal structure (Danziger 1979). For the nearby Galactic SNR the WFC can of course give finer spatial structure but there is even a possibility of measuring proper motion (up to 0.1"/year for Vela or Cygnus). For a few Galactic SNR one can even find an O star behind the remnant, so that one can observe absorption lines from the path through the remnant. One example is HD254755 behind IC443, a moderately young SNR (Malina et al 1976) which is a particularly interesting case: Besides the usual X-ray emission for a SNR (Winkler and Clark 1974), gas at about 10⁶K has also been observed recently (Woodgate et al 1974). Cool gas, including neutral atomic hydrogen 21cm emission (DeNoyer 1978) and even some molecules, is also associated with IC443 in a less direct manner. I again would like to urge observers with different techniques to select a few out of many (including IC443) for really intensive study - to provide the theorists with redundancy and discrepancies!

The determination of chemical abundances in the gas phase is of course an important incentive in the study of PN and SNR, as well as HII regions (Perinotto and Renzini 1979, Pagel 1979). For SNR (and their associated neutral intermediate-velocity clouds) an interesting question is whether destruction by sputtering of the dust grains lessens the gas-phase depletion (Jenkins et al 1976). For PN a mundane but important advance will be obtaining precision values for abundances of C, N and O: Abundance ratios of these species depend on the birthrate function for the stars from which the ISM was enriched (Tinsley and Larson 1977, Pagel 1979). Another important clue to the chemical evolution of galaxies lies in radial abundance gradients in galactic disks of various Hubble types. Groundbased observations (Searle 1971, Hawley 1978, James 1979) suggest such gradients for regular spirals but not for irregular galaxies such as the Magellanic Clouds. However, excitation conditions and dust/gas ratios are likely to vary with distance from a galaxy cen-

ter, as well as abundances themselves. To disentangle these various effects it is imperative to be able to measure as many different lines of different ion species as possible and the ST will surely help here.

The ISM is complex not merely in its region-to-region variations, but also in the coexistence of many components in one region of space (or at least one line of sight). I already mentioned the large range of temperatures associated with the supernova remnant IC443. For the Orion complex one not only has the contrast between the ionized region (Pankonin et al 1979) and the molecular cloud, but even for the molecular cloud alone one has the contrast between presumed thermal Doppler velocities of less than 1 km s^{-1} and some observed velocity structure up to 100 km s^{-1} (Nadeau and Geballe 1979). Coordinating ST observations with those on the VLA and the mm-wave telescope will be challenging, due to the complexity of the medium and the large increase in resolution of all three instruments (coupled with the fact that ISM observations will not have particularly high priority for the VLA). I also want to endorse Osterbrock's plea for a concerted effort on theoretical model calculations - redundancy in observations must be coupled with sophisticated data analysis.

This work was supported in part by NSF under Grant AST 78-20708.

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DISCUSSION

Jura (Discussion leader): The prime instrument for study of the interstellar gas is the High Resolution Spectrograph. Copernicus was able to detect absorption lines of equivalent width 1 mÅ. As compared with Copernicus, ST provides two advantages. First, lines of equivalent width 0.1 mÅ can be studied which means that very weak lines can be measured for which there are no corrections for optical depth in radiation transfer. Second, observations can be made over a very much larger dynamic range. Let me give two examples of the types of study which will be possible. From observations with Copernicus, it has been shown that there is a correlation of colour excess with H₂ column density in the solar neighbourhood. There is some residual scatter about this relation and it is important to know if this reflects a real scatter in the colour excesses or if it is due to poor estimates of the colour excesses. If the former is the case, it means that there are real non-uniformities in the abundances and this is important in relation to studies of abundance gradients in the Galaxy. There is some evidence that the D/H ratio is also variable and this may be closely related to variations in other element abundances as measured by the colour excesses. Very much more accurate data on this correlation will be obtained with the HRS. The second example concerns the microphysics of the interstellar medium. Hydrogen atoms stick to the surface of grains and are catalysed into H₂ molecules. What happens, for example, to an oxygen atom when it hits a grain? If it sticks, the atomic oxygen abundance is depleted in the cloud. If it comes off in molecular form, as OH, H₂O or CO for example, searches can be made for all three species and the relative efficiencies of molecule formation for hydrogen and oxygen atoms can be measured directly. The HRS will prove a very powerful tool for the study of such problems.

Field: How can you distinguish molecules formed on grains from those formed in gas-phase reactions?

Jura: You can look in the direction of regions containing very low abundances of molecular hydrogen and then there will be very little ion-molecule chemistry going on.

Snow: There are also molecular species which only form in endothermic gas phase reactions and these are again good candidates for formation on grains.

Ostriker: I have two comments on Dr. Salpeter's lecture. First, it is surprising to me how constant the initial stellar mass function may be. The existence of dark matter in the halo should not be used as an argument one way or another because we do not know what it is and it may not have anything to do with star formation. Second, in models of the interstellar gas in which hot and cold gas coexist, there are observa-

tional tests. In particular, if there are hot and cold regions with intermediate temperature gas in between, there should exist velocity correlations i.e. the intermediate gas should move at the same velocity as the cold gas.

van de Hulst: Dr. Salpeter mentioned in his talk that, of course, there will be a continuum of states of the interstellar gas. Does this mean that you believe there will not be distinct phases?

Salpeter: Observationally I merely note that, whenever an observing technique has become available which is sensitive to a particular temperature range, a positive detection followed. Theoretically, one can certainly get the coexistence of two phases, but the numerical value of temperature depends on the pressure so that even a given phase will have different temperatures at different places.

Savage: ST can be used to study the distribution of hot gas in the galactic halo. We have obtained spectra of stars in the Magellanic Clouds in the ultraviolet waveband using IUE. The profiles of CIV and SiIV show gas in absorption local to our own Galaxy and to the Magellanic Cloud. The strong Galactic features extend to positive velocities of about 150 km s^{-1} . If this gas corotates with the disc of the galaxy, there must be a halo of hot gas around our Galaxy extending up to 8 kpc from the galactic plane.

The present data are rather noisy and the minimum detectable equivalent width is $\sim 40 \text{ m}\text{\AA}$ which puts it on the flat part of the curve of growth which limits the analysis. With ST, we will obtain the following advantages: (i) The data will be of very high precision enabling detailed studies of the line profiles to be made. In particular equivalent widths very much less than $30 \text{ m}\text{\AA}$ may be readily detected. (ii) Some tantalising features of the spectra are barely resolved and the higher spectral resolving power of ST will enable these features to be studied. (iii) The assumption that the hot gas corotates with the disc may be checked by making observations in a number of different directions. This is not possible with IUE because there are too few bright stars. With the HRS, it will be possible to use fainter objects such as quasars, Seyfert nuclei, possibly the nuclei of galaxies and globular clusters.

York: With ST, it will be possible to measure the equivalent widths of absorption lines as weak as $0.1 \text{ m}\text{\AA}$ for stars brighter than $m_v = 5$. These weak features will be observable in components of hydrogen column density $3 \times 10^{19} \text{ cm}^{-2}$. Studies of Lyman- α in the direction of Orion stars have indicated column density $2-3 \times 10^{20} \text{ cm}^{-2}$ but studies of the sodium lines suggest that this consists of a number of individual components with column densities $\sim 2-3 \times 10^{19} \text{ cm}^{-2}$. The main problem is that we do not know hydrogen column densities as a function of velocity because of the great width of the Lyman- α and Lyman- β lines. However,

there are other elements which can be studied and which together lead to precise determinations of physical conditions. In particular, "volatile" elements such as CII, BII, BeII, NI, OI, SII, PII and ZnII should be present with Solar abundances in almost any cloud. With the high resolution of ST, b -values can be measured to $1\frac{1}{2}$ - 2 km s^{-1} and it is not unreasonable to expect to measure temperatures of HI regions accurately down to 3000 K. To go cooler, $T \sim 500 \text{ K}$, doublet techniques would have to be used. This should be reasonably precise for ST observations because we do not have to worry about blends.

A problem is that even along the simplest line of sight which shows only a single line with Copernicus, there may be as many as nine components according to current theories. We may expect a single cloud to have low velocity HI, low velocity HII, shocks at the edge giving high velocity HII and cooling gas behind the shock producing high velocity HI, and so on. It will be difficult to separate these out. However, using nitrogen and oxygen, the position of the neutral component can be found. Inside these neutral clouds, the warm edges may be separated from the cooler central regions. Most important is the determination of the neutral hydrogen distribution in the region. This is now possible with ST. From studies of the species listed above, we can derive all the important physical parameters, volume densities, electron densities, temperature, etc. It will be particularly important to study the formation rates of molecular hydrogen in these clouds.

Jenkins: It is important to measure the pressure in HI regions, its mean value, variations from the mean and their causes and the study of departures from equilibrium. The pressure is an elusive quantity to measure and can only be studied by indirect methods. For example, the relative abundances of neutral and ionised species can be used to find the pressure from ionisation equilibrium calculations if the photoionisation rate is known. This method is, however, sensitive to assumptions about the ionisation rate. Alternatively, the H_2 rotational populations can be used to provide estimates of pressures but these are complicated by details of the radiative cascade and the initial distribution of H_2 when it comes off grains.

I want to emphasise the importance of studying spectroscopically the relative populations of atoms of different stages of fine-structure excitation from the J-level splitting of the ground state. CI is particularly important in these studies since it is almost always found in HI regions. Except at very low pressures, the dominant excitation and de-excitation processes are collisional. A particular advantage of CI is that the excitation cross-section by atomic and molecular hydrogen is more or less the same so that the total excitation only depends upon the total amount of hydrogen present. CI is not strongly depleted in HI regions. In addition, the energy levels are close together so that the Boltzmann factor is not too important. Carbon has electronic levels

with three fine structure states which respond differently in different pressure regimes. It is therefore possible to get information not only about mean values but also about the distribution of pressure from a single observation. Many of these multiples are of different line strength and therefore one can use those of appropriate strength to avoid uncertain assumptions about the curves of growth.

Examples of goals for ST using the High Resolution Spectrograph are:

- (i) Study of distant stars, especially along lines of sight through spiral arms to test density wave theory of spiral structure.
- (ii) Studies of heavily reddened clouds to determine precise pressure enhancements and the dynamical evolution of the system.
- (iii) The differences in velocity dispersion between excited and unexcited lines giving better indication of structure in the clouds.
- (iv) Study of negative velocity material being compressed and ejected from OB association complexes
- (v) Extending Copernicus observations in an unbiased way through the study of faint objects.

Snow: A great deal of information about interstellar clouds can be derived in cases where radio and optical techniques can be applied to the same cloud. Currently there are few clouds where such overlap is possible, because of the low sensitivity of existing ultraviolet spectrographs. With the ST there will not be a great number of regions dense enough to produce complex millimeter molecular spectra and still be transparent enough for optical absorption-line measurements to be made, but certainly some progress in this direction will be achieved. There will be benefits for both the radio and optical observers, including the use of optical techniques to derive such parameters as atomic abundances, radiation field intensities, abundances of some molecular species that have no millimeter-wave spectra, and the nature of the extinction curve within dense clouds, all of interest to the radio observers. For their part, the radio data provide high velocity resolution so that the velocity dispersion of the gas will be measured directly, greatly reducing uncertainties in analyzing the optical data. For the first time we will have information on physical conditions in dense clouds where complex chemical processes have taken place.

Hemenway: As an astrometrists, I am trying to think of ways to help you. Apparently we see spatial structure in the interstellar medium at all spatial resolutions. One could expect to find filamentary structure at the resolution of the ST, i.e. $\theta \sim 0.1$ arcsec. If a star were moving through or behind a cloud, say with a velocity of 50 km s^{-1} relative to the cloud, perpendicular to the line of sight, then it would pass completely behind (through) a 100 pc filament in 10 years. By doing time dependent ($\tau \approx 1$ year) spectroscopy on the interstellar lines, one could study the microstructure of the filament. One must observe not only the time dependent spectrum, but also the relative motion of the star and filament, and perhaps do accurate simultaneous photometry.

11 N80-22136

LUMINOSITY FUNCTIONS AND EVOLUTION OF GLOBULAR CLUSTERS

K.C. Freeman
Mount Stromlo and Siding Spring Observatories,
Research School of Physical Sciences,
The Australian National University.

Why are globular clusters so important for astronomy? Here are some reasons. (i) Globular clusters are the oldest luminous objects in the Galaxy. They are samples from the early chemical evolution of the Galaxy, as the metal abundance $[m/H]$ rose from about -2.5 to about -0.5. (ii) They are large enough to give a statistically significant data set for stellar evolution studies over this whole abundance range. (iii) Their stellar dynamics is very inviting; globular clusters are relatively simple structurally, so there seems to be a real opportunity for a fairly complete understanding of their internal dynamics. (iv) Some of their chemical and dynamical problems are similar to those of galaxies (eg the large clusters 47 Tuc and ω Cen show galaxy-like radial abundance gradients). These problems are much more tractable for globular clusters, because we can measure directly the chemical abundances and kinematics of individual cluster stars.

I believe that ST will have a really profound effect on the course of globular cluster studies, in many areas. I will talk about a few areas now; others will come up during the discussion. Most of the urgent problems of globular clusters require observations of faint stars, and this is where we will see ST at its best.

I. LUMINOSITY FUNCTIONS

a) The old halo clusters

The initial mass function for recent star formation in the galactic disk appears to be fairly uniform. It may not have been so uniform at the time of formation of the oldest galactic populations. For example, the apparent existence and unknown content of dark galactic halos suggests that

star formation did not always proceed with the present IMF. This makes the mass functions of globular clusters particularly interesting, because they were probably among the first objects to form. Progress in this area is fairly recent, because the nearest globular clusters are in the South, and only three clusters have been studied in detail so far. Da Costa (1977) showed that the slope x of the IMF varies from about 0.9 for NGC 6397 through 1.5 for NGC 6752 to 2.9 for 47 Tuc ($x = 1.35$ for the Salpeter function). What cluster properties does x correlate with? This is not yet clear: for Da Costa's three clusters, x increases with chemical abundance and cluster mass. Probably chemical abundance is the important variable for the IMF. The clusters M15 and M192 have similar abundances and luminosity functions to those of NGC 6397, but they are significantly more massive (Sandage and Katem 1977, van den Bergh 1975).

What can ST contribute to the study of globular cluster mass functions? The small image size of the WFC wins twice here. It allows the detection of faint stars against the sky background, and it greatly reduces crowding problems. Crowding is the analog of confusion in radio astronomy. It causes star counts to become inaccurate when a significant fraction of the field is covered by stellar images. For example, with large groundbased telescopes, crowding problems become important for star densities of about 100 stars/sq arcmin. At magnitude $V = 22.5$, the galactic background alone is a few tens of stars/sq arcmin in typical globular cluster fields, so detailed luminosity function work from the ground is obviously limited to the outermost parts of the clusters. With ST, crowding problems become important at about 10 stars/sq arcmin: the galactic background is significantly less than this, even at the WFC limit (see van den Bergh's talk), except for some fields in the galactic plane.

Here are three obvious areas in which ST can make a really significant contribution to this problem of the stellar content of globular clusters.

(i) For the closest clusters, it will be possible to derive the luminosity function down to $M_V = +15$ ($m = 0.1m_{\odot}$). Reliable data on the mass function down to this low mass limit would be very valuable, both for its own interest and for dynamical modelling.

(ii) The data we now have on cluster luminosity functions is limited by crowding problems to the outer parts of the clusters. To derive the integrated luminosity function of a cluster, model-dependent corrections are required. These corrections depend on the level of thermodynamic equilibrium attained by the cluster, and this is not yet well understood. Also, some clusters have radial abundance gradients, which further complicate the problem. With ST it will be possible

to measure the luminosity function directly, almost in to the core of even the most concentrated nearby clusters, down to $M_V = +9$.

(iii) There remains the problem of the slope x of the cluster mass functions: does it depend on the cluster's chemical abundance? It seems very important to study a few more metal-rich clusters, to see if their mass functions are also steep, like that of 47 Tuc. This is a ST problem: although there are several metal weak clusters close enough for groundbased luminosity function work, there are no more nearby ($m-M < 14.5$) metal rich ones at galactic latitudes $|b| > 15^\circ$.

b) LMC clusters

Unlike our galaxy, the LMC contains globular clusters of all ages. The youngest, with ages of about 10^7 y, are globular-cluster-like in structure and total mass, and they have no known counterpart in the Galaxy. For these young clusters, it is possible to derive the mass functions from the ground, for the mass interval $1.2 < m < 6m_\odot$: for a sample of young clusters of similar ages, chemical abundance and environment, the slope x of the mass function can take any value in the range $0 < x < 3$ (Freeman, 1977). It would be very interesting to know whether the lower main sequence mass function is equally unpredictable. Again, crowding makes further groundbased work difficult, because the background density of LMC stars is already about 100 stars/sq arcmin at $V = 22.5$, even in the outer parts of the LMC. With ST it will be possible to measure the luminosity functions of these young clusters down to $M_V = +9$ ($0.4m_\odot$). The total observable mass range (about 6 to $0.4m_\odot$) will then overlap the presently observable mass range for the nearest galactic globular clusters (0.8 to $0.3m_\odot$). Direct comparison of the mass functions for these old and young globular clusters will then be possible, and it will be interesting.

c) The dwarf spheroidal galaxies

The chemical abundances of these old systems are like those of the halo globular clusters. However their mean stellar density is very low. Star formation in such low density systems is rather interesting, and it would be well worth deriving their mass functions, to see if the mass functions are like those observed for the globular clusters. The dwarf spheroidal galaxies are too distant for this to be done from the ground. With ST it will be possible to reach $M_V = +9$ for the Draco system, and about +7 for Fornax. The Fornax dwarf will be particularly important, because it contains a few globular clusters of its own. It will be very interesting to compare the mass functions of its clusters

with that of the Fornax galaxy itself.

II. CHEMICAL TOPICS

a) Individual clusters in the Galaxy

Several globular clusters are now known to be chemically inhomogeneous, so there is something to understand about the chemical evolution of individual globular clusters. At least two clusters [47 Tuc (Norris and Freeman 1979) and ω Cen (Norris Freeman and Seitzer, to be published)] have radial abundance gradients like some galaxies. For ω Cen in particular, there are now observations of about 200 member stars from the cluster center out to its tidal radius. The radial change of CN in this cluster is very similar to the radial change of globular cluster abundances in our Galaxy. Stars in the inner parts of the cluster show a wide range in CN, while those in the outer region are predominantly CN-weak; ie ω Cen appears to have its own low abundance halo.

The obvious spectroscopic experiments, needed to investigate this chemical structure within individual clusters, can be made from the ground. I have no immediate suggestions for ST spectroscopy in this area. But I would ask you to keep in mind that some clusters have chemical gradients like galaxies, and that the problems of their chemical evolution are interesting, and are probably more tractable than those in galaxies because we can observe individual cluster stars.

I have already discussed the apparent dependence of the mass function on chemical abundance. It would be very interesting to observe this within an individual cluster. The ideal object for this experiment is ω Cen. It shows a very clear radial abundance gradient. Also, its relaxation time is very long, so the approach to thermal equilibrium should not produce any significant radial change in the mass function. Crowding problems prevent us from measuring the radial dependence of the mass function from the ground, but this experiment should be straightforward with ST. The main problem will be to establish the galactic background luminosity function properly, because the numbers of background and cluster stars (per unit area) are about equal at half the cluster's tidal radius.

There is some evidence that the dwarf spheroidal galaxies are chemically inhomogeneous (eg Zinn 1978), and it is very important to find out whether they show heavy element inhomogeneities and radial chemical gradients. The

measurement of Ca abundances in RR Lyrae stars is a very direct and well calibrated probe of the heavy element abundances in metal-weak systems. Several dwarf spheroidal galaxies are rich in RR Lyrae stars, and are close enough for observation with the FOS. A resolution of 10^3 and S/N of 10 are adequate for this work

b) Young globular clusters in the LMC

The chemical inhomogeneity and chemical gradients in some old halo clusters suggests that chemical enrichment occurred during their formation. It would be interesting to see if there is any evidence for this enrichment in the young globular clusters of the LMC. These systems have ages of about 10^7 y, and their color-magnitude diagrams show evidence for an internal age spread of about $5 \cdot 10^6$ y (Robertson 1974), which is comparable to their free fall time. So, if enrichment does occur during cluster formation, then the stars forming later should be more enriched.

These young clusters have masses in the range 10^4 to $10^5 M_{\odot}$. For halo clusters in this mass range, the chemical inhomogeneities reported so far are in CNO only, and not in the heavier elements. It would probably be most useful, and give a fairly unambiguous result, to observe CN in the late F and early G main sequence stars of these young clusters. These stars have $V \approx 22.5$, so are within reach of the FOS in its $R = 10^3$ mode.

c) Extragalactic clusters

There is already some information about the distribution of globular cluster abundances with radius in our galaxy and M31 (eg Searle 1978, Searle and Zinn 1978). This gives a useful constraint on pictures of galaxy formation and chemical evolution. It would be very valuable to have similar data for the globular clusters around a few elliptical galaxies of different masses, because the metal abundance of elliptical galaxies appears to depend on mass. The Searle-Zinn technique gives an estimate of cluster abundances from low resolution spectrophotometry. With the FOS at $R = 100$, it should be fairly straightforward to observe globular clusters around the Virgo cluster ellipticals.

III. DYNAMICAL TOPICS

a) Cluster rotation

For elliptical galaxies, the ratio of their rotational velocity to their velocity dispersion is smaller than one would expect from their observed flattening (eg Illingworth,

1977). Most galactic globular clusters are nearly spherical: the most flattened ones have axial ratios of about 0.8. Omega Cen is one of the flattest, and we know now that it is rotating sufficiently rapidly to produce its observed flattening (Freeman, to be published). In the Magellanic Clouds, however, there are a few highly flattened globular clusters (eg NGC 121, NGC 1978), and it would be very interesting to know whether their flattening is associated with rapid rotation. Rapid rotation here means about ± 5 km/s, which is measurable. Accurate velocities (± 2 km/s) would be needed for about 50 stars at about $V = 19$. This would be a difficult experiment from the ground. With the FOS at $R = 10^3$, velocities of this accuracy should be possible (from recent groundbased experience); the observations should take 5 to 10 minutes per star.

b) Thermal equilibrium

Dynamical models are very important for interpreting the observed stellar content and kinematics of globular clusters. For example, there is no other way at present to estimate their content of nonluminous matter, like white dwarfs and neutron stars. To make these dynamical models, some assumptions must be made about the dynamical state of the clusters. One very important assumption is that of thermal equilibrium. However we do not really know observationally how close the clusters are to thermal equilibrium. We would expect that systems with the shortest relaxation times should be most nearly in thermal equilibrium. However 47 Tuc, which has a central relaxation time of about $2 \cdot 10^8$ y, shows a very clear radial gradient in CN. It is not at all clear how this gradient has survived the effects of relaxation, and it seems that our understanding of relaxation and the approach to thermal equilibrium may not be complete.

There are two fairly direct ways to estimate observationally how close a particular cluster is to thermal equilibrium.

(i) Mass segregation: the lightest stars should be least concentrated to the cluster center. This is very difficult to observe from the ground, because crowding problems limit observations of faint stars to the outer parts of the cluster. With ST it will be possible to derive the radial distribution of faint stars almost in to the cluster centers (see section I.a). Also the accessible mass range will be significantly larger: 0.8 to $0.1 m_{\odot}$ for the nearest clusters, compared to 0.8 to $0.3 m_{\odot}$ from the ground.

(ii) Velocity dispersion: this is approximately proportional to $m^{-1/2}$ (m is the stellar mass) for a cluster in thermal equilibrium. For the nearest clusters, we have a baseline of a factor 2 in mass between the red giants and the dwarfs with $V = 20.5$. The experiment would need accurate velocities

(± 2 km/s) for about 100 dwarfs, to get adequate precision. This is well within reach of the FOS (cf III.a)

c) Extragalactic clusters as probes of galactic potentials

From the radial distributions of number density and velocity dispersion for the globular cluster system in a galaxy, it is possible to derive some useful constraints on the potential field of the parent galaxy. In practice this is a fairly substantial program for galaxies outside the local group. Velocities accurate to about 30 km/s are needed for about 100 clusters with magnitudes mostly fainter than $V = 21$. Observations with the FOS at $R = 10^3$, $S/N = 3$ would be adequate, but would be timeconsuming because the clusters are extended objects.

There is another way to use the clusters as probes of the galactic potential. The tidal radius of a cluster is set by the tidal field it experiences near perigalacticon. From the observed tidal radii of clusters far from the galactic center, we can derive upper limits on the galactic tidal field at the location of the cluster. (We need to know the M/L ratio for globular clusters, which is now fairly well established). If some of these distant clusters are in approximately circular orbits around their parent galaxy, then the derived upper limit on the tidal field is close to the true value of the tidal field. There is good evidence now for globular clusters in our galaxy that some of the outermost clusters are really in orbits of low eccentricity, so the tidal radii of clusters in extragalactic systems offer a fairly straightforward way of estimating the galactic potentials in the outer parts of the galaxies. This will be particularly useful for ellipticals, for which no other direct method is known at present. Observationally the tidal radii can be measured from direct ST images of the clusters: typical tidal radii are about 1 arcsec at the distance of the Virgo cluster.

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DISCUSSION

Illingworth (Discussion leader): Can we take questions first?

King: My experience in measuring tidal radii of globular clusters is that I get the best results by extending the counts to $M \approx +3$ and not relying on the red giants alone. It will only be possible to measure the red giants in globular clusters at the distance of the Virgo cluster.

Freeman: At the distance of the Virgo cluster, individual stars will not be resolved and we will see only the diffuse distribution of red giants. I am basing my remarks on studies of globular clusters in the Magellanic Clouds where the photometrically determined tidal radii agree well with those determined by star counts.

King: Is a resolution of $R = 10^3$ adequate for measuring accurate velocities in globular clusters?

Freeman: My experience with the 3.9 metre Anglo-Australian Telescope is that a resolution $R = 4 \times 10^3$ is very much more than is necessary. Most of the scatter in the velocities is cosmic.

Hemenway: Even the nearest globular clusters are too distant to have their parallaxes measured by ST. However, over a period of 10 years it should be possible to measure their internal motions. With an accuracy of 2×10^{-3} arcsec over a period of 10 years, internal motions of km s^{-1} are measurable at a distance of 10 kpc. Similar studies are possible using the Yerkes plates taken at the turn of the century. However, they only enable the top of the HR diagram to be studied and with ST it will be possible to extend these studies to fainter stars, enabling internal motions as a function of star mass to be studied. It will also be possible to measure the absolute motions of the globular clusters by combining radial velocity measurements with mean proper motions so that their orbits in the Galaxy can be measured precisely.

Gallagher: Are there advantages in making star counts at $1 \mu\text{m}$ where you will be less sensitive to the problems of line-blanking in individual stars?

Illingworth: Yes. It is very much easier to use I-R colours and hence it is very important to use the red capability of the Wide Field Camera. The gain in going into space is that from the ground, the sky is very bright in I.

J.N. Bahcall: Garth Illingworth has asked me to describe briefly the potentialities of ST for detecting massive black holes that might exist in globular star clusters. My remarks will be based on work done earlier by Dick Wolf and myself (Bahcall and Wolf, Ap. J., 209, 214, 1976 and

Ap. J. 216, 883, 1977 paper I and II, respectively) The motivation for the work is that two-body relaxation times in clusters can be much shorter than stellar evolution times, suggesting something dramatic may have happened. The basic assumption is that there is a point source of gravitational potential with a mass M_{BH} that satisfies $M_{STAR} \ll M_{BH} \ll M_{cluster\ core}$. (This "point-source" could be a condensed subcluster of stars as long as its dimension is small compared to the core dimension.) The equilibrium star distribution was derived both analytically and numerically, using approximations whose accuracy was also studied and found to be satisfactory.

The predicted velocity dispersion and the density cusp were derived and discussed in §V of Paper I and §VI of Paper II. Also given (in equation 103 of Paper I) was the expected mean displacement of the massive black hole from the centre-of-light of the star cluster. Neta Bahcall and her associates (see e.g., N. Bahcall and M. Hausman Ap. J. 213, 93, 1977) have derived upper limits of $M_{BH} \leq 10^4 M_{\odot}$ on the basis of data obtained with ground-based telescopes. ST observations would be sensitive to masses $M_{BH} \geq 5 \times 10^2 M_{\odot}$. It will be important to obtain star counts with exposures of various durations and deep photometry in several colors, as well as velocity dispersion both inside and outside (necessary for setting the distance scale of the problem) the stellar core.

King: I would first like to direct some remarks specifically to what ST can do for globular clusters. One important area is the faint end of the luminosity function. Most of the mass of a globular cluster resides in stars too faint to observe from the ground. We can infer this from ground-based observations of velocity dispersions and core radii, but with ST we will be able to observe faint stars directly - both the red dwarfs and the white dwarfs. With ST resolution we will also be able to look into the centers of clusters. Of particular interest are the clusters with dense centers - both those that have X-ray sources and those that do not.

Meanwhile there is much current discussion of the X-ray globulars, often with the suggestion that such a cluster may have a black hole at its center. Let me remind you that neutron stars can do equally well, both in providing an X-ray source and in giving extra mass density that can explain the brightness excess at the center of M15. With regard to the latter problem, I have been looking at the other high-density clusters, getting material for velocity dispersions and for central light distributions. For what it is worth at a very intermediate stage of the reduction, I have not yet seen the M15 phenomenon in any other cluster.

Castellani: I would like to stress the importance of ST observations in the study of stellar evolution in Galactic and extragalactic globular clusters. The main point is that, by observing globular clusters, we

observe the oldest objects we know in our Galaxy and at the same time, a very general component of the Universe. We must remember that there is a major "mystery" in our understanding of stellar evolution - where do the heavy elements which we find in population II stars come from? In my opinion, it is difficult to escape the conclusion that we cannot claim to understand the evolution of the Universe before solving in detail such problems. In this context, observations of globular clusters have to be used in two steps. The first is to compare theory with observation in order to understand how far we can rely on theory, i.e., how well we understand the physical mechanisms at the basis of stellar evolution. The second step is to use theory in interpreting the observed evolutionary history of clusters, i.e., of obtaining "archaeological" evidence on the evolution of the Universe. My personal feeling is that by the time ST is launched, we will know how to apply such decodification procedures. We will be able to derive ages and primordial chemical compositions for every well-studied cluster, meaning all those for which the main sequence and later evolutionary phases have been exhaustively studied. At least, ST will give us quite a lot of information about the evolution of our Galaxy and of the Local Group.

In this context, I wish to draw attention to the problem of white dwarfs. There is no doubt that white dwarfs in globular clusters will be observed by ST if their luminosities and colours are the same as those indicated by current theory. If this turns out to be the case, we will rely more and more on the theoretical framework and we will obtain unique information about evolutionary parameters such as the amount of mass-loss and the effects of stellar rotation.

Finally, I note the recent suggestion of a very luminous white dwarf in the globular cluster NGC 6752 which is completely outside the range of theoretical expectations. Some astronomers of an Aristotelian frame of mind claim this is "impossible". I feel it is rather "highly improbable" when one takes into account the contamination of the cluster field by quasars. It will be most interesting if the original suggestion is true because every time we find something new, we learn a bit more about the Universe. I have no doubt that ST will also solve this important problem.

Gallagher: I would add that the problem of anomalous blue stars in globular clusters such as the B3 star in 47 Tuc is a general problem and may be studied by ST i.e. those blue stars which lie outside the normal horizontal-branch morphology.

Castellani: Some of these anomalous stars may be due to the effects of stellar rotation.

Gallagher: There is also the possibility that they are members of binary systems.

Freeman: The anomalous blue stars are not so anomalous. They can be understood in terms of post-asymptotic giant branch evolution and are the analogues of the nuclei of planetary nebulae.

Illingworth: I would like, finally, to emphasise the use of globular clusters in estimating the masses of early-type galaxies. There are problems in using most of the other methods of measuring masses in these galaxies. The use of globular clusters to measure velocity dispersions and their variation with radius in the galaxy provides not only mass estimates but important evidence about the chemical and dynamical evolution of these systems. It is evident that the study of globular clusters with ST will have important repercussions for many aspects of the evolution of stars and galaxies.

D7

N80-22137

POPULATION STATISTICS OF FAINT STELLAR AND
NON-STELLAR OBJECTS

Sidney van den Bergh
Dominion Astrophysical Observatory
Herzberg Institute of Astrophysics
National Research Council Canada
Victoria, B.C.

"You can't say more than you see."
Thoreau

ABSTRACT

1. A disc and halo population model is constructed to fit star counts and color data down to $V \sim 23$ at $|b| = 90^\circ$. This model is used to predict star counts and colors down to $V \sim 30$. Deviations from these extrapolated relationships might provide constraints on the number of faint quasars and "black dwarf" stars.
2. The model shows that extra-galactic globular clusters start contributing significantly to "star" counts at $V \sim 25$ and are more numerous than stars for $V > 31$.
3. Morphological studies of galaxies with $z \sim 0.5$, which are feasible with the Space Telescope, could provide significant constraints on theoretical models that describe the evolution of clusters of galaxies.
4. It is argued that the Space Telescope reduces the need for super-expensive earth-bound telescopes of heroic dimensions. Ground-based observations should, instead, exploit the advantage of low-cost photons that could be collected by mass produced $\sim 3m$ thin mirror "people's telescopes".

I. DEEP EXPLORATION OF "SELECTED AREAS"

The galactic nuclear bulge

Progress in galactic astronomy can be made by complete mapping of relatively bright nearby objects and by deep exploration of a small number of carefully chosen "selected areas". Baade's (1951) study of the galactic nuclear bulge in the low-absorption window surrounding NGC 6522 is a classic example of the latter approach. Unfortunately crowding effects, resulting from the exceedingly high density of stars

in "Baade's window" have made it difficult to follow up this initial breakthrough. Future progress in this particular area will, no doubt, depend heavily on the improved resolving power of the Space Telescope and on the use of advanced panoramic detectors that will allow the deconvolution of partially overlapping images. Since the nuclear bulge has a distance modulus $(m-M)_V = 16.4$ (van den Bergh 1971) the Space Telescope should be able to study the luminosity function down to $M_V \sim +10$. Such observations might place significant constraints on the possible relationship between environment and the mass-spectrum of star formation.

The galactic halo

A promising beginning has recently been made on the deep exploration of the galactic halo by a group in Berkeley working under the direction of Ivan King. In Selected Area 57, which is located close to the north galactic pole, Kron (1978) has done photometry to very faint limits and Chiu (1979) has performed proper motion studies. This work is supplemented by the high-latitude star counts of Peterson *et al.* (1979) and Tyson and Jarvis (1979). These investigations provide significant new information on both the stellar density distribution in the halo and, to a lesser extent, on the luminosity function of Population II stars. The main difficulty in the analysis of these data is that the density distribution $\rho(Z)$ and the stellar luminosity function $\phi(M_V)$ have to be determined simultaneously from star counts and color data. The main value of such work, as far as the present conference is concerned, is that it allows one to extrapolate $N(V, B-V)$ to the range $25 \leq V \leq 30$, which is of interest to Space Telescope observers. Hopefully deviations from these predictions will provide information on (a) very faint quasi-stellar objects, (b) distant young galaxies and (c) the hypothetical "black dwarfs" that might account for the missing mass that appears to be present in the outer regions of many galaxies (Bosma 1978, Ostriker and Peebles 1973, Rubin, Ford and Thonnard 1978). Furthermore, additional observations at intermediate latitudes will allow one to determine the shape of the galactic halo.

II. A GALACTIC DENSITY MODEL

To a first approximation (see de Vaucouleurs 1959, Freeman 1975) the distribution of light in spiral galaxies can be represented by two component models in which a spheroidal core is embedded within an exponential disc. Pritchett and van den Bergh (1980) have therefore attempted to fit star counts to a density law of the form

$$\frac{\rho}{\rho_0} = (1-f)e^{-|r \sin b|/B} + f \frac{(a_0^n + a^n)}{a_0^n + a^n} \quad (1)$$

In this equation the first term represents a disc of scale-height β and the second term describes a spheroidal population component (Chiu 1979), which accounts for a fraction f (by number) of the stars near the Sun. A point specified by r , ℓ , and b lies on a spheroid with semi-major axis a . The value of a is given by

$$a^2 = r^2 \cos^2 b - 2\bar{\omega}_\odot r \cos b \cos \ell + \bar{\omega}_\odot^2 + r^2 h^{-2} \sin^2 b, \quad (2)$$

in which $h = c/a$ is the axial ratio of the spheroidal population. For $(a_0/a)^n \ll 1$ eqn (1) reduces to

$$\frac{\rho}{\rho_\odot} = (1 - f)e^{-|r \sin b|/\beta} + f \left(1 + \frac{r^2}{h^2 \bar{\omega}_\odot^2}\right)^{-n/2} \quad (3)$$

at $b = \pm 90^\circ$. Clearly observations of $N(V, B-V)$ at the pole, such as those of Kron (1978), can not give a unique solution for the 4 parameters f , β , $\bar{\omega}_\odot h$ and n .

The best external evidence is available on β and n whereas only rather weak constraints can presently be given on f and h . Available data (Allen 1973, Hill, Hilditch and Barnes 1979, Schmidt 1975a) suggest $300 \leq \beta \leq 400$. From a study of globular clusters in the galactic halo Harris (1976) obtains $n = 3.5 \pm 0.5$. This value is consistent with the data on galactic RR Lyrae stars that have been analysed by Oort and Plaut (1975).

Values of f quoted by Harris (1976) fall into the range $2 \times 10^{-4} \leq f \leq 7 \times 10^{-3}$. Perhaps the best value (even though it is based on small-number statistics) is $f = 1.15 \times 10^{-3}$, which Schmidt (1975b) derives from application of the V/V_m test to high velocity stars near the Sun.

According to Chiu (1979) $0.7 \leq h \leq 1.0$. Van den Bergh (1979) finds $h \sim 0.5$ for globulars near the center of the galaxy and $h \sim 1.0$ for halo clusters. Significant constraints on the value of h for halo stars could be obtained from counts at different galactic latitudes.

As a first approximation we have fit the $N(V, B-V)$ data from Kron (1978) at $V \sim 21$ to a density model described by the following parameters:

$$\begin{aligned} \beta &= 350 \text{ pc} \\ f &= 1.25 \times 10^{-3} \\ \bar{\omega}_\odot h &= 9 \text{ kpc} \\ n &= 3.5 \end{aligned}$$

The luminosity function for main sequence stars was taken from Luyten (1968). For values of n in the range $3 < n < 4$ evolved stars above the main sequence turnoff make a negligible contribution to the counts at $V > 19$.

The contribution of white dwarfs to the counts was estimated from the luminosity function and M_V versus B-V relation of Sion and Liebert (1977). For $V \leq 22$ white dwarfs are found to contribute $< 1\%$ to the counts of stellar objects. The white dwarf luminosity function of Sion and Liebert gives a local white dwarf density that is ~ 3 times lower than that of Chiu (1978) and of Green (1978). The numbers of blue stars in our model might therefore have to be multiplied by a similar factor.

The calculated distribution of star counts in V, J and B is given in Table I. The color distribution of stars at different magnitude levels is shown in Figure 1. At $V \sim 20$ the major contributors are seen to be G dwarfs with $B-V \sim 0.6$ located at $Z \sim 10$ kpc and middle M dwarfs with $B-V \sim 1.5$ at $Z \sim 600$ pc. At $V \sim 25$ the relative contribution of G dwarfs to the counts drops whereas the contribution of K dwarfs with $B-V \sim 1.1$ and $Z \sim 40$ kpc rises. Finally at $V \sim 30$ the major contribution to the counts is provided by middle and late M stars at $Z \sim 50$ kpc.

Inspection of the model predictions shows that β is most strongly constrained by counts of M stars whereas f is primarily determined by the observed counts of the (much more luminous and hence more distant) G stars. Counts of $N(V, B-V)$ in the range $15 < V < 20$ would greatly

TABLE I
PREDICTED NUMBERS OF STARS

Mag	$\log N(V)^*$	$\log N(V)^\dagger$	$\log N(J)^\dagger$	$\log N(B)^\dagger$
16.5	1.97	2.02	1.88	1.84
17.5	2.11	2.17	2.04	1.99
18.5	2.34	2.36	2.23	2.18
19.5	2.58	2.56	2.44	2.40
20.5	2.78	2.76	2.64	2.59
21.5	2.94	2.93	2.81	2.76
22.5	3.05	3.07	2.95	2.91
23.5	3.14	3.18	3.07	3.03
24.5	3.22	3.27	3.17	3.13
25.5	3.30	3.35	3.25	3.21
26.5	3.40	3.43	3.32	3.29
27.5	3.50	3.51	3.41	3.35
28.5	3.59	3.59	3.50	3.45
29.5	3.64	3.64	3.57	3.53
30.5	3.66	3.66	3.63	3.59

*No stars per magnitude per square degree at $|b| = 90^\circ$ predicted from Wielen's (1974) function luminosity.

†Same as above but for Luyten's (1968) luminosity function.

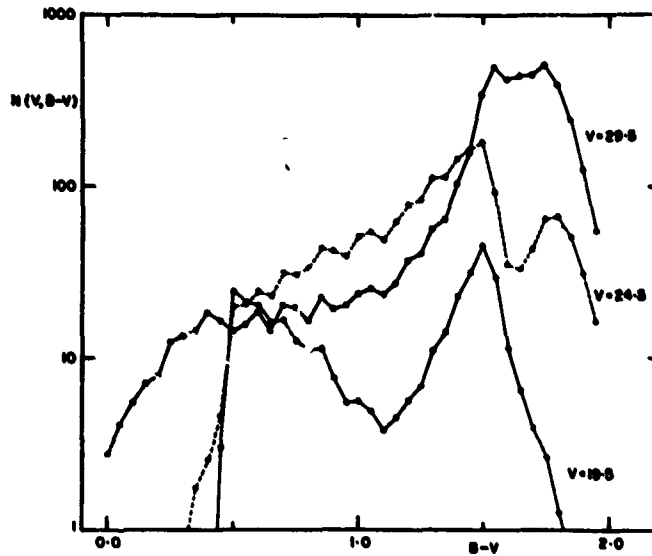


Figure 1. Calculated distribution of B-V colors for stars at $V = 19.5$, $V = 24.5$ and $V = 29.5$

strengthen the determination of β . The data in Table I show that the Luyten (1968) and Wielen (1974) luminosity functions yield rather similar predicted counts. This agreement is not surprising because the Luyten and Wielen luminosity functions for main sequence stars are so similar.

The slope of the faint end of the luminosity function, which is of critical importance for the "missing mass" problem is most strongly constrained by observations of stars in the range $25 \leq V < 30$, which can be explored with the Space Telescope. A proper motion study of a field centered on M87 by Prociuk (1976) shows that "black dwarfs" with $M_V > +15$ contribute $\leq 1\%$ to the star counts at $V \sim 22$.

More detailed numerical results will be given in Pitchet and van den Bergh (1980).

III. THE NUMBER OF GLOBULAR CLUSTERS

Contribution to field star counts

Luminous galaxies are embedded within extended halos of globular clusters. Since the number of globulars greatly exceeds the number of galaxies they might begin to contribute significantly to counts of star-like images at very faint magnitude levels. The computation of the number of globular clusters in various magnitude ranges that is

given below was based on the following simplifying assumptions:

1. The luminosity function of galaxies is that given by Felten (1977).
2. The number of globular cluster associated with each galaxy is proportional to the luminosity of that galaxy. The constant of proportionality is such that a galaxy of $M_B = -20.0$ contains 100 globulars. Galaxies fainter than $M_B = -13.5$ do not contain any globulars.
3. The luminosity function of globular clusters is Gaussian with $\langle M_B \rangle = -6.76$ and $\sigma = 1.1$ mag (Ilanes 1977).
4. Globular clusters are distributed uniformly in space.

In Figure 2 the luminosity function of globulars derived from assumptions 1, 2, and 3 is compared to that of galaxies (Felten 1977). The corresponding count - brightness relationship for globular clusters and for galactic field stars at $b = \pm 90^\circ$ are compared in Table II and Figure 3. In compiling these data $H = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$ was assumed. With this assumption the average space density of globular clusters is 0.41 Mpc^{-3} .

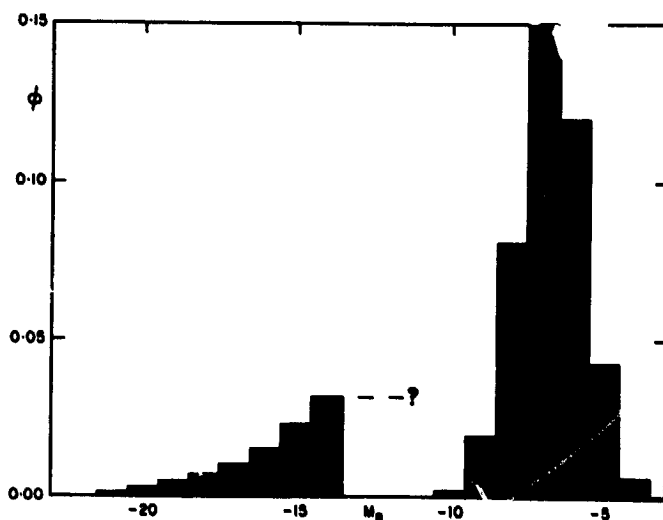


Figure 2. Comparison of the luminosity function of galaxies and globular clusters.

TABLE II
COMPARISON OF STAR COUNTS AND
GLOBULAR CLUSTER COUNTS*

B	log n(clusters)	log n(stars)
24.5	0.16	3.13
25.5	0.76	3.21
26.5	1.36	3.29
27.5	1.96	3.36
28.5	2.56	3.45
29.5	3.16	3.53
30.5	3.76	3.59

*No. per B magnitude per square degree.

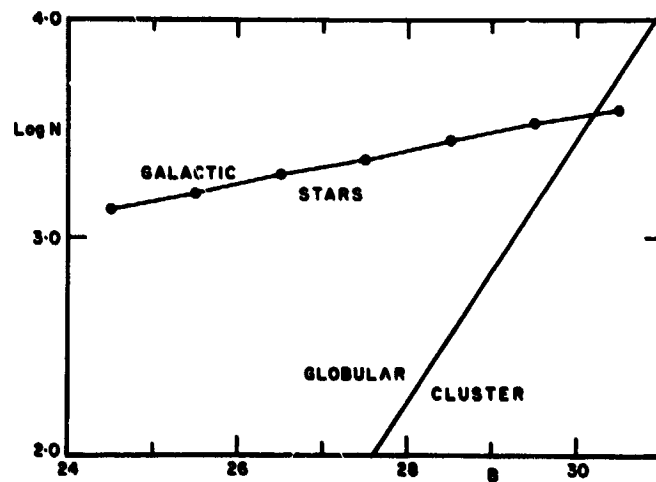


Figure 3. Comparison of predicted numbers of faint stars and globulars. For $B > 30$ star-like globular cluster images outnumber galactic halo stars.

It should, perhaps, be emphasized that the data in Table II overestimate the true number of globular clusters that will actually be observed by a factor of say 2 to 4. This is so because the present calculations do not take into account the fact that clusters projected on the main body of their parent galaxy will in general, be unobservable.

Inspection of the data in Table II, which are plotted in Figure 3 shows that $\sim 0.1\%$ of the star-like objects at $B \sim 25$ are globulars. This rises to $\sim 50\%$ at $B \sim 30$. Due to the clumpy distribution of galaxies in space $N(\text{clusters})/N(\text{galaxies})$ will, at a given magnitude level, show large variations over the sky. Below thirtieth magnitude globular clusters, which show much less "K-dimming" than do galaxies, will outnumber galactic halo stars.

Globular clusters in nearby galaxies

New observations of NGC 5128 (=Cen A) by van den Bergh (1978) show that this peculiar giant elliptical galaxy contains $\sim 10^2$ times fewer globular clusters per unit luminosity than does M87. Possibly this difference is related to the fact that NGC 5128 is a field galaxy whereas M87 is located near the center of the rich Virgo Cluster. Other factors that could correlate with the frequency with which globular clusters occur in galaxies might be flattening, intrinsic color and halo color gradient. The Space Telescope will be particularly suitable for studies of the total globular cluster content of relatively nearby galaxies because the images of globulars can be distinguished from stars out to distance ~ 20 times greater than that to M31. This circumvents the problem of statistical noise introduced by foreground field stars, which greatly reduces the accuracy with which the number of globulars in galaxies can be determined from ground based observations.

IV. OBSERVATIONS OF GALAXIES AND CLUSTERS

It has long been known from studies of the $\log N/\log S$ relation of radio sources that evolutionary effects become important near the edge of the observable Universe. Only recently has it become clear that a significant excess of radio activity persists down to redshifts as low as $z \sim 0.25$. Katgert, de Ruiter and van der Laan (1979) show that the population density of radio galaxies increases by a factor of 10 to 30 between $z = 0.0$ and $z = 0.5$, which corresponds to a look-back time of only $\sim 3(100/H) \times 10^9$ yr.

Most strong radio sources are of morphological types E and cD. Such objects are strongly concentrated in clusters of galaxies. Are the strong evolutionary effects that are observed in radio galaxies a function of time-dependent changes in the cluster environment, or do they result primarily from changes within the galaxies themselves? These are questions that can be attacked directly by morphological studies of

galaxies with the Space Telescope. A galaxy with a diameter of 10 kpc and a redshift $z = 0.5$ will have an apparent diameter of $3''.5$ in a Universe with $H = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$. The image of such a galaxy contains ~ 10 resolution elements for ground based and up to $\sim 10^3$ resolution elements for Space Telescope observations. The latter value is marginally sufficient for accurate morphological classification. Since the appearance of galaxies is strongly dependent on wavelength it is vitally important that nearby galaxies photographed in blue light be compared to distant ones at $\lambda \sim 4200 (1+z) \text{ \AA}$. It would be particularly important to see how the relative numbers of elliptical, lenticular, anemic, and spiral galaxies in distant clusters differ from those in nearby clusters of comparable richness.

Some insight into the kinds of effects that might be found in such studies is provided by the color observations of cluster galaxies that have recently been published by Butcher and Oemler (1978). These authors find that some distant clusters contain quite blue galaxies. In Cl 0024+1625 (with $z = 0.39$) these blue objects first appear ~ 2 mag below the brightest cluster galaxy. The fact that the luminosity function of nearby S0 galaxies peaks well below that of ellipticals (van den Bergh and McClure 1979) suggests that these blue objects are spiral or anemic galaxies that have not yet been completely stripped of gas (Gisler 1979). Additional support for this speculation is provided by the observation that the blue galaxies in Cl 0024+1625 are less concentrated to the cluster core than are the red galaxies.

Metamorphosis of spirals into lenticulars should not affect the frequency of strong radio sources, which are mainly located in galaxies of types E and cD. The strong evolution of the radio sources in E and cD galaxies therefore remains unexplained by presently available observations. In particular it is not yet clear whether blue cD galaxies in clusters, of which NGC 1275 is a nearby example, were more common in the distant past than they are now. The radio sources 3C 299 and 3C 330 (Kristian, Sandage and Westphal 1978) are possible examples of such objects at $z \sim 0.5$.

The stripping mechanism originally proposed by Gunn and Gott (1972), that was subsequently applied to the problem of the blue galaxies in clusters by Gisler (1979), is only effective in the cluster environment. The metamorphosis from blue galaxies to red galaxies should not, therefore, be observed in the field. In fact an excess of very blue galaxies does seem to occur (Kron 1978) among field galaxies with $V > 22$. This value may be significantly fainter than the value $V > 21$ that is observed in Cl 0024+2654. The reason for the observed color change in field galaxies is still obscure. Possibly it is simply due to the fact that young spirals form stars more vigorously than do older ones. Taken at face value the observation that faint, distant and hence presumably young, galaxies are blue tends to support scenarios incorporating strong evolutionary effects. A problem with this interpretation is, however, that it predicts that galaxies were much more luminous in the past than they are at the present time.

Counts of very faint extended objects, such as those reported by Peterson *et al.* (1979) and by Tyson and Jarvis (1979), do not show the dramatic increase in the number of galaxies with $V > 21$ that are predicted by models (Tinsley 1977a,b) which incorporate strong evolutionary effects. It follows that either (1) star formation does not start with a bang (Tinsley 1978), (2) the initial burst of star formation in early-type galaxies is shrouded in dust or (3) newly forming galaxies are mis(?)classified as quasi-stellar objects. Hopefully observations with the Space Telescope will enable us to make a choice between these alternatives.

V. THE SPACE TELESCOPE AND THE FUTURE OF GROUND-BASED ASTRONOMY

When we go to the marketplace we expect to pay dearly for exotic wares from far away places. By the same token astronomers are willing to pay a stiff premium for photons that either a) have wavelengths that do not allow them to penetrate the earth's atmosphere or b) come from very faint distant objects.

Until recently it was necessary to build ever larger ground-based telescopes to expand the astronomical horizons towards the edge of the observable Universe. With the advent of the Space Telescope, which can study objects fainter than those visible from Earth, this situation has changed dramatically. This development leaves Earth-bound astronomy free to exploit its ability to gather photons at relatively low cost. Furthermore the recent advent of thin-mirror telescopes has, I feel, shifted the advantage of wholesale photon collecting even more decisively towards earth-bound observatories. In my view ground-based astronomy must face this new development squarely by vigorously exploiting its cost effectiveness.

This suggests that we should not aim to build super-expensive Earth-bound telescopes of heroic dimensions. Although detailed engineering studies of this subject have not yet been made I strongly suspect that thin-mirror alt-azimuth telescopes with apertures of ~3m of standardized design and produced in large numbers will turn out to be the most cost-effective photon collectors.

If past history is a reliable guide, these Earth-based "people's 3m telescopes" will be kept very busy studying the plethora of fascinating objects discovered by orbiting observatories.

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DISCUSSION

King (Discussion leader): Since Dr. van den Bergh based parts of his discussion on Berkeley work that has not yet appeared in print, I should like to begin with a brief description of that work. The basic material is colors, magnitudes, and proper motions of stars down to $V = 21$ or 22 in three high-latitude fields. It is important that we have 3 fields at different latitudes and longitudes, because our ability to discriminate between disc and halo stars depends on the contrast between these 3 directions.

Two Ph.D. theses have involved this material. Kate Brooks' thesis project consists of the fitting of models of density distributions and luminosity functions, for both Populations I and II. The density functions are very like those that Dr. van den Bergh quoted. George Chiu's proper motions are of unusually high accuracy, and practically every star has a measured motion. With these motions he can make a fairly good population classification of individual stars. Interestingly, he seems to find a gradual transition between the two populations, not just in their relative proportions, but in the metal abundances and velocity dispersions of the stars themselves. Also, both studies seem to require a rather strongly flattened halo, although there is some possibility that this is really a manifestation of the population transition that I just mentioned.

With regard to Richard Kron's thesis, the data paper is in press (Ap. J. Suppl.). The interpretation paper will be written jointly with Bruzual, since Bruzual models of early galaxy evolution are intimately involved. The problems of faint galaxies continue to be actively pursued at Berkeley.

As for observations of faint stars with ST, it is worth noting that much of this work can be done on serendipity exposures made with the WFC. To do it properly, however, requires a little more, because it is important to determine colors and proper motions. ST will be directed, under control of other instruments, to the same primary field again; but in order to get the same secondary field again we will have to specify that the ST roll angle be the same. This makes the repeated observations "secondary observations," according to the scheme in which Ed Groth classifies things.

ST proper motions should be measurable over a short time interval. Whereas the best ground-based astrometry can get relative positions of stars to ± 0.010 arcsec, ST pictures should have little difficulty achieving ± 0.002 arcsec and can even aspire to ± 0.001 arcsec. With this sort of accuracy we can even contemplate doing parallaxes of the stars in random field exposures!

Finally, I would like to make some remarks on the faint end of the luminosity function. Such stars are very rare in a magnitude-limited sample, and in indiscriminate surveys they tend to be lost among the more numerous stars in the medium-faint-luminosity range. From the ground they will best be studied by pre-screening the faint stars through large-proper-motion surveys like those of Ciclas and particularly of Luyten.

ST offers an interesting opportunity to study the luminosity function directly, however. If we find an opaque dark nebula at 500 pc distance (and such can be found), then a WFC field in this direction will include a volume of 25 cubic parsecs, and a picture will record all stars in this volume down to absolute magnitude +17. A few such fields, with colors, proper motions, and possibly some crude parallaxes, will go a long way toward determining the faint luminosity function with a single blow.

Bahcall: Ray Soneira and I have constructed a detailed model for the disk and spheroid components of the Galaxy. The stellar luminosity functions and scale heights were determined from observations in the Solar neighborhood. The global distribution of matter was assumed to be an exponential disk plus a de Vaucouleurs spheroid. All of the available data on star counts for the observationally well-studied range of $4 \lesssim m_v \lesssim 21$ are consistent with the derived model over the observed five orders of magnitude variation in the projected star density at the Galactic pole. The calculated latitudinal and longitudinal dependences of the star counts are also in good agreement with existing observations. The computed M/L ratios for the disk and spheroid are in agreement with observations of other galaxies.

Further ground-based observations at attainable faint magnitudes ($m_v \leq 23^m$) would be important. The predicted strong longitudinal dependence of the spheroid star counts would permit a more accurate determination of the spheroid star density and axial ratio if the appropriate measurements were made. Our knowledge of the scale length of the disk could also be improved by star counts with ground-based telescopes.

The Galaxy model of the disk and spheroid is used to predict the star densities (in B and V) that may be observable with the aid of the Space Telescope down to very faint magnitudes. The stellar density to $m_v = 28$ from the disk and spheroid is predicted to be 10^4 stars per square degree. The predicted star counts are insensitive to many of the model parameters, although drastic changes in the shape of the luminosity function outside the presently determined magnitude range could produce measurable departures from the predicted star counts at faint magnitudes. The rotation curve computed solely from the disk and spheroid components decreases beyond about 10 kpc from the center of the Galaxy. A halo with even a relatively small mass density in the Solar neighborhood

($\rho_H(\text{Sun}) = 0.01 M_{\odot} \text{pc}^{-3}$) can give rise to a flat rotation curve. The stellar content of such a halo would be revealed by observations with Space Telescope cameras if the halo consists of main sequence stars with $M_V^{\text{MS}} \lesssim 19.0^{\text{m}}$ (existing observations imply $M_V^{\text{MS}} \approx 12.5^{\text{m}}$) or faint white dwarfs with $M_V^{\text{WD}} \lesssim 17.5^{\text{m}}$ (existing observations imply $M_V^{\text{WD}} \approx 11.5^{\text{m}}$). Existing data imply $(M/L)_{\text{HALO}} > 250$ (Solar Visual units).

This work has been submitted for publication to the *Astrophysical Journal* with the title "The Universe at Faint Magnitudes: I Models for the Galaxy and the predicted Star Counts."

Rubin: There is now no evidence that the rotation curve of our Galaxy is falling at the position of the Sun. Classically, the evidence for a falling curve came from values of Oort's constants A and B with $A > -B$, i.e., values of A of 15 and B of -10, each with uncertainty ± 3 or so. The recent publication of Fricke and colleagues shows that $A \approx -B \approx 13 \text{ km s}^{-1} \text{ kpc}^{-1}$ for early type stars at 2 kpc distance. This evidence that $A = -B$ means that the rotation curve of our Galaxy is flat in the vicinity of the Sun.

Gunn: By studying the neutral hydrogen velocity distribution, Knapp, Tremaine and I found the same result from techniques very different from the classical one. There is other direct evidence as well from the velocities and distances of distant HII regions that the rotation curve is sensibly flat out to at least 25 kpc.

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SPACE TELESCOPE OBSERVATIONS OF NORMAL GALAXIES

Augustus Oemler Jr.
Yale University Observatory
New Haven, Connecticut

The subject of normal galaxies is much too large to cover even superficially in this paper, and I shall necessarily be giving a very limited and incomplete review. I shall tend to emphasize elliptical and peculiar galaxies at the expense of spirals, partly from personal interest, but largely because the Space Telescope will break more new ground in our knowledge of the former. Because we live in one, we have quite detailed knowledge about the structure and contents of at least one spiral galaxy. Therefore, the fact that the Space Telescope will allow us to study M31 in the same detail that the Magellanic Clouds can be studied from the ground, and to study spirals in the Virgo Cluster in the same detail that we have been able to study M31 is less important than, for example, the fact that we will be able to directly observe, for the first time, the stellar content of an elliptical galaxy.

Basically, I shall be discussing observations of the stellar content of galaxies, with a few detours to consider other interesting problems. In terms of observations, this divides into two parts: those objects near enough for us to observe individual stars, and those so distant that only their integrated light can be observed. Although the former may yield more information, I shall spend less time on it. This is partially because it is being discussed elsewhere, and partially because the observing programs are, in many cases, more obvious, being extensions to nearby galaxies of observations that have long been made in our own.

Before beginning to discuss particular problems, it might be worthwhile to consider for what types of observations of galaxies the Space Telescope will be most and least suited. Most important will be its greatly increased limiting magnitude as a panoramic detector and its ultraviolet capabilities. This will be an enormous gain in the photometry of individual stars and unresolved star clusters. The high resolution of the Space Telescope will permit observations in star fields too crowded to observe from the ground and will enable us to study the complex structure of regions of active star formation in moderately distant galaxies. A lesser improvement can be expected in spectroscopy

of the same types of objects: even at the limiting magnitude of ground-based observations, the low photon flux from the faint objects is becoming the dominant factor. One area where the ST will not be of much use is in the study of faint extended objects, such as the halos of galaxies. The improved resolution does one no good here and the decrease in sky brightness will almost be offset by the smaller collecting area, compared to the largest ground-based telescopes.

1. NEARBY GALAXIES

By nearby galaxies I mean those in which a substantial fraction of the color-magnitude plane can be observed. This, in turn, depends on the nature of the observations. If we take 27 mag as a nominal limiting magnitude for photometry, we shall be able to observe stars at the main sequence turn-off of an old population out to a distance of 400 kpc and horizontal branch stars out to a distance of 1.5 Mpc. Thus, even from space, the number of "nearby" galaxies will be small. There are innumerable observations which can be made of these galaxies, but many of them really belong under the heading of studies of the interstellar medium, supernova remnants, star formation, etc. However, I would like to mention two subjects of particular interest to extragalactic astronomy.

The first concerns the formation history of galaxies. Elucidating this history could be an important achievement of the Space Telescope and may produce some surprises. Although the history of our own galaxy may (or may not) be fairly simple and well understood, we have no assurance that ours is typical. Indeed, even our nearest neighbors, the Magellanic Clouds, appear to be different. The cluster population of the clouds is certainly different, and there are some indications (Butcher 1977) that at least the LMC is younger, too. Also, contrary to our expectations for an elliptical galaxy, O'Connell (1979) has concluded, on the basis of detailed spectral synthesis, that the nearest typical elliptical, M32, had a significant amount of ongoing star formation as recently as a few billion years ago.

The data necessary to understand the history of star formation in nearby galaxies include kinematics, ages, elemental abundances and luminosity functions of various stellar subsystems. The most important information is ages and the most valuable data for this are photometry of stars at the main sequence turn-off. Unfortunately, for old populations, these will be easily obtainable only in companions of our own galaxy, even M31 and its satellites being too distant. This limits us to the Magellanic Clouds and a few dwarf spheroidals. The Clouds have distance moduli between 18.5 and 19, which means that the main sequence turn-offs of all populations are observable from the ground, and the Space Telescope is not needed. Most of the dwarf spheroidals are more distant, though, and one particularly straightforward question which the Space Telescope should be able to answer concerns their age. Was there only one epoch of star formation, and did it coincide with the

epoch of formation of our own Galactic halo? The expected answer to both of these questions is "yes". A "no" answer to either would upset the conventional view of the almost-primeval nature of Population II.

If we wish to study a wider range of systems we will have to go to the distance of M31, M33 and their companions, which will not be easy. There are two possible approaches. One is to make the extra effort necessary to observe the 28th magnitude turn-off stars in these galaxies. I personally think this would be worthwhile, but the many astronomers with different interests competing for the very limited amount of observing time may not agree. The other approach is to only use observations of brighter stars. For example, the morphology of the giant branch and especially the horizontal branch are both rather sensitive to age. Unfortunately, they are even more sensitive to metallicity, which introduces complications to which we will return later. Similarly, if we can just reach the turn-off, we should still be able to obtain some information about the main sequence luminosity function, by comparing the integrated luminosity of the stellar sample to the sum of the light from all of the brighter post-main sequence stars which we can observe individually.

The other very important observation to be made in nearby galaxies is of the stellar content of elliptical galaxies. Unlike spirals, a few of which have been studied in some detail, our knowledge of the make-up of ellipticals is very slim indeed. Painstaking spectral synthesis of their integrated light has carried us one scant step beyond Baade's original insight into the similarity of the stellar population in M32 and the halo of our own galaxy. The prospects for much further progress from the ground are rather poor. Unfortunately, not even the Space Telescope will enable us to reach below the main sequence turn-off in the nearest ellipticals, but there are still innumerable observations to be made of the ages, metallicities and luminosity functions of stars in the dE companions of M31. The importance of the observations justifies, I think, the extra effort which will be required to reach at least the top of the main sequence in these galaxies. It is also unfortunate that there are no nearby giant ellipticals and no SO's, but it may be that we can at least infer something about the former by extrapolating the trends which emerge from dwarf spheroidals through the dwarf ellipticals.

On a related topic, much can be learned from a study of the peculiar dE NGC 205, in which star formation is still occurring. Besides the obvious interest in the young stellar populations themselves, we will here for the first time have an opportunity to study star formation in a spheroidal potential field rather than in a disk perturbed by spiral density waves. Detailed kinematic and structural studies of this process should be very relevant to understanding the early history of elliptical galaxies and the bulges of spirals.

2. THE CONTENT OF DISTANT GALAXIES

2.1 Star Clusters

Beyond the local group, individual stars in galaxies are and will remain unobservable. In these more distant galaxies, star clusters provide the only samples of stellar populations free, we hope, of the complications of a range of metallicities and ages. Clusters, therefore, must be our main tool for unravelling the population structure and history of distant galaxies. The practical limits on how poor and how distant a cluster may be observed will obviously depend on the type of observations to be made. Where sufficient, photometry is much to be preferred over spectroscopy, because of the greater limiting magnitude, and especially because the panoramic detectors used will often permit one to photometer many clusters in a galaxy at one time. With a nominal limiting magnitude of 27 for photometry, the brightest globular clusters will be observable at least as far away as the Coma Cluster.

Using star clusters to study the stellar content of galaxies requires, however, that we be able to reliably determine the ages and metallicities of clusters from their integrated light. It is important, therefore, to consider how well we can do this and what, if any, the advantages of the ST over ground-based telescopes will be. First, to

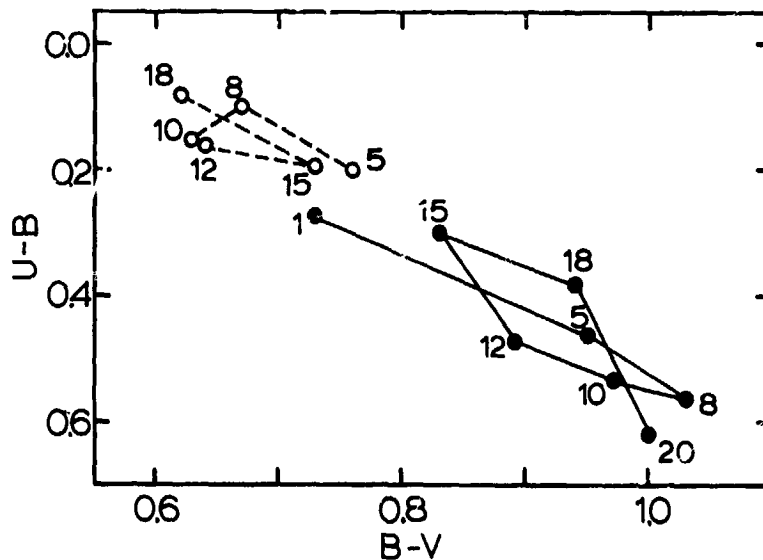


Fig. 1. Variation with age of the colors of two clusters, from Ciardullo and Demarque (1978). Open circles and dotted lines-metal poor ($z=10^{-4}$) cluster. Filled circles and solid line-metal rich ($z=10^{-2}$) cluster. Numbers are the ages in billions of years.

dispose of the obvious point, the Space Telescope will permit a gain in the faintness of the clusters that can be studied, assuming they are unresolved; but this, by itself, will not be revolutionary. A potentially more important advantage may be illustrated by considering the difficulties in simultaneously determining the age and metallicity of a cluster from its colors alone. Fig. 1 presents some calculations by Ciardullo and Demarque (1978) of the colors of high and low metal abundance clusters as a function of their age.

This is a very discouraging diagram because it shows that the age of a given cluster cannot be uniquely determined from its colors, and that the effects of age and metallicity are often indistinguishable. One possible source of hope, and one reason for discussing this subject here, is illustrated by some unpublished calculations, also by Demarque, presented in Fig. 2. These results for a metal rich cluster are only provisional because they are partially based on very early ultraviolet observations, but they should be qualitatively correct. The advantages of ultraviolet data are obvious.

The increased sensitivity to age in the UV is due mainly to changes in the blue end of the horizontal branch; (for younger clusters the main sequence turn-off is also important). But, of course, the horizontal branch is also very sensitive to metallicity (mainly CN). Therefore, it is not obvious how one separates the two effects. One possibility is

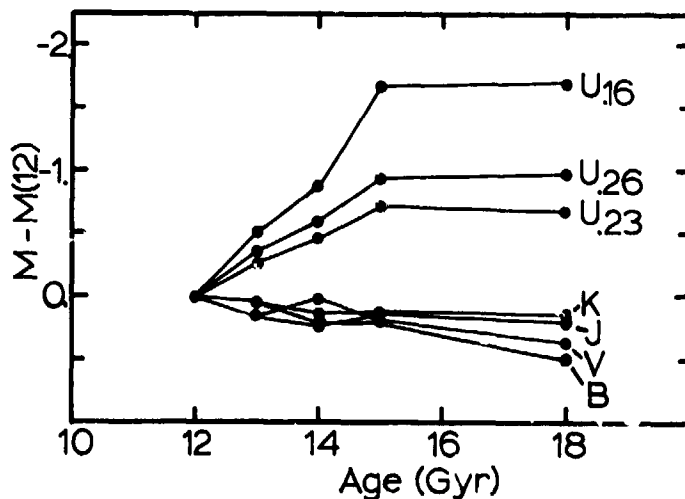


Fig. 2 Calculations by Demarque of a metal rich model cluster, showing the variation with age of the luminosity in various bands. Zero point of all bands is the luminosity at an age of 12 billion years.

that line and band strengths in the red, where the light is dominated by the giants, may permit an independent determination of the metallicity. Other complications include blue stragglers and the UV bright post-horizontal-branch stars. The latter may be particularly troublesome: they are so bright and so rare that statistical fluctuations in the colors of even rich clusters may be large (Ciardullo and Demarque 1978). Unfortunately, much of the theoretical and observational work which would demonstrate (or refute) the practicality of these observations has not been done. It is crucial that they be done before the Space Telescope is launched.

In addition to their interest as individual objects, the properties of cluster systems in galaxies may tell us much about their history. For example, Hanes (1977) has shown that the number of globular clusters in elliptical galaxies in the Virgo cluster displays both intriguing regularities and irregularities. In most ellipticals, and some spiral bulges, the number of clusters is proportional to the galaxy's - or bulge's - luminosity. M87, on the other hand, has several times more clusters than one would expect from this trend. Also, Harris and Smith (1976) have shown that within at least one elliptical, the surface density of clusters is strictly proportional to the galaxy's surface brightness.

These results raise many questions which observations of more - and necessarily more distant - galaxies may answer. Do the globular clusters really constitute a fixed percentage of the mass of a spheroidal component? If so, may we use them to delineate quantitatively the Population II component of a galaxy? If not, does this percentage depend on the metallicity, mass, angular momentum or other physical properties of the galaxy? Why is M87 peculiar? Do other brightest cluster members, or X-ray galaxies, or galaxies with active nuclei display this same peculiarity?

Similar questions may be asked about the clusters in the disks of later-type galaxies. How does the ratio of young clusters of various masses to the present star formation rate depend on galaxy properties? The Magellanic Clouds contain young clusters as massive as the old globulars, but our own galaxy does not. Is this typical of Irr vs. Sbc galaxies? What about clusters in the disks of SO galaxies? The smooth potential should permit all but the poorest to survive. Are there such things?

Another intriguing but generally ignored question concerns the luminosity function of globular clusters. Most astrophysical objects - stars, galaxies, clusters of galaxies - have luminosity or mass functions which rise monotonically toward smaller objects, but that of globulars in our own and nearby galaxies is approximately gaussian, with a width of only about 1.5 mag. Are they preferentially formed at only one mass, a very significant fact if true? If so, is this mass a universal constant,

or does it depend on the galactic parameters? Or has a more usual luminosity function been progressively truncated by the tidal disruption of the poorer clusters? Observations with the Space Telescope of globular clusters in a variety of environments should answer this question. (This is not the place to discuss it, but should the luminosity function turn out to be universal, its usefulness as a distance indicator is obvious.)

If the relationship between halo populations and globular clusters can be well established, clusters will provide a very effective probe of the extent and stellar content of ellipticals and the bulges of disk galaxies. I have mentioned above my skepticism about the suitability of the Space Telescope for observing the very low surface brightness outer parts of galaxies, but globular clusters may allow us to study these regions indirectly. It would be particularly interesting to study the extended envelopes of cD galaxies. The information that the globular clusters tell us about their composition may help us answer the question of the origin of these very massive envelopes.

2.2 The Contents of Early-type Galaxies

One of the most important aspects of galaxy studies to which the Space Telescope can be expected to contribute is the contents of elliptical galaxies. Because of the limited amount of data which will be obtainable even with the ST in nearby galaxies, observations of the integrated light of more distant ellipticals will be very necessary for this task. One obvious area in which ST observations will be useful is in improving spectral synthesis of the integrated light of galaxies. Most of what I discussed earlier about star clusters is equally relevant here. One may hope that the additional UV data will resolve ambiguities such as blue stragglers vs. early turn-off and age vs. metallicity, but we don't really know yet. In one way galaxies are easier than star clusters: the post-horizontal-branch stars, while still important, are at least present in sufficient numbers in these richer systems so that small number statistics are not a problem.

Another UV observation which may be informative is of the 2200 Å feature due to dust absorption. Dust is easy to observe in external galaxies if it is strongly clumped. However, if it is smoothly distributed it is very easy to miss, especially in poorly resolved galaxies. We are very familiar with dust in spiral galaxies, because it is confined to spiral arms in a thin disk. It is not at all obvious that the same amount of dust, if distributed rather smoothly throughout a spherical volume, would be visible in even the nearer ellipticals. A search for the 2200 Å feature in "normal" elliptical galaxies would be a valuable test of the conventional wisdom.

This brings us to the larger subject of the Population I content of elliptical galaxies. How well founded is our belief that they do not have any? They don't look like they do, but is that a very sensitive test? A list of all of the early-type galaxies within 10 Mpc, taken from the Second Reference Catalogue of Bright Galaxies (de Vaucouleurs, de Vaucouleurs, and Corwin 1976), is presented in Table I. The remarkable

Table I
Early-type Galaxies within 10 Mpc

Galaxy	Type	Galaxy	Type	Galaxy	Type
NGC 147	E	NGC 1428	S0	NGC 3115	S0
NGC 185	Ep	NGC 1705	S0p	NGC 4150	S0
NGC 205	Ep	NGC 2784	S0	NGC 5102	S0p
M32	E	NGC 3034	IO	NGC 5128	Ep
NGC 404	S0	NGC 3077	Ep/IO	NGC 5253	Ep/IO
NGC 1400	S0				

thing about this list is that, unlike the Catalogue as a whole, there are very few ellipticals which are not "peculiar", and their peculiarity is always related to the presence of Pop I material: gas, dust and young stars. Now, this may be a statistical quirk, but it may be due to the effects of distance usually hiding what is a common feature of most elliptical galaxies.

There are some hints that this may be so. Duus and Newell (1979) have obtained photometry of many dwarf E's in the Fornax cluster which shows that many are bluer than even the most metal poor galactic globular clusters. The implication of their data is that either all ellipticals are producing stars at a modest rate, thus shifting the entire color-magnitude relation to the blue, or that about one half of the dE's have a substantial amount of ongoing star formation. Oemler and Tinsley (1979) have recently concluded that the statistics of type I supernovae may be most easily explained if ellipticals are producing young stars at a rate sufficient to use up the gas lost by evolving stars.

A modest amount of star formation in any but the nearest galaxies would be easy to hide from ground-based observers. O'Connell (1976, 1979) has recently done very detailed spectral syntheses of a number of elliptical galaxies. He has concluded that star formation at several times the gas loss rate cannot be excluded by the observations. A very striking example of the invisibility of star formation in ellipticals is provided by NGC 1510. Its optical image provides only very slight

hints that it is anything but a normal elliptical, but radio observations show that it contains a large mass of HI and its optical colors and spectra show that it is forming stars at a high rate (Disney and Pottash 1977). The Space Telescope offers two means of detecting star formation in ellipticals. Provided that the problems discussed earlier are solved, UV spectrophotometry will be much more sensitive to young, hot stars than any ground-based observations. Equally important, the improved resolution of the ST will permit scrutiny of thousands of galaxies in the same detail with which the objects in Table 1 have been observed from the ground. If the same large fraction turn out to be "peculiar", we may have to revise our notions of what is "normal".

Another class of object about which the ST can be expected to tell us much are the peculiar galaxies. Among these I include the peculiar ellipticals, Irr II's, ring galaxies, blue compacts and interacting galaxies. Since each is different, there are as many questions one could ask as there are individual examples. In general, however, there are two types of data which would most help in understanding the origin of the peculiarity.

One type of data is the internal motions within the object. (In some cases this can be obtained from the ground, but often it cannot.) For example, a comparison of the motions of the gas and stars in Ep and Irr II galaxies can help decide whether the gas came from within or without the galaxy. The detailed motions inside the ring of a ring galaxy might distinguish between the various models of these objects. Motions within interacting galaxies can tell us much about the interaction.

The other important class of observations is of the stellar population in the peculiar galaxies. The Space Telescope should allow us to see the giant branch stars in enough galaxies to help decide whether the "intergalactic HII regions" have an old population, whether the material which has fallen into NGC 5128 was a gas cloud or another galaxy and perhaps whether there are remnants of a disk in the central holes of ring galaxies.

3. GALACTIC CORES

Spheroidal stellar distributions, whether ellipticals or the bulges of spirals, seem to possess several characteristic length scales which, if we knew how to interpret them, would tell us something about the formation processes of the system. One characteristic length is the core scale, a , in for example the Hubble law,

$$I \sim I_0 \frac{1}{(r/a+1)^2} \quad (1)$$

or King's (1966) modified isothermal law

$$I \sim I_0 f(r/a, a/r_c). \quad (2)$$

For a typical elliptical, a seems to be some fraction of a kiloparsec which puts it, in most cases, beyond the resolving power of ground based observations (see, especially Schweitzer 1979). Thus, although there are some theoretical ideas around about the significance of the core size, there is little empirical data with which to compare them. One would like to know how core size depends on galactic mass, and whether other secondary parameters like metallicity or angular momentum are important. One would also like to know how core size evolves through mergers with other galaxies and whether the cores as well as the envelopes of cD galaxies show the effects of whatever processes have built these galaxies to their present enormous size.

On an even smaller scale than the cores are the almost point-like cusps found in the central light distributions of some galaxies. I shall leave the discussion of M87 and other active galaxies to Sargent, but less massive (and less active) mass concentrations exist in at least some normal galaxies. The example of M31 has been well studied. Stratoscope observations by Light, Danielson and Schwarzschild (1974) have shown the nucleus of M31 to be a distinct feature, with a scale length of $0''.28 = 0.95$ pc, superimposed on the bulge light distribution. Its dynamics are interesting, for the observed equality of nuclear and bulge velocity dispersion (Morton, Andereck and Bernard 1977) is not what is expected in the most straightforward models (Ruiz and Schwarzschild 1976). Tremaine, Ostriker and Spitzer (1975) have suggested that the nucleus has grown by the accretion of globular clusters from the bulge, but van den Bergh (1979) has disputed this because the nuclear colors are not consistent with this origin. Faber and French (1979) have recently reasserted Spinrad and Taylor's (1971) claim that the nucleus is dwarf enriched, a conclusion based on the strength of the Na I 8190 line. This would also be inconsistent with the Tremaine et.al. theory, but could explain the high nuclear velocity dispersion. The Space Telescope should help elucidate the nature of the M31 nucleus by permitting a more detailed study of its internal structure, dynamics, and, perhaps, luminosity function. It should also be possible to search for and study similar features in more distant galaxies; although their small scale will limit the number of galaxies which are accessible even from space.

The ideas in this paper have been stolen from many sources, but I would especially like to thank Pierre Demarque and Beatrice Tinsley for many helpful conversations. This work has been partially supported by the Alfred P. Sloan Foundation.

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DISCUSSION

Jura: An important technique for studying dust with the Space Telescope is to look for polarisation away from the centre of a galaxy. If the grains are similar to those in our own Galaxy, there might be as much polarisation in the U-V as there is in the optical waveband. This would be particularly true if the grains are small because then the dominant source of opacity would lie in the ultraviolet waveband because of the λ^4 law.

Baum: Photometric ST imaging observations of regions in galaxies to distinguish stellar population differences involve some practical cautions and complications. Filter bands cannot be wide, because of the substantial wavelength dependence of the "flat-field" calibration of the CCD, and because of the high demand on photometric precision needed for detecting the presence of spectral features that indicate chemical composition differences. Another problem is that relatively narrow-band filters centered on specific features (examples, MgH, H β) have to have different central wavelengths for galaxies at differing redshifts (such as Local Group, Virgo Cluster, Coma Cluster, and beyond). This takes careful planning in the choice of filters and in the number of special filters required.

Van den Bergh: There is some direct evidence that tidal forces can and do destroy globular clusters. Globulars with small values of r_t/r_c are found to be ~ 5 times fainter than those with large values of this parameter. For 51 galactic globulars with $\log(r_t/r_c) \geq 1.25$, $\langle M_V \rangle = -7.96 \pm 0.13$ compared with $\langle M_V \rangle = 6.19 \pm 0.24$ m.e. for 11 cluster with $\log(r_t/r_c) \leq 1.00$. The best example of a dying globular is "E3" in which (presumably binary) blue stragglers outnumber evolved red giants.

The last object in your list, NGC 5253, is also one of the most exciting. A deep 4-metre plate shows this object to be embedded in a cloud of ~ 50 star clusters. These clusters probably provide fossil evidence for a violent burst of star formation that took place $\lesssim 10^9$ years ago. Possibly this activity was triggered by an encounter in which the ScI galaxy NGC 5236 dumped gas in NGC 5253. The high rate at which supernovae of type I occur in NGC 5253 is almost certainly due to the burst of star formation. The star clusters extend out to and beyond the distances at which the two supernovae in NGC 5253 occurred.

Oemler: The funny thing about that cluster is that all the early-type galaxies are peculiar which is odd considering how widely separated they are.

Ostriker: A couple of years ago Scott Tremaine and I investigated whether the form of the luminosity function of globular clusters could be due to dynamical effects. We concluded that it could not. This

suggests that the shape of the luminosity function and the fact that there is a peak in it may be intrinsic. There is some evidence for this feature in the luminosity function of globulars in other galaxies but it needs checking for many more galaxies. The peak may provide a distance indicator. Two possible theories of its origin are either the standard Peebles-Dicke arguments or perhaps these are the kinds of gas clouds which are left over from an early phase of galaxy formation.

Freeman: I would like to make two comments. First, blue stars are needed in E galaxy population models. If these stars are like the UV-bright stars in globular clusters ($M_V \approx -3$), then they will be resolved in E galaxies out to the Virgo cluster with ST. Second, if galactic winds are responsible for keeping E galaxies almost gas free, then it may be possible to see these winds with ST by their UV absorption spectra against galactic nuclei.

Gallagher (Discussion leader): Let me re-emphasise some of the points raised by Oemler in his review. In the present discussion, we want to review the current physical state of affairs in a galaxy rather than evolutionary questions which will be dealt with after Dr. Tinsley's talk. Among the things we want to know are (i) the distribution of mass as a function of radius, (ii) the metallicity and the dispersion in metallicity as a function of position in the galaxy, which is particularly well suited to UV spectroscopy with ST, (iii) the stellar population, (iv) the present and past birth rates of stars, (v) the spatial structure of the stellar populations and (vi) the interstellar matter and what its properties are. We need to know these things in galaxies other than our own and there are clear and obvious impacts of Space Telescope on all these endeavours.

Rubin: The high spatial resolution obtainable with the Space Telescope will permit the study of the dynamics of the central regions of spiral galaxies on a scale not presently possible. At M31, $1'' = 3$ pc; velocities for regions smaller than this can not now be studied. Only the Stratoscope observations (Light, Danielson, and Schwarzschild, Ap. J., 194, 257, 1974) reveal the nuclear structure with a resolution of 0.2 arcsec. In M31, individual stars will be resolvable very close to the center with ST. At the center of M31, the stellar density is 10^5 pc^{-3} , much like the densities in some globular clusters discussed today by Freeman. If the sun were viewed at the distance of M31 with infinite resolution, it would subtend an area of 10^{-15} pc^2 . A comparison of the surface brightness for the central $1''$ in M31 with that of the sun indicates that only 10^{-10} of the available surface area in the central $1''$ is covered by stellar discs. Even at the finite (0.2 arcsec) resolution of ST, individual stars will be observable very close to the center of M31. For a very few spirals, studies of their central dynamics will be able to proceed star by star.

For spirals at larger distances, integrated nuclear spectra will be obtainable with ST, but at added resolution due to the higher spatial scale. Moreover, although low surface brightness may be a problem for many extragalactic programs, nuclear spectra will not be photon limited. For 21 Sc galaxies with a wide range of physical properties, we (Rubin, Ford and Thonnard) have obtained rotation curves. By their kinematic behavior out to nuclear distances of a few kpc, Sc's can be separated into two groups. Some galaxies, generally small and of low luminosity, have shallow initial velocity gradients, weak or absent stellar continua in the red, and H α emission stronger than [NII], as in conventional HII regions. Other galaxies, most often large and of high luminosity, have steep nuclear velocity gradients, a strong red stellar continuum, and nuclear emission with [NII] stronger than H α . All spatial and velocity details near the nucleus are lost in the inner few seconds of the galaxy spectrum; the observed velocity is high at the first measured position (2" or 3") off the center. For these galaxies, the nucleus is a black box which takes incoming velocities at $V \sim -250$ km/s and sends them out at $V \sim +250$ km/s. With the 10 times increase in scale from ST, we can hope to study some details of this phenomenon.

NGC 766



Three Sc galaxies with velocity discontinuities across the inner few seconds of the galaxy spectrum

The inner velocity gradient, V/R , is a measure of the inner mass and density, for $M \sim V^2 R$, and $\rho \sim V^2/R^2$. For the nine galaxies in the Sc sample observed at 13-cm (Dressel and Condon, Ap. J. Suppl., 36, 53, 1978), there is also a correlation of 13-cm flux with central velocity gradient. Hence this gradient is also a measure of nuclear activity. For the largest galaxies in the sample, the mass within 1 kpc is $\sim 10^{10} M_{\odot}$; the distribution of this mass is unknown because of the lack of spatial velocity resolution. With the high spatial scale and UV spectra from ST, it should be possible to relate the kinematics to the nuclear abundances and history of the inner galaxy. For spiral galaxies at moderate distances, the increase in knowledge from ST nuclear spectra should be enormous.

Humphreys: I will briefly discuss how observations with the ST can be used to study in some detail the structure, stellar content and even evolution of other galaxies by observations of individual member stars.

With imaging to $m_v \approx 28$ with the WFC we will be able to obtain magnitudes and colors for the Population I stars in galaxies as distant as the Virgo cluster and beyond (≈ 100 Mpc). With the FOS spectra will be obtainable to $m_v \approx 22-23$, putting the very brightest stars in the Virgo cluster galaxies within reach of spectroscopic analysis.

Observations of this type will permit us to get a detailed picture of stellar evolution as a function of location in a galaxy. In our own Local Group of galaxies, stars on the main sequence will be observable. In more distant galaxies, such as the M81 group, M101 group and the Virgo cluster, the supergiants will be readily accessible. We will be able to study how stellar evolution, at least of Population I stars, depends on galactocentric distance and possible abundance gradients in the galactic disks. We may also ask if there are variations in the initial mass function with position in a galaxy and with galaxy type. Color-magnitude diagrams for associations of young stars in the spiral arms will allow us to age-date these stellar groups and discuss their evolution as a function of position in the arm - along and across a spiral arm. Such information may allow us to decide between various theories for the origin and maintenance of spiral arms - the density-wave theory and the stochastic formation process of Gerola and Seiden. If the radial velocities obtained with the FOS are sufficiently accurate we could also study the motions within the arms as well as their structure.

Some of these suggestions for the use of Space Telescope are illustrated by recent work on the stellar content of two Local Group galaxies M31 and M33 (see Humphreys, R.M., 1979. Ap. J., D.c. 15, Sandage and Humphreys, 1979. In preparation).

King: Dr. Oemler referred to a controversy about observed core radii of elliptical galaxies. This is based on a paper by Francois Schweizer that is in press. Schweizer notes that the core radii of M31 and M32 are so small that at the distance of Virgo they would be completely unresolved. He then convolves deVaucouleurs profiles with seeing discs and gets results that closely resemble my dynamical models, but with apparent core radii that are much larger than the true cores. He therefore suggests that most of my "observed" core radii in Virgo might be quite fictitious, reflecting only seeing.

Schweizer and I are attempting to resolve our difference like gentlemen: instead of arguing, we have jointly secured letter data and are analyzing it. If it turns out that I am right, then we know something about the cores of ellipticals. If Schweizer's right, we will have to wait for ST.

Burbidge: The mention of UV luminosity in nuclei of normal ellipticals and their luminosity profiles brings to mind a long-standing puzzle to me. Why are the two nuclei of the dumb-bell double elliptical NGC 4782/ so different structurally? The galaxies are similar in total luminosity but one has a strongly concentrated nucleus and the other has a diffuse one. I wonder what the UV luminosities of the two are like - are they different? The WFC on ST could give this information.

Collin-Souffrin: A comment on Dr. Humphrey's talk: I would like to draw attention to the work of a group of astronomers working at the Observatoire de Marseille, France. From what I know of their extensive study of M33, it seems very similar to what Dr. Humphrey has described. In particular, they reach the same kind of conclusions concerning the asymmetry of the northern and southern arms in excitation, luminosity functions of stars, and kinematics.

Dr. Schwarzschild has asked if there is a possibility of distinguishing between O stars and the nuclei of planetary nebulae, in the nuclei of galaxies. I think there is indeed one possibility: if gas is present, it is ionized by these hot stars. If the [OII] line $\lambda 3727$ and not the [OIII] line $\lambda 5007$ is present in the spectrum - as is generally the case in non-active nuclei - it is more likely that the ionizing stars are O stars and not nuclei of planetary nebulae, which are rarely colder than 35000 K.

Dr. Gallagher has discussed the importance of studying stellar populations in the nuclei of galaxies with ST. I would like to emphasize also the importance of performing stellar population syntheses in giant extragalactic HII regions, dwarf blue compact galaxies etc., which are in an active stage of star formation. Indeed, early type stars, such as A stars, would probably largely dominate the spectrum in the UV range. A detailed study, involving the comparison of the spatial distribution of ionized gas, its abundance and excitation, with the stellar population and eventually with kinematic properties, would certainly give us very interesting information concerning the process of star formation in bursts.

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GALACTIC EVOLUTION WITH THE SPACE TELESCOPE

Beatrice M. Tinsley
Yale University Observatory

Since almost every facet of astronomy is relevant to the evolution of galaxies, most of the topics discussed at this Colloquium are important to the field. For example, stellar populations and interstellar matter in galaxies are to be understood in the context of evolution, and when galaxies are used as probes in cosmological studies it is vital to know how their intrinsic properties vary with time. Some aspects of research on galactic evolution with the Space Telescope are discussed by several authors in the recent ESO/ESA Workshop (Macchetto et al., 1979). In this paper, I concentrate on "lookback" studies that compare present-day and younger galaxies directly. Many of the theoretical ideas mentioned here are quite speculative; the aim is to provide viewpoints from which ST (and related ground-based) studies can be planned, knowing that the real world billions of years ago will surely contain more surprises than verifications of any projections.

1. ELLIPTICAL GALAXIES

Elliptical galaxies are populated now almost entirely by old stars, raising questions about how they looked in the distant past when the stars were forming, and about the more recent, quiescent evolution of the old population.

1.1 Primeval Galaxies

Elliptical galaxies are believed to have been very bright at an early stage when most of their stars were forming - the stage of so-called primeval galaxies (PGs). The high angular resolution and faint limits attainable by the ST may help to answer questions about the angular size, redshift, and luminosity of PGs, which in turn will shed light on how elliptical galaxies form.

Various models for the formation of elliptical galaxies differ

substantially in their predictions for the appearance of PGs (see reviews by Larson, 1976; Tinsley, 1979a). At one extreme, Partridge and Peebles (1967) presented a model in which star formation occurs fairly uniformly over the face of an extended protogalaxy before it has collapsed to its present size; this would occur at a redshift $z \sim 10 - 30$, and the objects would have angular diameters of at least $5''$. An alternative picture is that the maximum star formation rate (SFR) and luminosity occur after the collapsing protogalaxy is very centrally concentrated (Larson, 1974; Meier, 1976; Sunyaev et al., 1978); such PGs would be found at $z \sim 2 - 20$, with angular sizes of only $\sim 1''$. Another idea is that elliptical galaxies formed their stars in bursts resulting from violent mergers of gas-rich protogalactic fragments (Tinsley and Larson, 1979; see also Toomre, 1977); in this case, the time scales suggest $z \sim 2 - 10$, and again star formation would be in regions with small angular sizes, although the structure would be less symmetrical than in models where a single gas cloud collapses.

Whatever the details, PGs are likely to be fairly gas-rich, so that little radiation will emerge at wavelengths below the Lyman limit; detection is therefore unlikely if the observer's passband is below $912(1+z) \text{ \AA}$, i.e. if the time of star formation is too soon after the Big Bang. Another problem is that PGs could be very dusty, so that most of the light from hot stars appears in the far infrared (Kaufman, 1976), as is the case for regions of intense star formation in a number of nearby galaxies.

Let us suppose that we are lucky, in that giant E galaxies do form most of their stars at $z \sim 5$ (times ~ 1 Gyr after the Big Bang), and that most of the UV light from hot stars is not absorbed by dust. The detectability of a PG then depends on the redshift, the size of the region of star formation, and the absolute luminosity, which is proportional to the SFR. Scaling from Meier's (1976) models, I estimate that PGs corresponding to rather modest E galaxies, with present $M_V \sim -21$, should lie above the magnitude limit for the ST even if star formation occurs on a time scale as long as several times 10^8 years; their surface brightnesses should be bright enough if the region of star formation is smaller than ~ 10 kpc. These are only approximate, model-dependent estimates, but they suggest that the ST should have no difficulty finding PGs if their UV light is neither absorbed nor too highly redshifted. The density of bright PGs on the sky is also encouragingly high; estimates depend on many parameters, including whether the spheroidal bulge components of spiral and S0 galaxies form in the same way as ellipticals, and range from a few to a few hundred per square arc minute. The most sensitive searches for PGs to date (e.g. Partridge, 1974; Davis and Wilkinson, 1974) would have mistaken for stars any objects as small as $1''$, but to the ST these would be clearly resolved. Even if star formation is concentrated in a region a few kpc across, the angular size will be several times $0''.1$ at all redshifts where detection

itself is possible. Thus if PGs are found, pictures from the ST will provide information on the morphology of young elliptical galaxies with rapid star formation, perhaps distinguishing between a symmetrical system or a chaotic collection of merging pieces.

It is worth remarking that an intrinsically bright, blue galaxy at high redshift will almost certainly be the precursor of a present *early*-type system (an E galaxy or a large nuclear bulge of an S0 or early spiral), rather than a young irregular galaxy or late spiral. This is because the bright stage corresponds to the rapid formation of many stars, and the present colors of late-type galaxies are too blue for them to possess such a large population of old stars. Part of the fascination of PGs is thus that they will be galaxies looking extremely different from their present-day descendants. (There is a loophole in this argument: Late-type galaxies could have been bright and blue already many billions of years ago if the stellar initial mass function then included few low-mass stars that would survive to the present. However, this in turn could be reconciled with the chemical compositions of the galaxies only by introducing further artificial assumptions.)

In §3, I discuss the possibility that PGs have already been detected in faint galaxy samples, which are therefore important candidates for further study by the ST.

1.2 Evolution of the Old Stellar Population

The colors and luminosity of an old elliptical galaxy evolve as successively less massive stars peel off the main sequence, spend a brief time as giants, then disappear. A naive expectation is that the colors should grow redder with time, since the main-sequence turnoff becomes redder and the locus of the red giant branch moves slowly to cooler temperatures; models for elliptical galaxies using conventional stellar evolutionary tracks do indeed predict that the integrated colors become redder with age (Tinsley and Gunn, 1976). On the other hand, Ciardullo and Demarque (1978) have pointed out that even a metal-rich galaxy will ultimately acquire a blue horizontal branch, and its integrated colors will evolve back to bluer values, when the turnoff mass has become so low that stellar mass loss before core helium ignition leaves only a small envelope mass. The age at which this happens depends on the metallicity and on the rate of stellar mass loss, which is not well enough known for firm predictions to be made. Ciardullo and Demarque present models allowing for mass loss at a plausible rate, in which metal-rich elliptical galaxies evolve toward bluer colors after ages of 8 Gyr.

It would therefore be interesting to test whether elliptical galaxies had bluer or redder colors a few Gyr ago, i.e. at redshifts of a few tenths. Ground-based data have been inconclusive on this

question because of uncertainties in K corrections. For example, Kristian et al.'s (1978) plot of B-V versus z for first-ranked cluster ellipticals suggests that the colors at $z \sim 0.2$ are somewhat redder than predicted with no evolution, but the K corrections at this redshift depend on uncertain UV spectral energy distributions. Spinrad (1977) finds colors bluer than those of nearby galaxies for a few ellipticals at $z \sim 0.5$, but these are radio galaxies so could be unusual. With the ST, it should be possible to measure colors at the same wavelengths of emission out to lookback times of at least 5 Gyr ($z \gtrsim 0.5$), in a large enough sample of elliptical galaxies to determine the direction of color evolution in a typical old population.

This test will be complicated by scatter in the present colors of elliptical galaxies. One factor causing variations is metallicity, which correlates with absolute magnitude but with considerable scatter (Faber, 1977; Sandage and Visvanathan, 1978). Another source of scatter may be low-level star formation in elliptical galaxies (Oemler, this conference); if this is common, color evolution will depend partly on the rates of star formation now and in the recent past. Detailed spectra and population syntheses will be needed to sort out metallicity effects and to clarify the possible importance of blue horizontal-branch giants and young stars in the light of ellipticals. The ST will be valuable in supplementing ground-based photometry with UV data, and then in reaching galaxies with significant lookback times.

A further application of these results will be to estimate the rate of luminosity evolution of elliptical galaxies, which affects the Hubble diagram as a method for measuring q_0 (see review by Gunn, 1978). Luminosity evolution at visual and longer wavelengths depends almost exclusively on the slope of the stellar mass function, and not on metallicity or low-level star formation, but the slope itself cannot be estimated accurately from population syntheses unless the metallicity, possible young stars, and position of giants in the HR diagram are also unravelled.

1.3 Cannibalism

It has been argued persuasively that the cD galaxies found (usually) at the centers of rich clusters have grown by accretion of smaller cluster members, via dynamical friction (e.g., Hausman and Ostriker, 1978). This process not only is interesting in itself but also plays havoc with the Hubble diagram as a cosmological test (Gunn, 1978); in order to use cluster galaxies as standard candles, we must assess the effects of cannibalism on their luminosities within a given aperture, which depend on details of the accretion process that probably vary from one cluster to the next.

High-resolution imagery of galaxies in clusters out to $z \sim 1$ will

give valuable information on the occurrence of multiple nuclei and close encounters, detailed surface brightness profiles, and color maps, as a function of cluster morphology, redshift, and the location of a galaxy within its cluster. Such data will help to determine how and under what circumstances galaxies swallow each other, and to find estimators - such as surface-brightness profiles - of the extent to which individual galaxies have been affected.

Interactions and mergers among galaxies probably play other important roles in their evolution, not only for ellipticals. For example, the colors of strongly interacting galaxies suggest that collisions between gas-rich galaxies induce bursts of star formation (Larson and Tinsley, 1978). Pictures at high resolution of such systems will help to clarify the processes involved, especially in showing details of where star formation occurs. Studies of nearby gas-rich galaxies undergoing collisions will also be relevant to the suggestion that star formation in primeval elliptical galaxies occurs during mergers of protogalaxies (§1.1). More generally, broad-band images at $0''.1$ resolution of many galaxies will contain unprecedented information about the process of star formation, which is fundamental to galactic evolution.

2. DISK GALAXIES

Spiral and SO galaxies must have had more varied and complex histories than ellipticals, but few lookback studies have yet been made. The ST will offer opportunities to test a number of current ideas, by exploring the evolution not only of photometric properties but also of the morphology of disk galaxies. An important point is the ability to resolve structure on scales of a few kpc at redshifts of at least 1, thereby distinguishing disk galaxies from ellipticals and even measuring the relative sizes of their disks and bulges.

2.1 Disk-to-Bulge Ratios of Spirals

Star formation is still continuing in the disks of spiral galaxies, while their bulge components have old stellar populations similar to those of elliptical galaxies. The luminosities of the disk and bulge components are therefore expected to evolve at different rates. An interesting project for the ST is suggested by the fact that different time dependences of the disk-to-bulge ratio (D/B) are predicted by alternative scenarios for the formation of galactic disks (see review by Larson, 1977). One possibility is that a gaseous disk forms almost as early as the stars of the bulge component, in a rapid collapse, after which stars form in the disk at a decreasing rate as the gas is consumed; if the SFR in the disk declines fast enough, its luminosity would decrease faster than that of the bulge, so the D/B luminosity ratio would decrease with time. An alternative picture is that the

disk forms by accretion of gas on a time scale of billions of years; the SFR would then depend on the accretion rate (see also Saar and Einasto, 1977), and it could have been constant or even increasing with time in the outermost regions. Such a long time scale for disk formation is suggested by several pieces of evidence, including the young age of most stars in the solar neighborhood (McClure and Twarog, 1977), the very low metallicity of a young cluster in the galactic anticenter (Christian and Janes, 1979), the consistency of stellar kinematics with a slow collapse of the Galaxy (Tinsley and Larson, 1978; Wyatt and Cahn, 1979), and the very blue disk colors of many spiral galaxies. A constant or increasing SFR, averaged over the disk, would lead to an increasing disk luminosity and an increase with time of the D/B ratio.

What changes in D/B might be observed to $z \sim 1$ according to these alternative scenarios? Consider a model in which the bulge stars are all very old and the SFR in the disk is either decreasing exponentially (with a time constant of 5 Gyr) or remaining constant; let the age of the system be 15 Gyr at present and 7 Gyr at $z = 1$. Calculations then show that between 7 and 15 Gyr of age the bulge component becomes fainter by 0.9 mag in the V band; the disk becomes fainter by 0.9 mag in V if it has the decreasing SFR, or brighter by 0.2 mag with a constant SFR. The intrinsic D/B ratio in V light would therefore be constant in the first case, but it would increase by a factor of 3 in the second case; in other words, if the SFR in the disk is constant, the D/B ratio would be 3 times smaller at $z = 1$ than it is locally. More generally, D/B luminosity ratios are predicted to be smaller at high z than locally in galaxies with a long time scale for star formation in the disk.

Tests for this effect will not be entirely straightforward. For one thing, spiral galaxies have a wide range of present D/B ratios, so it is not possible a priori to identify "equivalent" galaxies at different redshifts. Another point is that the apparent D/B ratios, if measured in the same observer's passband at low and high z , will depend on the colors as well as the luminosities of the components. In particular, bulges are redder than disks so they will suffer more K-dimming, and D/B will tend to appear too big at large z ; if D/B were measured at an observed wavelength of, say, 7200 Å in the above model with a constant disk SFR, the apparent ratio would be 30% larger at $z = 1$ than locally, instead of 3 times smaller. Thus it will be necessary to compare the observations with quite detailed models for the expected distributions of D/B ratios in samples of spirals at different redshifts. A careful study could lead to valuable information on the time scales for disks of spiral galaxies to form.

2.2 The History of S0 Galaxies

S0 galaxies have disks, but no spiral structure and normally no signs of ongoing star formation. There has long been a controversy as

to whether S0s are former spirals that were stripped of their interstellar matter, or an intrinsically separate class of galaxies. Recent data have put this problem into a new light, and I shall summarize the situation then suggest how the ST can provide further information on the origin of S0 galaxies.

That "stripping" of spirals produces S0s is strongly suggested by the large numbers of S0s relative to spirals in dense clusters (Spitzer and Baade, 1951). The dependence of galaxy populations on environment has been strikingly documented by Butcher and Oemler (1978b), who find that among nearby clusters only those with negligible central concentration are spiral-rich, while condensed clusters are all spiral-poor. In addition, Butcher and Oemler (1978a) find two condensed clusters at $z \sim 0.4$ with large proportions of blue galaxies, suggesting that about 5 Gyr ago the disk galaxies in such clusters were mostly spirals, whereas today they are S0s. The picture is not entirely simple, however. Dressler (1979) notes that the S0/S ratio in clusters exceeds its value in the field even in regions with only a slight excess density, where it appears impossible to sweep the interstellar matter from the disks of spirals - either by collisions between galaxies (Spitzer and Baade, 1951) or by ram pressure of the intergalactic medium (Gunn and Gott, 1972). Another argument against the stripping hypothesis is that S0 galaxies are no bluer than ellipticals, at a given absolute magnitude, which suggests that their disks do not contain relatively young stars (Sandage and Visvanathan, 1978). Moreover, S0s have certain structural differences from spirals: their average bulge size is larger (Sandage et al., 1970; Dressler, 1979), their average D/B ratio is smaller (Burstein, 1978; Dressler, 1979), and they may have faint "thick disks" that are not found in spirals (Burstein, 1978).

These structural differences show that stripping of typical present-day spirals will not produce typical present-day S0s. However, the more relevant question is *whether spirals and S0s have common ancestors*. This question is considered by Larson et al. (1979), with the following results. We ask first what would happen to spiral galaxies if they continued to form stars at their current rates using only the gas content of their disks; the answer is that 90% of spirals would run out of gas within 7 Gyr and 50% would do so within 4 Gyr; the solar neighborhood has enough gas to last for only ~ 1 Gyr. These short time scales imply that star formation in spirals has been sustained by accretion of external gas, and we suggest that spirals have possessed for most of their lives extended gas-rich envelopes - including tidal debris and companion galaxies as well as leftover primordial gas - which have been gradually accreted to build the disk. S0s are then disk galaxies that used up or lost such envelope material at an early stage. After loss of the envelope, star formation would continue for a few Gyr until the gas in the disk itself was consumed.

This modified "stripping" hypothesis appears to account for the observations mentioned above: (1) A diffuse outer envelope can be stripped much more easily than the dense gas in a disk, so it is not surprising that S0s appear in regions with only a slight density enhancement. (2) S0s are expected to have metal-rich disks, which would be redder than observed if they were as old as elliptical galaxies; when this factor is considered, the colors of S0s are consistent with their being former spirals in which most star formation ceased a few Gyr ago. (3) The envelope gas would be stripped from cluster galaxies during the cluster's collapse, but continuing star formation from gas left in the disk accounts for the blue colors of galaxies in Butcher and Oemler's (1978b) condensed clusters at high z . Estimates of the time scales for cluster collapse and for star formation to consume the disk gas lead further to a prediction that most of these blue galaxies will run out of gas shortly after they are seen, and so evolve by the present time into S0s with normal red colors. (4) The formation of S0s by truncation of star formation in a disk implies that S0s *should* have D/B ratios smaller than those of spirals, by the observed amount. (5) It has been suggested that spheroidal systems form by violent mergers among gas-rich protogalaxies (§ 1.1), in which case elliptical galaxies and disk galaxies with the largest bulges would tend to form in the densest regions of space, where indeed they are found (Dressler, 1979); since the disk galaxies in dense regions are those most likely to lose their surrounding gas and become S0s, this explains why S0s have larger bulges than spirals.

Several aspects of this picture could be tested by ST observations. One possibility is to test whether S0s have had no star formation in their disks for many billions of years, or whether they had the same ancestors as spirals until typically a few Gyr ago. The observations required are broad-band images with the best possible angular resolution, to give colors and to distinguish disk from elliptical galaxies out to $z \sim 1$. If the disks of S0s are all very old, the proportion of disk galaxies with colors as red as ellipticals should not vary with redshift, but if S0s were spirals until recently there should be many more blue disk galaxies at redshifts of a few tenths than there are at present. Butcher and Oemler's (1978a, b) cluster data strongly suggest that this is the case in dense clusters, and a first test should be to verify that the blue galaxies in distant clusters are indeed disk galaxies. O'Connell (1979) has made the alternative suggestion that they are young ellipticals; if so, they should appear spheroidal and (probably) bluest at their centers, readily distinguishable from galaxies with red bulges and blue disks.

Absorption lines in quasar spectra may also contain information on the past history of disk galaxies. If much of the material that is now in the disks of spirals used to be in extended gaseous envelopes, the effective cross-section of these galaxies for producing absorption lines

at high z would be much greater than the present optical disk diameters. The proposed origin for SOs implies that they also had gaseous envelopes like those of spirals, so the comoving density of gas-rich galaxies at high z would be greater than locally. This picture will therefore receive some support if the statistics of quasar absorption lines imply very extended and/or numerous intervening galaxies, as has often been suggested (e.g. Bahcall, 1978; Boksenberg, 1978; Weymann and Williams, 1978).

3. GALAXY COUNTS

Several of the studies of galactic evolution suggested above are of a statistical nature, and closely related to some recent ground-based work on counts of galaxies as a function of apparent magnitude and color.

The results of recent 24th-magnitude surveys are reviewed by Kron (1979), and their interpretation is discussed in more detail by Kron (1978), Bruzual and Kron (1979), and Tinsley (1979b). Briefly summarized, these papers find that models for galaxy counts are consistent with the data only if substantial amounts of galactic evolution are allowed for. Kron's (1978) data show an excess of very blue galaxies at a photographic J magnitude ~ 23 ; their colors are bluer than any nearby galaxies, and are in the range expected if a young stellar population is seen in the redshift range $\sim 1 - 4$. The absolute luminosities of these galaxies are then in the range expected for primeval galaxies of the type described in § 1.1 - early-type galaxies seen during the rapid formation of stars in a spheroidal system. The counts already show clear signs of evolution at $J = 21$, where the models predict that most galaxies would have $z \sim 0.2 - 0.3$ in the absence of evolution but redshifts up to at least 0.5 (and possibly a few greater than 1) with consistent evolutionary models.

One source of uncertainty in the models is a lack of reliable K corrections for all types of galaxy. At present, one has to use scant satellite UV photometry, supplemented by synthetic spectral energy distributions based on the hot stars that are predicted to contribute most of the UV light of galaxies; these syntheses are uncertain, especially because interstellar extinction could affect the spectra strongly. A survey of UV spectral energy distributions of nearby galaxies of many types would therefore be an important contribution by the ST to the interpretation of counts and color distributions; of course, the data would also give valuable information on the stellar and interstellar contents of the galaxies themselves.

Redshifts and high-resolution images of a sample of the very blue 23rd-magnitude galaxies would also be especially interesting. The present data, giving just numbers and colors, cannot distinguish

between alternative models in which they are (1) mostly elliptical galaxies and the bulges of early-type spirals and S0s, undergoing a primeval burst of star formation, or (2) mostly spirals at a later stage of evolution, with vigorous star formation in their disks. The latter alternative is inconsistent with the scenario of slow disk formation discussed in § 2, since in this picture the disks would not be much brighter at $z > 1$ than they are now. It is therefore possible that Kron's faint blue galaxies are the long-sought primeval galaxies. In any case, their redshifts will provide unique data on time scales for galaxy formation; and morphological information from pictures with 0".1 resolution will be an exciting new dimension in lookback studies of galactic evolution.

This work was supported in part by the National Science Foundation (Grant AST77-23566) and the Alfred P. Sloan Foundation.

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DISCUSSION

Heidmann: A remark about the question of primaeval galaxies : yesterday I referred to the existence of supergiant HII regions, which are 100 times larger than giant HII regions. They were found in what we called clumpy irregular galaxies, which contain 5-10 such supergiant HII regions. My suggestion is that these clumpy irregulars, which possess a tremendous rate of star formation, may serve as live models for primaeval galaxies. At present their properties may be investigated by ground-based means : spectroscopy for chemical abundances, the Westerbork radio-telescope for neutral hydrogen distribution, the VLA for ionized hydrogen, I-R for dust, CO line for molecules, the Einstein X-ray telescope for end products of short-lived stars. Later on they could be probed with the ST and shed light on the problem of galaxy evolution.

Tinsley: The colliding galaxies may be even better models for primaeval galaxies.

King: Objective-prism exposures in the UV with ST can potentially determine individual redshifts from the position of the Lyman break. Do you expect galaxies to be bright enough in the UV that we can really do this ?

Tinsley: IUE observations of normal galaxies have shown that they are very much brighter in the far ultraviolet than would be predicted by models which account for the optical spectrum. There is a good chance this may be possible.

Westphal: The problem with galaxies is that they are extended and consequently features in objective prism images are smeared out.

King: We can now take limiting IV-N plates and get infrared magnitudes of faint galaxies. Do you expect that observations with J, F, and N plates can solve these problems from the ground without waiting for ST ?

Tinsley: Kron and Bruzual believe it is possible to get redshift information from these plates.

Gunn: It is well-known that the redshift-magnitude relation for brightest cluster galaxies as a cosmological test is bedevilled by evolutionary corrections to the luminosities of galaxies. There are two corrections to be made. The stars of a galaxy evolve and it can be readily shown that the correction depends only on the slope of the initial main sequence mass function. This is difficult to estimate but probably can be done with effort. The more difficult correction, first described by Tremaine and Ostriker, results from cannibalism in which the brightest cluster galaxy eats less massive galaxies. In a simple theory, it can be shown that, if energy is conserved and if the galaxies are homologous,

the core (or characteristic) radius $r_c \propto M^\beta$ where $\beta \approx 1 - 2$, being 1 if the galaxy eats members of mass similar to its own mass and 2 if very much less massive members are eaten. One can work out what happens to the luminosity of a galaxy seen through an aperture of fixed radius as a function of added mass and it depends only on β and $\alpha = d(\log L)/d(\log r)$. The galaxy grows in size and it follows that, for β constant, the amount by which the galaxy grows depends only on α . Therefore, if we can measure α , we can hope to make a correction for cannibalism according to this very simple theory.

Hoesel and I have studied the correlation of absolute magnitude with α for the brightest galaxies in 107 Abell clusters and there is a clear trend in the data which is in very encouraging agreement with the simple theory. The dispersion in absolute magnitude of the brightest cluster galaxies is reduced from 0.4 to 0.2 magnitudes. Thus, if one can measure α for distant galaxies with ST, it may be possible to make this most difficult correction.

Concerning the correction for stellar evolution, it is well known that the surface brightness of a galaxy is independent of the cosmological model. Thus, if there were only the stellar evolution correction to be made, this could be done by measuring the surface brightness of distant and nearby galaxies. This is obviously complicated by variations in the sizes of galaxies due to cannibalism. However, these corrections can be made by measuring α and corrections for stellar evolution measured directly. Surface brightnesses for distant galaxies are very difficult to measure from the ground but, from ST, it will be very easy with the WFC or with the higher resolution cameras.

Thus, contrary to my previous views, I now believe that cosmological studies for q_0 using brightest cluster members are a viable enterprise using ST.

Spiral (Discussion leader): The Space Telescope will tell us a great deal about the evolution of galaxies with cosmic epoch but there are problems. For example the predicted V magnitudes of giant elliptical galaxies at redshift $z \approx 1.0$ vary considerably with the assumptions made about how their luminosities have evolved with time. ST can do precise photometry at $V = 24$ but spectroscopy will be very difficult, partly because of the aperture of the telescope and partly because the apertures of the FOS are all small. There may be ways of obtaining redshifts using ST, for example, by multicolour photometry, or it may be necessary to measure these redshifts from the ground.

The direct imaging mode is the most important and this will provide much crucial data for studying the evolution of galaxies, for example, the disc-to-bulge ratios for galaxies and their angular diameters at large redshifts.

A serious problem is how to find standard candles, especially giant elliptical galaxies, for cosmological tests. I list few possibilities, two of which are old and two new.

- (i) Optical identification of distant radio galaxies. These are similar in absolute magnitude to the brightest galaxies in clusters and some indeed are brightest cluster members.
- (ii) The search for distant rich clusters of galaxies. This will be difficult with ground-based electro-optical devices and with those on board ST because of the small field of view. If they are found by chance, it is essential to make sure that they are the same types of objects observed nearby.
- (iii) Some quasars are now known to be in clusters. By searching for these companion clusters, brightest cluster members in the normal sense may be discovered.
- (iv) At faint magnitudes, $V > 21$, it can be shown that only giant ellipticals in the redshift range $0.4 \lesssim z \lesssim 0.9$ have colours $J-F > 2.0$. Such tests are just beginning from the ground now. An interesting approach would be to use a combination of (iii) and (iv) for quasars in the range $0.5 \lesssim z \lesssim 0.9$

Two final comments : studies of the UV continua of elliptical galaxies can give information about the epoch of the last major burst of star formation. Surface brightness tests and associated tests of galaxy luminosity evolution (similar to those described by Gunn) will be very much better with ST than from the ground because of the very high angular resolution of ST.

N.A. Bahcall: The dynamical evolution of galaxies in dense clusters can be studied with Space Telescope. This evolution is closely related to the observed X-ray emission from clusters. Essentially all rich clusters are found to be X-ray emitters. The X-ray emission comes from a hot intracluster medium, most of which is believed to have originated in the galaxies (the iron X-ray lines correspond to roughly solar abundance). Therefore, a correlative study of the galaxy properties such as type, color, and spectra (with ST) in comparison with the observed properties of the intracluster gas such as density, temperature, and structure (X-ray satellites) should yield important information regarding the dynamical evolution of galaxies and clusters.

It has been shown (Bahcall, N.A., 1977a. *Ap. J. Letters*, 217, L77; 1977b. *Ap. J. Letters*, 218, L93) that for nearby clusters ($z \lesssim 0.2$) strong correlations exist between the X-ray luminosity of a cluster (i. e., intracluster gas density and temperature) and the stage of dynamical evolution of the cluster. In part ular, it has been shown that X-ray

luminosity is, on the average, highest (i.e. gas density and temperature) for compact cD-B type clusters and lowest for irregular clusters. The X-ray luminosity was found to increase with central galaxy density in clusters, as expected, and to strongly decrease with increasing spiral fraction in the cluster. This latter correlation agrees well with a ram-pressure stripping model in which the spiral galaxies are converted to SO (or E) by the dense ($\sim 10^{-3} \text{ cm}^{-3}$) intracluster medium. Similar correlations should be carried out at higher redshifts in order to better understand the evolution of galaxies. The blue galaxies found in two $z \sim 0.4$ clusters by Butcher and Oemler (1978, Ap. J., 219, 18), and the relatively strong extended X-ray emission detected from at least one of these two clusters (Henry et al. 1979, Ap. J. Letters, in press) are other manifestations of the interactions between the intracluster gas and the galaxies that can be studied at large redshift.

Collin-Souffrin: I would like to add to Dr. N. Bahcall's talk that it would be also interesting to correlate the optical and X-ray studies of clusters of galaxies with 21 cm observations. Indeed Chamarant has recently shown, that the HI deficiency of spiral galaxies is well correlated with the richness and with the intensity of the X-ray emission of clusters.

N80-22740

THE CENTRAL REGIONS OF ACTIVE GALAXIES AND QUASARS

Wallace L. W. Sargent
Hale Observatories
California Institute of Technology
Pasadena, California 91125, USA

There is a growing body of evidence that the non-thermal extragalactic sources in the Universe--the Radio Galaxies, Seyfert nuclei, QSO's, BL Lacertae objects and the X-ray galaxies--are all powered ultimately by collapsed objects at the centers of galaxies. Moreover, there is no reason at this stage to doubt that the central energy source is probably the same in all cases. At this point, five years before the Space Telescope is to be launched, the fundamental problem is to identify the nature of the central engine and then to understand in detail the variety of observed phenomena.

The main properties of the central source may be listed as follows:

- a) It must be able to produce an amount of energy up to 10^{63} ergs (corresponding to a rest mass of $3 \times 10^8 M_{\odot}$).
- b) It must be able to achieve rates of energy production as high as 10^{47-48} ergs s^{-1} .
- c) The size of the energy production region must not exceed a few light days (or $\sim 10^{16}$ cm).
- d) The recent studies of radio jets on vastly different scales show that the source must be able to remember the direction of ejection over periods of at least 10^6 years.

1. THEORIES

The main theories that have been proposed for the central engine in active galaxies and QSO's are

- a) The collapse of a dense stellar system.
- b) The supermassive star using nuclear energy.
- c) The spinar.
- d) Accretion of stars or gas onto a black hole.

It is widely, but not universally, believed that the fourth possibility is the most plausible. Rees (1977), in a recent review of

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the situation, described the black hole as the "best buy" amongst the current theories, in part because as far is known, the other entities must eventually evolve into black holes, anyway.

The history of the study of active galaxies and QSO's has been marked by an enormous gap between theory and observation. It is one of the prime tasks of the Space Telescope to close this gap. Therefore, in the rest of this paper, I shall adopt the view that the notion of accretion onto a black hole is basically right. I shall then discuss how observations with the Space Telescope might be aimed to prove or disprove the notion.

2. ACCRETION ONTO A BLACK HOLE

If the black hole idea is right then the rate of fueling required is

$$\dot{M} = 0.1 \epsilon^{-1} L_{46} M_{\odot} \text{ year}^{-1}, \quad (1)$$

where ϵ is the efficiency conversion of mass into energy and L_{46} is the luminosity of the object in units of 10^{46} ergs s^{-1} . Efficiency factors in the range $0.01 \lesssim \epsilon \lesssim 0.1$ are commonly discussed; therefore, the accretion rate required to produce a typical QSO luminosity is $M \sim 0.1$ to $1 M_{\odot}$ per year.

It is now becoming apparent that the great variety of observed phenomena associated with active galaxies and QSO's may result, at least in part, from a variety in the mechanisms by which the black hole is fueled. Possible fueling mechanisms which come immediately to mind are:

- a) General infall of the products of normal stellar mass loss into the center of a galaxy. (This is estimated to be $\sim 10^{-11} M_{\odot}$ per year per solar mass in the Galaxy.)
- b) Stellar disruption through either tidal forces produced by the black hole or through stellar collisions in the dense cusp of stars around it. For black holes of reasonable mass, stellar collisions are more important than tidal disruptions.
- c) Infall of interstellar gas around the nucleus of a galaxy.
- d) Tidal interactions with other galaxies. (A surprising fraction of Seyfert galaxies are in interacting systems--e.g., VV 150.)
- e) The capture of intergalactic clouds. (This possibility is suggested by the existence of elliptical galaxies such as NGC 5128 and NGC 4278 which contain rotating disks of gas with the rotation axis inclined to the principal axes of the elliptical. Such a state of affairs is unstable on a time scale of $\sim 10^8$ years.)
- f) Galactic mergers. (NGC 5128 has also been discussed in this context as a possible merger between an elliptical and a Magellanic irregular galaxy.)
- g) "Freezing out" of hot gas in the gravitational potential well

at the centers of certain X-ray clusters--e.g., NGC 1275 at the center of the Perseus cluster (Fabian and Nulsen 1977).

In order to account for the energies observed, black holes with masses in the range $M_H = 10^6 - 10^9 M_\odot$ are required. The Schwarzschild radius $R_s = 2GM_H/c^2 = 3 \times 10^5 (M_H/M_\odot) \text{ cm}$ thus lies in the range 10^{-7} to 10^{-4} pc. The normal angular resolution quoted for the Space Telescope is $0''.1$; this corresponds to a linear resolution of 10 pc at the distance (20 Mpc) of M87, which is one of the closest active galaxies. Thus it is evident that the Space Telescope will not achieve direct imaging on a scale anywhere near that of the Schwarzschild radius even for black holes at the upper end of the expected range. However, as we shall see the ST should lead to less direct observations of great interest, particularly if imaging close to the diffraction limit ($0''.02$ at $\lambda 2500$) can be achieved by the use of suitable sophisticated deconvolution techniques.

3. THE AIM OF THE RESEARCH

In decreasing order of importance, the main aims of work on active galaxies and QSO's, both with the ST and with ground-based telescopes, will be seen to be

- a) To identify with certainty the nature of the central energy source.
- b) To understand the fueling mechanisms.
- c) To understand the detailed phenomena which result from different fuels and circumstances. This includes the problem of the generation of the relativistic particle beams which are responsible for the radio emission from many of these objects.

4. THE ADVANTAGES OF THE SPACE TELESCOPE

As everyone knows, the main advantages are

- a) The ultraviolet response for imaging and for spectroscopy.
- b) The high angular resolution of $0''.1$. (Moreover, the expected high stability of the image profile should enable the diffraction limit to be reached even on very faint objects. In this respect the ST will have an overwhelming superiority over the largest ground-based telescopes using speckle techniques.)
- c) The stability for photometry through small apertures or on small angular scales in the optical and at UV wavelengths.

As a spectroscopist, I am surprised to find that I regard the last two items as the major advantages of the ST. Point (c) has not been sufficiently stressed in discussions of the ST; it will have enormous advantages over ground-based techniques for such observations as the light variations of the active nucleus seen against the surrounding

galactic background.

5. OUTLINE OF RESEARCH PROGRAMS WITH THE ST

These can be divided into two main categories. The first is those observations that deal with (mostly phenomenological) questions regarding the general environment of the central engine. The second category comprises those observations that directly attack the question of the nature and structure of the engine itself. Let us first consider the environmental observations.

a) It will be possible with the ST to determine morphological types of galaxies out to a redshift of $z \sim 0.3$ to 0.5. Moreover, a typical galaxy with a linear extent of around 10 kpc (corresponding to ~ 10 arcseconds at these redshifts) will always be much larger than the bright active nucleus. It will thus be possible to find out whether QSO's are giant Seyfert nuclei in the centers of galaxies as we commonly suppose and, if so, we shall be able to determine what kinds of galaxies are associated with QSO's. Such observations may reveal new correlations between the kind of activity and galaxy type. However, the most important possibility is that the identification of the type of galaxy associated with QSO's would enable time-scale arguments to be made. As an example, we know that the classical Seyfert nuclei are found in roughly 1 percent of spiral galaxies. Accordingly, we can estimate that the Seyfert phenomenon must last at least 1 percent of the Hubble time, or 10^8 years. This type of argument, if it could be applied to QSO's would lead to an estimate of the total energy released by a QSO during its lifetime and hence to an estimate of the minimum mass of the central engine.

b) A search for faint Seyfert nuclei. The least luminous Seyfert nucleus known is NGC 4051 whose nucleus has $M_B = -17$; this galaxy is also one of the nearest Seyferts. Work by Huchra and Sargent (1973), recently improved on by Veron (1979) showed that the luminosity function of Seyfert nuclei rises rapidly as one goes from $M_B = -23$ to $M_B = -17$ and is not observed to turn over. This must clearly be an effect of observational selection; from the ground it is difficult to separate a faint Seyfert nucleus from the light of the surrounding galactic bulge. Thus, at present we do not know whether or not there is a lower limit to the luminosity of the QSO-Seyfert phenomenon. It would clearly be important to undertake a search for faint Seyfert nuclei in nearby galaxies with the ST. This could be done either spectroscopically or by first looking for galaxies with point UV nuclei.

c) Observations of the fueling mechanism in more distant systems (for example, in Markarian 78 which has two sets of emission lines), and at higher spatial resolution in nearby objects such as NGC 1275.

d) Observations of optical jets: it is now becoming clear that the jets are the means whereby the non-thermal energy is directed from

the central engine to the outer regions. A prime object for study is obviously the optical jet of M87 which contains discrete, bright knots, at least one of which appears to be unresolved at the diffraction limit ($0''.02$) of the 200-inch telescope (Arnold, Boksenberg, and Sargent, unpublished). If the knots are moving at the speed of light, then in 10 years they should move through a distance of 3 pc or $0''.03$; this should be detectable with the ST.

The second category of observations deals with direct attacks on the problem of the mass, size, and structure of the central engine, the main question being whether or not it is in fact a black hole. There seem to be two lines of investigation:

- a) Studies of the continuum and the broad emission line region in nearby Seyfert nuclei.
- b) The search for central mass concentrations in nearby elliptical galaxies.

6. THE CENTERS OF SEYFERT GALAXIES

As is well known, the spectra of Seyfert nuclei lead to a fairly sharp division into two kinds of objects. The Type I Seyfert galaxies have spectra in which the Balmer emission lines have broad wings while the forbidden lines of such ions as O III are much sharper; the Balmer lines have sharp cores like the forbidden lines. On the other hand, in the Seyfert galaxies of Type II Balmer lines do not have broad wings. In general terms, the spectra of QSO's resemble those of Type I Seyfert galaxies.

Considerable work over the past few years, particularly on NGC 4151, the archetype of Seyfert I galaxies, and on NGC 1068, the archetype of Seyfert II's, has led to the following picture of the structure of a Seyfert nucleus. There is a central source of non-thermal radiation which, from its variability at optical and X-ray wavelengths, is thought to be a few light days (10^{16} cm) in extent. This is surrounded by relatively dense gas clouds ($10^9 < n_e < 10^{11}$ cm $^{-3}$) which produce the broad components of the permitted lines. This region, which we shall discuss in more detail later, has a size of order 0.1 pc ($\sim 3 \times 10^{17}$ cm) and contains about $10^2 M_\odot$ of gas. The wide wings on the emission lines are due to mass motions, perhaps in part by rotation around the central energy source which serves to photoionize the surrounding clouds. Outside the broad emission line region there are more tenuous clouds which produce the forbidden emission lines and the sharp cores of the Balmer lines. This region is a few hundred pc ($\sim 10^{21}$ cm) in radius and, with a density $n_e \sim 10^4$ cm $^{-3}$, the gas has a mass of about $10^5 M_\odot$. The velocities in this gas are in the range 300 to 1000 km s $^{-1}$. The Type II Seyfert galaxies have nuclei in which the broad-lined region is absent or weak and in which the central non-thermal source does not dominate the light from the central parts of the galaxy at optical wavelengths.

Osterbrock (1978) has deduced from his extensive spectroscopic studies a model for Seyfert nuclei which is along the lines sketched above, out which is able to account for such refinements as the detailed differences between the emission spectra of radio galaxies and those of Type II Seyfert galaxies. The essential additional feature of Osterbrock's model is that the broad emission line region is supposed to be in the form of a thick disk which is optically thick in the equatorial direction to Lyman continuum from the central source. However, the disk, which is envisaged to have a filamentary structure, is optically thin to such radiation in the vertical direction. According to Osterbrock the broad components of the Balmer emission lines are produced partly by rotation of the disk and partly by turbulent motions in it.

7. EVENTS CLOSEST TO THE CENTRAL ENGINE

If the energy emitted by Seyfert galaxies and QSO's is due to accretion onto a black hole, then the non-thermal parts of the optical, ultraviolet and X-ray continua come from about a radius of about $10 R_g$. This is 3×10^{14} cm (corresponding to a light travel time of hours) for $M_H = 10^8 M_\odot$. In Seyfert galaxies and QSO's there are several components to the continuum radiation:

- a) A non-thermal (power law) component with $f_\nu \sim \nu^{-1}$.
- b) Stars near the center of the system (this component being very important in the optical spectra of Seyfert II galaxies).
- c) Hydrogen recombination radiation from the broad and sharp emission line regions.
- d) The "blue bump" observed in the near UV region of Seyfert galaxies and in 3C 273. This is possibly thermal radiation from the dense gas in the broad line region where the temperature is $T \sim 10^4$ K.

An important goal of the Space Telescope will be to sort out these components on the smallest angular scales both in the optical and in the ultraviolet.

The broad emission lines also arise close to the central engine. There are several empirical indications that the broad-line region is small:

- a) The ionization equilibrium in the broad-line region is such that

$$y \sim \frac{L_{UV} e^{-\tau}}{r^2 \rho c^2} \sim \frac{\text{radiation energy density}}{\text{mass energy density}} \sim 10^{-11},$$

and so the electron density comes out to be

$$n_e \sim 10^{11} L_{46}^{-1} r_{pc}^{-2} e^{-\tau},$$

where L_{UV} is the flux in ergs s^{-1} beyond the Lyman limit and r_{pc} is the radius of the region in parsecs. The total flux in the hydrogen emission lines is such that

$$n_e^2 V = 10^{69} L_{46} ,$$

which leads to a small filling factor $f = V / \frac{4}{3} \pi r_{pc}^3$.

- b) The broad emission lines have been observed to vary on time scales of months both in their shape (e.g., 3C 390.3) and intensity.
- c) In NGC 4151 there are absorption components in the blue wings of the Balmer lines and the He I line $\lambda 3889$ whose lower level is metastable. These absorption lines have been observed to vary on time scales as short as 2 weeks.
- d) The relative strengths of the broad hydrogen emission lines (e.g., the $L\alpha : H\beta$ ratios) are anomalous in Seyfert galaxies and QSO's. This indicates that the region has a high electron density and hence, via the ionization equilibrium, a small radius.
- e) There are time variations in the wavelength of the low energy cutoff produced by the broad-line region in the X-ray emission from the central source.

Finally, a lower limit to the size of the broad emission region comes from the requirement that the maximum emissivity in the lines has to be less than that of a blackbody with $T = T_e$. This condition leads to a limit

$$r_{em} \gtrsim r_{min} = 3 \times 10^{16} L_{46}^{1/2} \left(\frac{T_e}{10^4} \right)^{-2} \text{ cm} .$$

The evidence summarized above leads to the conclusion that the actual radius of the broad-line region is close to this limit. Accordingly, the region may more resemble the outer parts of the photosphere of a hot star than an H II region--thus giving rise to the thermal "blue bump" observed in the near-ultraviolet continuum radiation.

8. PROJECTS FOR THE ST ON THE CENTERS OF SEYFERT GALAXIES AND QSO'S

The foregoing considerations suggest the following observations which would help to pin down the nature and structure of the central source:

- a) It should not be possible to resolve the broad emission line region or the non-thermal continuum source.
- b) On small angular scales is there evidence from the velocity field in the sharp emission lines for rotation around the central source? If so, what is the central mass?
- c) It is important to follow the time variations in the continuum (optical and UV), the broad emission lines and associated absorption features and in the low-energy X-ray cutoff in order to further elucidate the structure of the broad-line region.

d) The broad emission lines have bumpy profiles when observed at high spectral resolution; they also change with time. It is important to search for any evidence for rotation in the time variations of the profiles. If found, this would lead to an estimate of the central mass.

e) As will be discussed later, estimates of the central mass could also be obtained from studies of the radial distributions of the luminosity and velocity dispersion of the stars in Seyfert nuclei. Here the high spatial resolution afforded by the ST would enable the stellar radiation to be distinguished from the other components much closer in towards the center than is possible from the ground.

9. THE SEARCH FOR SUPERMASSIVE OBJECTS IN ACTIVE E GALAXIES

The velocity fields revealed by the emission lines from the centers of active galaxies are so chaotic that no estimates of the masses of the central sources have been obtained so far. Therefore, one is led to the idea of examining the effect of a central black hole on the stars near the center.

Normal elliptical galaxies appear to have distributions of light and velocity dispersion σ_v that are well fitted by King's (1966) models. These models are characterized by an isotropic distribution function $f(E)$ with a cutoff in the energy E so that the star density ρ reaches zero at a finite radius $r = r_t$, the tidal radius. Thus

$$E = \frac{1}{2} m^* v^2 - \frac{GM(r)m^*}{r} \quad (2)$$

where m^* is the mass of a star, and where

$$M(r) = \int_0^r 4\pi v^2 \rho(r) dr \quad (3)$$

is the mass inside radius r . The distribution function is

$$f(E) = A \exp(-\beta E) - A \exp(-\beta E_{esc}) \quad (4)$$

so that $f = 0$ for $E > E_{esc}$, the escape velocity from the system. As $E_{esc} \rightarrow \infty$ the models tend towards isothermal spheres; near the center the models are nearly isothermal so that $\rho(r) \sim r^{-2}$.

The effect of a central black hole (or other effectively "point" mass) on the star distribution near the center of a galaxy which otherwise obeys a King model has been considered by several authors. Some analytical solutions exist for the case in which the gravitational potential of the black hole

$$\phi = - \frac{GM_H}{r} \quad (5)$$

is dominant.

Following a suggestion by Peebles (1972), several authors have

explored the consequences of assuming a self-similar power law

$$f(E) = K|E|^P, \quad E < 0 \quad (6)$$

for the distribution function. In this case

$$\rho(r) = \rho_a \left(\frac{r}{r_a} \right)^{\left(-\frac{3}{2} + p \right)} \quad (7)$$

where $\rho = \rho_a$ at some scale length $r = r_a$, and

$$\sigma_v(r) = \frac{2}{5+2p} \frac{GM_H}{r} \quad (8)$$

Three solutions of interest have been discussed, They are

a) Relaxed models, in which the system of stars has had time to completely relax under the gravitational influence of the black hole. In this case

$$p = 1/4, \quad \rho(r) \sim r^{-7/4} \quad (9)$$

b) Adiabatic, unrelaxed models, in which the black hole mass grows slowly as compared with the orbital revolution of time of a star. In this case the stellar orbits are slowly pulled in and

$$p = 0, \quad \rho(r) \sim r^{-3/2} \quad (10)$$

c) Unbound stars; the stellar system is not relaxed and the stellar orbits are merely deflected as they pass close to the black hole. In this case

$$p = 1, \quad \rho(r) \sim r^{-1/2} \quad (11)$$

In all of these cases, the outer edge of the sphere of influence of the black hole will be at a radius r_a such that

$$\frac{3}{2} \sigma_v^2 = \frac{GM_H}{r_a} \quad (12)$$

where σ_v is the velocity dispersion near the center of the galaxy in the absence of the black hole. Inside this radius we expect the stellar distribution to assume the form of a cusp with one of the three radial density distributions described above. In suitable units we find

$$r_a = 70 \left(\frac{M_H}{10^9 M_\odot} \right) \left(\frac{\sigma_v}{200 \text{ km s}^{-1}} \right)^{-2} \text{ parsecs} \quad (13)$$

We note that at the distance of the nearest active elliptical galaxies (for example, M87) 1 arcsecond ~ 70 pc, so that a central black hole of order $10^9 M_\odot$ is required before its effect on the light distribution could be detected from the ground.

The inner edge of the cusp around the black hole occurs at some critical radius r_c at which either

- a) Stars are tidally disrupted by the black hole (r_D),
or b) Stars have to physically collide during the relaxation process (r_{coll}).

In suitable units, we find that for main-sequence stars

$$r_D = 2.1 \times 10^{-5} \left(\frac{M_H}{10^9 M_\odot} \right)^{1/3} \text{ pc} , \quad (14)$$

which is to be compared with the Schwarzschild radius

$$R_S = 10^{-4} \left(\frac{M_H}{10^9 M_\odot} \right) \text{ parsecs} , \quad (15)$$

(We note that stars are swallowed whole for $M_H \gtrsim 10^9 M_\odot$.)

The collision radius occurs at the point where the velocity dispersion of the stellar system equals the velocity of escape from an average star. We find

$$r_{coll} \sim r^* \left(\frac{M_H}{m_*} \right) [\ln \Lambda]^{-1/2}; \quad \Lambda = \frac{\text{radius of system}}{\text{radius of a star}} \quad (16)$$

We find for main-sequence stars of one solar mass that

$$r_{coll} = 5 \left(\frac{M_H}{10^9 M_\odot} \right) \text{ parsecs} , \quad (17)$$

so the inner edge of the cusp is always determined by collisions.

For the star-star relaxation time we may take Spitzer's reference time

$$t_R = \frac{8 \times 10^5 N^{1/2} R_{pc}^{3/2}}{\left(\frac{M_*}{M_\odot} \right)^{1/2} \log_{10} N} \text{ years} , \quad (18)$$

where N is the number of stars and R_{pc} is the core radius of the system in parsecs. For a typical giant elliptical galaxy $N \sim 10^9$ (inside the core radius) and $R_{pc} \sim 10^3$ so that $t_R \sim 10^{14}$ years.

From these considerations it follows that the most likely cusp around a black hole would have a density distribution $\rho(r) \sim r^{-3/2}$, so that the projected luminosity goes like $\sigma(r) \sim r^{-1/2}$. For a really massive black hole with $M_H \sim 3 \times 10^9 M_\odot$ the cusp would extend from a few hundred parsecs radius in to about 5 pc radius. At this point, inside the collision radius, the star distribution would flatten off.

Young et al. (1978) and Sargent et al. (1978) have respectively

measured the light distribution and the radial distribution of velocity dispersion in M87 and have concluded from their measurements that M87 contains a central mass concentration (which may be a black hole) with a mass of about $5 \times 10^9 M_{\odot}$. More recently, Young *et al.* (1979) have studied the light distributions in the centers of the radio galaxy NGC 6251 and in NGC 4874 and NGC 4889, the two giant central galaxies of the Coma cluster. The latter two galaxies can be fitted to King models, while NGC 6251 cannot; again the required central mass for NGC 6251 is about $3 \times 10^9 M_{\odot}$.

There are, therefore, preliminary indications that at least some active galaxies contain massive black holes whose effects can even be discovered by ground-based observations. What are the implications for the Space Telescope?

9. PROJECTS ON ACTIVE ELLIPTICAL GALAXIES WITH THE ST

There are several obvious observations:

- a) To study the light distribution in the "cusp" in the center of M87 down to the diffraction limit of the telescope ($0''.02$ or ~ 2 pc). Note that, according to the considerations made earlier, the whole of the cusp down to the collision radius should be observable if there is indeed a black hole of $M_{\text{H}} \sim 5 \times 10^9 M_{\odot}$ present.
- b) Does the light distribution obey a law similar to $\rho(r) \sim r^{-3/2}$?
- c) By spectroscopic or color measurements show whether or not the light is dominated by ordinary stars down to the diffraction limit.
- d) Measure the velocity dispersion σ_v as near as possible to the center of M87. It should be $\sigma_v \sim 1000 \text{ km s}^{-1}$ at $r \sim 0''.1$. Such a measurement could be done at low resolution ($\sim 10 \text{ \AA}$) but the integration time would be tens of hours.
- e) Make similar observations of other, nearby ellipticals and of the nuclei of spirals, including Seyfert galaxies.

10. CONCLUDING REMARKS

As I remarked at the beginning, there has been a gap between theory and observation in the study of QSO's and active galaxies which the Space Telescope could do much to fill. I am convinced that the maximum scientific benefits will be obtained by pushing the capabilities of the telescope to their limits on nearby objects--particularly M87 and NGC 4151. In my view, in our present state of knowledge, it would be better to devote observation time to the study of time-variable phenomena in a few well-chosen objects rather than give fleeting attention to many.

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DISCUSSION

J.N. Bahcall: In the calculations of Wolf and myself, we find that the velocity distribution of stars in the central cusp is very far from Maxwellian. Most of the light is due to stars with small velocities but the velocity dispersion is much larger because of a few stars with high velocities.

Sargent: I agree. The velocity distribution has a central cusp and a long tail. I would avoid this problem by ignoring the very centre of the galaxy. At somewhat larger radii, the increase of velocity dispersion with decreasing radius should be definable in some sense and it should be a big effect.

Weymann: It is striking that the densities in the broad-line regions are always about 10^9 - 10^{10} cm^{-3} . This may be due to the fact that our diagnostic tools are only sensitive to densities in this range but one would like to know how this scales with luminosity. Do these regions get bigger and denser with luminosity? One would have to study more than a few objects to find this out.

Sargent: I am struck by the fact that there are very few empirical correlations, especially with luminosity, between the properties of active nuclei. This is despite the fact that their luminosities range over a factor of 10^4 .

Illingworth: I have measured the velocity dispersion as a function of radius for several galaxies, including two normal galaxies, and in these cases the velocity dispersion increases with decreasing radius within the core radius, as has been found for M87. This suggests either that we are making errors in measuring $\sigma(v)$ or that these normal galaxies also have mass concentrations in their centres.

Gunn: I would make a cautionary remark about the way in which the velocity dispersions $\sigma(v)$ are measured. Using the Fourier technique, there turns out to be a disturbing correlation between line strength γ and $\sigma(v)$. These are highly correlated statistically so that large $\sigma(v)$ goes with large γ . If γ is constrained to be constant, then so is $\sigma(v)$. Probably this is not the whole of the observed effect. It is likely to be most important in the outer regions where the S/N ratio is low.

Illingworth: We have tested this possibility using data of high S/N ratio in the region where the velocity dispersions vary with radius and altering the metallicities makes a very small change to the velocity dispersion.

Tinsley: I would like to mention the recent preprint by Faber and French, finding a possible excess of M dwarfs right at the centre of M31. Is it

still possible, on the basis of present data, that the mass concentrations at the centers of E galaxies are due to low-mass dwarfs?

Sargent: I think the data are consistent with that now but you could push things in such a way with ST that it would not be.

Weymann (Discussion leader): I propose we discuss the paper in two parts. First, the environment, ranging from the region immediately around the central engine, to the surrounding galaxy, to the group and cluster environment. Second, we should look at the physics of the emission line regions. All contributors said they would make remarks provided Wal did not cover the topic adequately and thoroughly so it is not clear what there is to be added.

Osterbrock: Let me re-emphasise what Sargent has said about the importance of direct pictures, with the best possible angular resolution, of the central regions of Seyfert galaxies. I think that the "best bargain" would be to look at approximately 10 of the nearest to try to see their morphology right at the centre - as close to the central source as possible. There is a very strong correlation between the featureless continuum and the presence of broad emission-lines, yet the broad lines have a variety of widths. This strongly suggests a non-spherical velocity distribution - perhaps ejection more or less in a plane of broad line gas that has interacted with a central rotating disc. Direct pictures in the continuum and in one or two strong emission lines would be very helpful in revealing structure near the centre.

Burbidge: I'd just like to underscore the need to make velocity measures in the gas around the very active Seyfert nucleus in 3C120, with high spatial resolution. In the regions one can resolve from the ground there is a disordered velocity field, with a sort of line of zero velocities that doesn't agree with the minor axis of light distribution. These velocities have been measured by Baldwin et al. Right in the nucleus is one of the "superluminal" VLBI expanding sources, and the axis agrees with the velocities further out. What happens in between? Although the ST won't achieve the less than milliarcsec resolution of VLBI measurement capability, it will be able to probe closer into the "active engine" and this is a very important observation.

Now I'd like to follow Kay's invitation to make some further remarks. A discussion of extragalactic research with the ST is surely not complete without a consideration of what observations with ST might best address the problem of "discrepant redshifts". Arp, who could best outline what he would see as the most important observations, is unfortunately not here. Neither is Geoff Burbidge, who always acts as our astronomical conscience, reminding us that it is unscientific to ignore data because it doesn't fit pre-conceived patterns or favorite hypotheses. We should rather examine those data particularly carefully, and look for

additional data - i.e. look at what Fred Hoyle calls \dot{D} - the trend of the data. Arp's results would be most exciting if ST observations confirmed his work.

Since he isn't here, I can only suggest that I think of the important tasks here is looking at "connections" between discrepant redshift objects, e.g. the BL Lac object AO 0235+164, with two absorption redshifts 0.524, 0.851 and its companion 3 arc sec away, with emission redshift 0.524. Is this really stellar? Is the slight connection between them real? Only the 10 times better imaging of ST can do better than the 4-m plate. Another case is 3C303, with a radio source enveloping and seeming connected with both a radio galaxy, with $z = 0.14$, and QSO with $z = 1.57$. The two other UV objects discovered by Wierick *et al.* are miserably faint to work on from the ground but should be OK for the FOS; one is noticeably extended on a 4-m plate but has a point-like central condensation. Notice that there seems to be a faint loop of material in an arc between the galaxy and the QSO. Arp is trying to see if this is real. It looks real on this 4-m plate. Does it have knots in it, as looks to be the case? If so, their spectra might be observable with ST.

Another case is the first "double QSO" - 1548+114, discovered by Wampler. These have very different redshifts, 0.4 and 1.90. Does the lower redshift object produce Ly α absorption in the other? ST can look at the UV spectrum to see. Also it can image this object and see if the "fuzz" which Butcher *et al.* have marginally detected round this object is real, and if so what its luminosity gradient is with respect to the central object. Of course, fuzz wherever known around QSOs should be studied with ST (e.g. 3C48 fuzz, which has emission lines but no absorption has been detected).

Finally, we can look at the apparently stellar very faint objects found in radio lobes of e.g. 3C285, by Tyson, Saslaw and Crane. What are these? Are they like the 3C303 case?

These are just examples which come to my mind for addressing the "discrepant redshift" problem. There must be many others.

Boksenberg: Wehinger, Wycoff and myself have found evidence for an early-type stellar component in the fuzz around the quasar 0837-12 which has redshift $z \approx 0.2$.

Tarcnghi: The problems of observing galaxies in clusters with the Space Telescope are that the galaxies are extended objects and associations of galaxies subtend rather large angles in the sky compared with the field of view of Space Telescope. Because galaxies have typical sizes ~ 1 arcsec at cosmological distances, the photons will be spread over many pixels and the only gain in the optical waveband is the lower background from space which is about 1 magnitude fainter than from the ground.

The precise gain depends upon the profile of the galaxy. The gain in the UV is, of course, very much greater.

The problem with the small field of view may be expressed as follows. With a field of view of 3 arcmin, the core of a rich cluster of galaxies will only be observed in a single WFC frame if its redshift is greater than 0.5. For comparison, a single 4 metre plate can include the whole Abell diameter of a rich cluster in a single exposure if it has $z > 0.5$ and a single Schmidt plate can contain a whole supercluster if $z > 0.5$. However, observations of the cores of distant clusters with the WFC will be important. For example, the stripping of spiral galaxies at redshifts $z \approx 0.5$ can be studied by classifying galaxies on WFC images. Probably these classifications will be possible out to redshift $z \approx 0.7$.

Let me mention two interesting examples of quasars in clusters of galaxies. 3C66A is a BL-Lac object in a rich cluster of galaxies. The quasar 2251-17 is an X-ray quasar with several nearby galaxies at the same redshift. There is evidence that the quasar is exciting the intergalactic gas close to the quasar.

Gunn: In studying galaxies at large redshifts, the K-corrections are much more important than the distance effects. If one looks in the near infrared, the photon rates are large and the gain in going into space is about 3-4 magnitudes compared with the one magnitude gain in the V band. I will show tomorrow that what you can hope to do at $1 \mu\text{m}$ with the WFC is really quite encouraging.

Groth: You also gain from the high angular resolution. For objects at a given redshift, the faintest galaxies observable have unresolved core radii. It is only at $z \approx 1$ that the faintest galaxies observable have their cores resolved.

Spinrad: I will show two examples of what will be possible with ST on the basis of ground-based observations. Boksenberg has already mentioned the "fuzz" around the quasar 0837-12 which has redshift 0.20. I have surface photometry of this quasar in the red region which shows that the brightness distribution can be decomposed into a point-like object associated with the quasar and a smooth distribution which is identical to that of an elliptical galaxy with $M_V = -23.3$. The system lies in a cluster which Abell would probably have classified as of richness class 0.

Similarly, the quasar PKS 0405-123 has redshift $z = 0.57$ and is embedded in a cluster of faint galaxies at roughly the same redshift. It is impossible to search for a giant elliptical galaxy underlying this quasar from the ground but from ST with its high angular resolution, this study should be very easy. Clusters around quasars can be studied

from the ground out to redshifts $z \approx 0.7$.

Thus quasar environments are, at least sometimes, the normal moderately rich cluster containing elliptical and probably spiral galaxies.

N.A. Bahcall: If quasars with redshifts $z \gtrsim 0.5$ are found in clusters of galaxies, this may indicate an evolutionary change with cosmological epoch because at smaller redshifts, we found very few real associations of quasars with clusters.

Gunn: I wonder if this evolutionary change may not just be statistical. There is a contradiction if you suppose that quasars lie preferentially in clusters. However, if you look at the fraction of galaxies in rich clusters and compare that with the number of quasars which have been carefully studied at small redshifts, I do not believe there is any contradiction.

Oke: I will mention some results to come out of observations with IUE which have implications for observations with Space Telescope. Sargent mentioned the similarity of quasars and Seyfert I galaxies. In the UV, this similarity disappears. In particular the CIV line is very much stronger in Seyfert I galaxies than in quasars by a factor of 2-3. The anomalous Ly α /H β ratio is found in Seyfert I galaxies, the value being 15-20 times smaller than the recombination value. There is a hint that interstellar reddening in the object itself may be important because a weak 2175 Å absorption feature may be present in some objects. This would alleviate partially the Ly α /H β ratio problem. Finally, it is very important to study time variability in the profiles of Lyman α and other lines in Seyfert galaxies as emphasised by Sargent. This might indicate the origin of the Ly α /H β discrepancy.

Collin-Souffrin: I would like to point out the importance of the ST for our knowledge of the broad line region in type I Seyfert galaxies, even if it cannot be observed directly. It is not so clear to me that the broad line region is photoionized by the UV continuum source, and I think that there are some problems with this interpretation. One of these problems has been mentioned by Dr. Oke, and it is called the La/H β problem. As a matter of fact, all the lines observed in the UV range and not only La, seem to be weaker with respect to the visible lines of the same ions, than the classical photoionization models predict. One example of this is the extreme weakness of the UV lines of Fe II, which, I think, can only be produced by collisional excitations in a very optically thick medium. Such a medium would likely correspond to a kind of thick "atmosphere" activated by some mechanical process of energy dissipation, and we are trying presently to work out such an alternative model, to see if it could explain the La/H β ratio.

However, it has recently been proposed by Netzer and Davidson, on

the basis of their detailed computations of photoionization models, that external reddening can explain the $L\alpha/H\beta$ ratio, and more generally the UV emission spectrum. The implications of this idea are very important: in particular, the intrinsic continuum, corrected for the reddening, will be quite different from a synchrotron spectrum, and should look more or less like that of a black body at $\sim 10^6$ K.

On the other hand, the recent UV observations of 3C390.3 and NGC1068 have shown that the narrow line region has a typical "recombination ratio", $L\alpha/H\beta \approx 40$; and then, if the reddening explanation is correct, the absorbing dust should be located somewhere between the broad line and the narrow line region.

A way to test this model would be to look in great detail, in nearby Seyfert galaxies, at the ionization structure and to the distribution of dust (obtained through some line intensity ratios and through the 2200 Å feature), in the narrow line region which has typical dimension of a few arc seconds. On the other hand, such an observation could also lead to knowledge of the shape and of the coverage factor of the broad line region, which is optically thick to the ionizing radiation.

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ABSORPTION LINES IN THE SPECTRA OF DISTANT OBJECTS

John N. Bahcall
Institute for Advanced Study
Princeton, New Jersey 08540

I shall discuss studies that can be carried out with the Space Telescope (ST) of absorption-line systems which may be expected to occur in the spectra of distant objects.

Absorption-line systems with redshifts very different from the emission-line redshift have so far been observed only in the spectra of quasars and BL LAC objects. However, the fact that quasars exhibit rich absorption spectra and galaxies have not yet been observed to do so may be explained by two selection effects. Galaxies are by definition fainter than quasars and most of the strong absorption lines occur in the far ultraviolet. Thus galaxies at the redshifts sufficient to shift the absorption systems into the visible region are too faint to be studied at the high resolution necessary to detect narrow absorption lines.

ST observations of galaxies (with, e.g., $0.1 \leq z_{em} \leq 0.5$) may be expected to reveal quasar-like absorption lines if many of the absorption systems observed in quasar spectra are due to absorption by material along the line of sight at cosmologically significant distances from the quasar.

For convenience only, I shall describe all of the proposed observations as if the continuum sources were only quasars. The listener will easily recognize that many of the suggested observations could be carried out with distant galaxies (irrespective of the origin of the already-observed quasar absorption lines). Galaxies are more numerous per square degree than are quasars. For some observations (see § VI and VII), the advantage of being able to choose galaxies behind specified regions may outweigh the disadvantage of their relative faintness.

Most of the absorption systems have been observed in the spectra of quasars with large emission-line redshifts. How-

ever, one may anticipate some general advantages in studying the small absorption redshifts, $z_{\text{abs}} < 1$, that are accessible with ST. Relatively bright quasars can be used. Also the spectra may be less crowded (see equation (1) below) than is the case when large values of z_{abs} are considered. The observed region between 1100 Å and 1200 Å will be especially interesting since it is both accessible to the ST spectrographs and free of confusion due to Ly- α absorption lines.

In § I, I describe the phenomenology of quasar absorption-line systems. In § II, I summarize the principal explanations that have been suggested. I also add one new proposal, i.e., that the numerous Ly- α systems are caused by "extremely large" hydrogenic halos around galaxies or clusters of galaxies. In Tables 2 and 3 of § III, I list the absorption lines that are likely to be strongest. In § IV, I describe two tests for the origins of known absorption systems. In § V, I discuss observations in which distant sources of ultraviolet radiation can be used as continuum probes to search for gas in previously-known, relatively-nearby systems. I describe four special projects in § VI. Finally, I present a sample observing program in § VII.

1. PHENOMENOLOGY

The main characteristics of the absorption lines observed in quasar spectra are summarized in Table 1. The properties listed are described in greater detail in several recent review articles [see for example Bahcall 1978; Boksenberg 1977, 1978; Burbidge 1978; Sargent 1977; Weymann and Williams 1978]. It is an encouraging augury for the ST program that participants in this colloquium [especially Boksenberg, Burbidge, Lynds, Morton, Sargent, and Weymann] have accomplished most of the crucial, ground-based observational work on quasar absorption lines that is summarized in the above-cited reviews.

Quasar ultraviolet spectra have many absorption lines. There are typically of order 0.05 absorption lines per Å with rest equivalent widths $\geq 0.3\text{Å}$ for wavelengths, in the rest frame of the quasar, in the approximate range 1600 Å to 1216 Å (\equiv Ly- α). For wavelengths shortward of the Ly- α emission line, the number of absorption lines rises dramatically to of order 0.2 absorption lines per Å. This increase in the density of absorption lines below the Ly- α emission line was explained by Lynds (1971) as being due to many Ly- α lines. The metal lines and the higher members of the Lyman series are mostly too weak to be detectable with present techniques [see also Lynds and Oemler 1975 and Young et al. 1979].

Table I. CHARACTERISTICS OF OPTICAL ABSORPTION LINES

This table summarizes the main characteristics of the optical absorption lines that have been observed in QSO spectra.

<u>General Property</u>	<u>Detailed Characteristics</u>
Many Lines	$\left\{ \begin{array}{l} 0.2 \text{ per } \text{\AA}, \lambda_{\text{quasar}} < \text{Ly-}\alpha \\ 0.05 \text{ per } \text{\AA}, \lambda_{\text{quasar}} > \text{Ly-}\alpha \end{array} \right.$
Many Redshifts	$\left\{ \begin{array}{l} 10^{1 \pm 0.5} \text{ per spectrum} \\ \text{mostly } z_{\text{abs}} < z_{\text{lim}} \end{array} \right.$
Distribution in Redshifts (may be homogeneous)	More detected at large z (~ 2.5) than small z (~ 0.7). Requires great care in avoiding selection effects.
Variety of Ionization Stages (HI and HII)	HI, CII, CIV, NII, N V, OI, OVI, MgI, MgII, AlII, AlIII, SiII - SiIV, MnII, FeII, FeIII ($T \sim 10^{4.5 \pm 1} \text{ OK}$)
Mostly narrow lines	$\left\{ \begin{array}{l} \frac{\Delta\lambda}{\lambda} \sim 10^{-3.5 \pm 0.5}, \text{ most lines} \\ \frac{\Delta\lambda}{\lambda} \sim 10^{-1.5}, \text{ in a few cases} \\ \text{with } z_{\text{abs}} \sim z_{\text{lim}} \end{array} \right.$
Line Splittings	$\sim 10^2$ km/sec (metal lines) (some cases of $\sim 10^3$ km/sec)
Excited Fine Structure States mostly absent	$n_e \leq 10^3 \text{ cm}^{-3}$
No established transitions from metastable states	CIII λ 1175.7 absent
Wavelengths are constant in Time	$\left \frac{1}{\lambda} \frac{d\lambda}{dt} \right \leq 10^{-5} \text{ yr}^{-1}$

There are many independent absorption-line redshifts in each (large redshift) quasar spectrum. For the systems containing heavy elements, this conclusion was established shortly after the discovery of rich absorption spectra by a detailed statistical analysis [Bahcall 1968]. Subsequent work, cited above, validated the identification with separate Ly- α systems (by Lynds) of most of the many lines shortward of the Ly- α emission line.

A well-defined technique for analyzing spectra is required in order to establish the existence of multiple redshifts, because of the many degrees of freedom that are available in fitting the data. Typically [Bahcall 1968] one tabulates a predetermined set of standard lines that are expected, on the basis of some hypothesis about the nature of the absorbing region, to appear in the absorption spectrum. One also formulates a set of rules for determining whether a candidate redshift is physically reasonable (e.g., the weaker component of a doublet is successfully identified only if the stronger component can also be present). The actual redshifts are determined by a systematic search (with a computer) for acceptable redshifts. Finally, a Monte-Carlo simulation is made using nonsense spectra (or some other statistical estimate is carried out) in order to establish the level of statistical significance. Only if the number, N_{Obs} , of redshifts identified in the real spectrum is large compared to the average number of spectra identified in the Monte-Carlo simulation (or found by another statistical estimator), N_{Nonsense} , can one conclude that there are indeed a multiplicity of redshifts produced by the standard lines in the observed spectrum. In the computer analysis of many moderate dispersion spectra, $N_{\text{Obs}} \gg N_{\text{Nonsense}}$. The precise value of N_{Nonsense} that should be associated with a given set of rules depends on the distribution of lines that is assumed for the nonsense spectra. It has become clear [Bahcall and Joss 1973; Aaronson, McKee, and Weisheit 1975; Colvin 1975; Joss and Ruffa 1977; Young et al. 1979; Roberts 1979] that the original prescription of a uniform distribution underestimates the value of N_{Nonsense} by a factor that may be of order of fifty percent, but which is still uncertain. However, as long as one uses only identifications for which $N_{\text{Obs}} \gg N_{\text{Nonsense}}$, the precise value of N_{Obs} is not crucial. One must be very cautious about making inferences based on individual lines since only the total pattern of identifications is shown to be statistically significant.

There are now in use a number of computer programs that differ in varying degrees from the original identification procedure (Bahcall 1968). Some of these (e.g., Boksenberg and Sargent 1975; Young et al. 1979) are described by the authors as essentially the same as the original procedure and some make rather far-reaching modifications (e.g., Joss and Ruffa 1977; Roberts 1979). In any event, the software that will be appropriate for analyzing ST observations will differ in some details from all of the above since it will depend upon the quality of the data that is obtained and on the as yet unknown character of high resolution quasar spectra in the region $1100 \text{ \AA} \leq \lambda_{\text{observed}} \leq 3200 \text{ \AA}$.

The distribution of absorption redshifts can be predicted

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(Bahcall and Peebles 1969) as a function of the standard cosmological parameters q_0 and Λ/ρ_0 , if one assumes that most of the absorption lines arise in material that is randomly distributed along the line of sight between us and cosmologically distant quasi-stellar sources. We shall refer to this assumption as the "cosmological hypothesis." The probable number of absorption lines in a redshift range between z and $z + dz$ is then

$$dP = \frac{\pi R^2(0)N(0)c(1+z) \left[\left(R(z)/R(0) \right)^2 \left(\frac{N(z)}{(1+z)^3 N(0)} \right) \right]}{H_0 \left[1 + 2q_0 z - (\Lambda/3) \left\{ (1+z)^2 q_0^{-1} + z^2 + 2z \right\} \right]^{1/2}} dz, \quad (1)$$

where $\pi R^2(0)N(0)$ is the suitably averaged product of projected surface area and present number density of absorbing regions, H_0 the present Hubble constant; q_0 the acceleration parameter, and Λ , the cosmological constant. For simplicity, we assumed that the absorbers did not evolve with redshift [i.e. the bracketed quantity in the numerator of equation (1) was unity], although the possibility of evolution was recognized as an important factor determining the observed distribution (see especially Bahcall 1971).

Two tests of the cosmological hypothesis were proposed (Bahcall and Peebles 1969) that are based on equation (1). The first test expresses the fact that the total number of absorption redshifts in each quasar should be given by the integral $\int dP(z)$ over the allowed range of z . If all of the objects are studied in the same way over the same range of z , then the number of absorption redshifts in each quasar should be Poisson distributed with a mean given by the integral of the right hand side of equation (1). The second test does not require a constant detection efficiency for each object. The observed distribution of redshifts, $\frac{dP(z)}{dz} dz$, can be determined by counting all the redshifts found in just one object. The simplest application of the second test is to ask whether the observed function, $dP(z)$, can be represented by equation (1). It may be necessary to average $dP(z)$ over large enough bins of z to eliminate peaks due to several correlated absorbers, e.g., galaxies in a rich cluster, cf. Boksenberg (1978).

There has been a more or less continuous controversy over whether or not these tests are satisfied in the ten years since they were first proposed. Only very recently, Boksenberg (1978) and Burbidge (1978) reached opposite conclusions on this question in successive review talks that were given at the same conference. My own opinion has been [Bahcall 1971, 1978], until very recently, that the required observational material, sufficiently free of selection effects, was not available. Most recently, Sargent, Young, Boksenberg, and

Tytler (1979) have applied both tests described above to high resolution data obtained for six quasars. They have constructed well defined samples from the Ly- α absorption lines observed in these objects and have paid scrupulous attention to possible selection effects. They have carried out a rigorous statistical analysis that, in my opinion, will constitute a standard of excellence for years to come. Sargent et al. (1979) conclude that the results in each object are consistent with equation (1) (test 1 above) and that the inter-comparison of the spectra of different objects is also consistent with spatial homogeneity (test 2 above).

Both of these results were obtained assuming no evolution of the absorbers (bracketed quantity in the numerator of equation (1) set equal to unity). Ellis (1978) earlier reached a similar conclusion regarding test 1 which he made by taking account of the selection effects in inhomogeneous data.

Quasar absorption spectra show lines from a wide variety of ionization stages. The ions that contribute the most prominent lines are shown in Table I; they range from ions characteristic of HI regions (HI, OI, MgI) to highly ionized atoms (CIV, NV, and OVI). The observed lines arise primarily from ground-state transitions (see below) of the elements with the largest solar abundances. The lines that are observed were predicted [Bahcall and Salpeter 1966; Bahcall 1968] to be the strongest lines that would be seen in quasar spectra on the basis of atomic physics considerations, solar abundances and the hypothesis that absorption systems are low-density gases. The strong lines are essentially the same as those observed by Copernicus to be produced in the instellar medium of our Galaxy (see Boksenberg 1978 for a discussion of this similarity).

Most of the observed optical absorption lines are very narrow; in many cases they are unresolved at the highest resolution available ($\Delta\lambda \sim 1 \text{ \AA}$). [Observations of some systems at 21 cm even show velocity widths of individual components that are only 20 km/sec or less wide (see, e.g. Brown and Roberts 1973)]. In a few cases, very broad optical absorption lines are present. Such features were first seen in the spectrum of PHL 5200 [Lynds 1967], which exhibits absorption troughs shortward of Ly- α , NV, SiIV, and CIV, extending over a range of 12,500 km/sec. One of the most extreme examples of this phenomenon is seen in the spectra of Q1246 - 057 [Boksenberg 1978], which shows a broad absorption system of width \sim 5000 km/sec separated by \sim 1500 km/sec from the emission lines. Most observers have interpreted the broad-line systems in terms of material flowing out of the quasar [see Boksenberg 1978 and Burbidge 1978].

Absorption line systems, when studied at high resolution, are frequently observed to be split into separate subsystems [see, especially, Boksenberg and Sargent 1975; Morton and Morton 1972; Wiggert 1975]. These splittings are often of the order of 10^2 km/sec. Boksenberg and Sargent (1975) originally suggested that the numerical value of these splittings, $\Delta z \approx 0.0012$ or 141 km/sec might be a constant with special significance. It was proposed instead (Bahcall 1975) that the observational results could be explained by a velocity dispersion of less than or of order of 10^2 km/sec among individual absorbing clouds and a comparable instrumental resolution. A specific model was suggested in which the splittings were supposed due to absorption in clouds in halos surrounding galaxies or small groups of galaxies. This interpretation implied that there are many absorption redshifts that are split with velocity separations less than 10^2 km/sec, a prediction that has been confirmed recently with very high resolution spectra by Boronson, Sargent, Boksenberg, and Carswell (1978). It was also proposed [Bahcall 1975] that splittings of order 10^3 km/sec might be expected from absorption in the halos of galaxies that are themselves in clusters of galaxies. A splitting of order 10^3 km/sec has in fact been observed in some cases [see, e.g., the results of Strittmater et al. 1973 on 1331 + 170 and Boksenberg and Sargent 1975 on Pks 0237 - 23].

Transitions originating on excited fine structure states of Si II, CII, and NII are usually weak and undetectable. However, they have been detected in a few cases and occasionally are strong [see, e.g. Stockton and Lynds 1966; Boksenberg 1978; Roberts 1979]. The absence of excited fine structure transitions implies that the electron density must be relatively small [Bahcall and Wolf 1968; Bahcall 1967]. Typical limits on the ambient electron density are $n_e \leq 10^3 \text{ cm}^{-3}$ [Bahcall 1967; Burbidge and Burbidge 1969], although in one case (B2 1225 + 31.7) a much more stringent limit ($n_e \leq 2 \text{ cm}^{-3}$) has been deduced (Boksenberg 1978) using the absence of a line from CII*. The absence of excited fine structure states can also be used to establish a lower limit on the separation, D , between the continuum source (the quasar) and the absorbing system. Typical limits are (Bahcall 1967) $D \geq 1 \text{ kpc}$, as long as the transitions that populate the excited fine structure states are optically thin (Sarazin, Flannery, and Rybycki 1979). Direct infrared transitions are presumably optically thin for clouds close to a quasar, but this condition may not be satisfied for the lines that might provide ultraviolet pumping.

Absorption lines originating on metastable states have not been identified in recent spectroscopic analyses of quasar spectra [see Bahcall 1978 for a detailed discussion

of this point]. Such lines (e.g., CIII $\lambda 1175.5$) are observed in the solar corona and, with P Cyni profiles, in all hot galactic supergiants earlier than B0 [Snow and Morton 1976]. The obvious inference, consistent with the results cited above for the fine structure transitions, is that the ambient electron densities are much less in the quasar absorption systems than in the stellar atmospheres or winds in which CIII $\lambda 1175.7$ is observed.

There are no confirmed observations of variations in the wavelengths (or strengths) of quasar absorption lines. The strongest limit on wavelength variations has been given by Boksenberg and Sargent (1975) who find, for 28 strong lines in PKS 0237-23, individual rms upper limits of $|\lambda^{-1}d\lambda/dt| \leq 2 \times 10^{-5} \text{yr}^{-1}$.

2. THEORETICAL MODELS

A number of theoretical suggestions have been made for explaining the absorption lines observed in quasar spectra. However, the question of where the observed lines originate remains controversial.

E. M. Burbidge (1978) and G. R. Burbidge (1978) have recently reviewed arguments which they believe suggest that many or nearly all of the observed lines arise in material associated with the quasar. They cite especially evidence for an inhomogeneous distribution of redshifts, including "line-locking" and a peak in the redshift distribution at $z = 1.95$.

I have been an advocate for a long time (see Bahcall and Salpeter 1965; 1966; Bahcall 1971) of the opposite point of view, i.e., that many or nearly all of the observed lines (with $z_{\text{absorption}} < z_{\text{emission}} - 0.01$) originate in material not associated with the quasar. In this interpretation, absorption arises in material distributed along the line between us and the quasar at cosmologically significant distances from the quasar. The implied (Bahcall and Peebles 1969 and equation 1) smooth redshift distribution can be reconciled with the evidence of apparent redshift inhomogeneity cited by E. M. Burbidge (1978) and G. R. Burbidge (1978) by noting (see Bahcall 1971) that the reported redshift distribution is sensitive to observational selection effects and the identification procedures.

Many explanations have been advanced of specific sources that might produce absorption at cosmological distances from the quasar. The first such suggestion (made just before absorption lines in quasars were discovered) was that absorption lines would be formed in clusters of galaxies [Bahcall

and Salpeter 1965, 1966]. This model was abandoned as incorrect as soon as quasar absorption lines were discovered and the narrowness of the observed lines became apparent. I think this conclusion was premature. Recent discoveries, discussed above, of redshift splittings in optical observations have taught us that the absorption lines may be formed in individual clouds and hence need not have widths comparable to the total velocity dispersion in a cluster. Moreover, recent x-ray observations of Fe emission lines have shown that the intracluster gas is rich in iron and presumably other heavy elements (Mitchell, Culhane, Davison, and Ives 1976; Serlemitsos, Smith, Boldt, Holt, and Swank 1977).

Other absorbers at cosmological distances from the continuum source that have been suggested include the discs of spiral galaxies [Wagoner 1967], dead galaxies [Peebles 1968], large galactic halos [Bahcall and Spitzer 1969], intergalactic hydrogen clouds [Arons 1972; Sargent, Young, Boksenberg, and Tytler 1979], and protogalaxies [Roser 1975].

It is useful in discussing the various theoretical models to rewrite equation (1) in a form that makes explicit the average cross section times number density that is required to produce the observed absorption-line density.

One has:

$$R^2(0) N(0) = \left[(1+2q_0 z)^{1/2} \mathcal{N}(z) / \pi(1+z) C/H_0 \right], \quad (2a)$$

or in convenient units:

$$\left(\frac{R(0)}{100 \text{kpc}} \right)^2 \left(\frac{N(0)}{0.003 h_{50}^3 \text{Mpc}^{-3}} \right) \sim 3 h_{50}^{-2} \mathcal{N}(z) / 5. \quad (2b)$$

Here $\mathcal{N}(z)\Delta z$ is the number of redshifts in the interval Δz from independent absorbers [i.e., counting split redshifts from different clouds in the same absorber as one system]. I have set $\Lambda = 0$ and abbreviated $(H_0/50 \text{ km/sec Mpc}^{-1})$ as h_{50} . I use illustrative reference values for the radius (from Bahcall and Spitzer's hypothesis of large galactic halos), for the number density of absorbers (the local number density of observed galaxies from Felten's 1977 renormalization of Schecter's 1976 luminosity function), and $z_{\text{abs}} \sim 2.5$, with, for systems containing metal lines, $\mathcal{N}(2.5) \sim 5$ [see, e.g., Young et al. 1979]. In deriving equation (2), I assumed that the effective radius is independent of the observed luminosity of the individual absorbers. This assumption is plausible if, as supposed by Bahcall and Spitzer (1969), the low-density gas that produces the absorption

lines extends to much greater distances than does the boundary of the region producing detectable optical or radio emission. [Radii that depend upon luminosity are more appropriate if the gas is related to visible stars, see the discussions of models of this kind by Wagoner (1967), Burbidge, O'Dell, Roberts, and Smith (1977), and Weymann, Williams, Peterson, and Turnshek (1979), all of whom scale the effective radius with visible luminosity.]

The original estimate of $R \sim 10^2$ kpc still seems to be of the right order to explain the observed number of absorption systems that produce detectable lines from heavy elements if we adopt for $N(0)$ the observed number density of (reasonably bright) galaxies.

The Lyman-alpha systems, however, are much more numerous. For them (using the number densities reported by Sargent et al. 1979):

$$\left(\frac{R_{\text{Ly-}\alpha}(2.5)}{100 \text{ kpc}}\right)^2 \left(\frac{N_{\text{Ly-}\alpha}(0)}{0.003 \text{ Mpc}^{-3}}\right) \sim 35 h_{50}^{-2} \quad (3)$$

Arons (1972) and Sargent et al. (1979) have suggested that the Ly- α systems are due to intergalactic hydrogen clouds.

I would like to propose a different interpretation of the Ly- α systems, i.e., extremely large hydrogen halos. These halos may be associated with either galaxies or clusters of galaxies. It is possible that essentially all galaxies, even those not luminous enough today to appear in the observed local samples of galaxies, once had large gaseous halos composed largely of hydrogen. This may require, in the above notation, $R_{\text{Ly-}\alpha} \sim 200$ kpc and $N_{\text{Ly-}\alpha}(0) \sim 0.01 \text{ Mpc}^{-3}$. Many other combinations of R^2 and $N_{\text{Ly-}\alpha}(0)$ are, of course, possible, since only R^2N is determined at present from the observations.

It is also possible that the Ly- α halos are associated with clusters of galaxies. Illustrative parameters not inconsistent with available observations (N. Bahcall 1977) are: $R_{\text{cluster}}(0) \sim 30$ Mpc and $N_{\text{cluster}}(0) \sim 7 \times 10^{-7} \text{ Mpc}^{-3}$.

Both of the "large Ly- α halo" hypotheses described above can be tested by ST observations that are discussed in § V. Both suggestions are consistent with the observation (Sargent et al. 1979) that the Ly- α systems exhibit less small-scale splitting than do the metal (i.e., CIV) lines. In the explanations proposed here, the Ly- α lines arise in a region outside that which produces the metal lines. This picture is also consistent with the idea (see Sarazin 1979; Bahcall 1975) that the heavy elements in the halo are produced by

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supernova remnants in the Galaxies.

3. EXPECTED STRONG LINES

The ST observatory will make possible high resolution spectroscopic observations, a region that is inaccessible with ground-based telescopes, from 1100 Å to 3200 Å. This wavelength range is particularly important because many of the strongest absorption lines have rest wavelengths in this region. In addition, one will be able to observe for the first time very short wavelength absorption lines ($300 \text{ Å} \leq \lambda \leq 900 \text{ Å}$) in the spectra of very large redshift objects ($z \geq 3$).

Table II shows the strongest lines that may be expected to occur. This list is essentially the same as was used by Bahcall (1968) to identify absorption-line systems of large redshift quasars (with the addition of the MgI λ 2852.97 and MnII λ 2576.88 lines that have been observed in some small-redshift quasars). (The original line list was constructed by determining which transitions would be strongest assuming: solar abundances; estimated transition probabilities; and equilibrium populations of initial states in a low density gas. The fact that this list accounts well for the observed lines indicates that the initial assumptions are not grossly incorrect.)

Table III lists some important short wavelength lines that can be searched for in the spectra of objects with appreciable emission redshifts. The lines in this table have been selected in much the same way as were the longer wavelength lines in Table II.

4. COSMOLOGICAL VERSUS INTRINSIC HYPOTHESES

The cosmological and intrinsic hypotheses for the origins of the absorption lines predict spectra with qualitatively different appearances.

The cosmological hypothesis predicts (Bahcall 1971, 1978) that there will be many fewer absorption lines in the far ultraviolet spectrum ($\lambda \leq 2300 \text{ Å}$) of nearby quasars ($z_{em} \ll 1$) than in the spectra of large redshift quasars observed at the same rest wavelengths. Table II shows that the strongest lines that have been observed in the visible spectra of large redshift quasars can be studied conveniently with ST in the spectra of small redshift quasars in the far ultraviolet ($1100 \text{ Å} \leq \lambda \leq 2300 \text{ Å}$).

Table II. Lines Most Likely to Appear in the Range $1100 \text{ \AA} \leq \lambda_{\text{observed}} \leq 3200 \text{ \AA}$.

Ion	$\lambda_{\text{Vacuum}} (\text{\AA})$ ($\lambda > 1215.67 \text{ \AA}$)	Ion	$\lambda_{\text{Vacuum}} (\text{\AA})$ ($\lambda \leq 1215.67 \text{ \AA}$)
Mg I	2852.97	Si III	1206.51
Mg II(1)	2803.53	Si II	1193.28
Mg II(2)	2796.35	Si II	1190.42
Fe II	2600.18	Fe II	1144.95
Mn II	2576.88	Fe III	1122.53
Fe II	2586.64	N II	1083.99
Fe II	2382.76	O VI(1)	1037.63
Fe II	2374.46	C II	1036.34
Fe II	2344.21	O VI(2)	1031.95
Al III(1)	1862.78	H I(0.2)	1025.72
Al III(2)	1854.72	Si II	989.87
Al II	1670.81	C III	977.03
C IV(1)	1550.77	H I(0.07)	972.54
C IV(2)	1548.20	H I(0.03)	949.74
Si II	1526.72	Some Excited State Fine Structure Lines	
Si IV(1)	1402.77	Si II	1533.45
Si IV(2)	1393.76	C II	1335.70
C II	1334.53	O I	1304.86
Si II	1304.37	Si II	1264.76
O I	1302.17	Si II	1194.50
Si II	1260.42	N II	1084.58
N V(1)	1242.80	N II	1085.55
N V(2)	1238.82	N II	1085.70
H I(1)	1215.67		

The number of absorption redshifts expected in the spectrum of a quasar with $z_{\text{emission}} \ll 1$ can be computed simply on the basis of the cosmological hypothesis. The predicted number is $\mathcal{N}^0(z)z_{\text{em}}$, where $\mathcal{N}^0(z)dz$ is (as defined earlier) the number of redshifts in the interval Δz . The value of $\mathcal{N}^0(z \sim 2.5)$ has been determined by the many available observations of large redshift quasars and is, for the Ly- α systems, $\mathcal{N}_{\text{Ly-}\alpha}^0(z \sim 2.5) \sim 60$ (see, e.g., Sargent et al. 1979). Note $\mathcal{N}^0(z) \sim (1+2q_0z)^{1/2} \mathcal{N}^0(z)/(1+z)$. For 3C 273, one expects ≤ 4 Ly- α absorption systems on the basis of the cosmological hypothesis. If the product NR^2 was larger, as seems likely, at earlier times [i.e., the bracketed term in equation (1) is less than unity for large z], then the inequality applies.

On the other hand, if most of the absorption occurs in material intrinsic to the quasars, then a similar number of absorption systems ought to be present in the spectra of both small and large redshift quasars. In many cases, the observed number of Ly- α systems is of order 10^2 . Thus the intrinsic

hypothesis requires more than an order of magnitude more absorption systems for small emission-line redshift quasars than the cosmological hypothesis predicts.

There is another qualitative difference between the cosmological and intrinsic hypotheses. No blueshifts ($z_{\text{abs}} < 0$) are possible on the cosmological hypothesis. Blueshifts are natural and expected, in quasar spectra with z_{em} relatively small, on the intrinsic hypothesis. Let $R \equiv (1+z_{\text{em}})/(1+z_{\text{abs}})$, where z_{em} and z_{abs} are, respectively, emission and absorption redshifts. The apparent ejection velocity is
$$\frac{v_{\text{ejection}}}{c} = \frac{R^2 - 1}{R^2 + 1}$$

The maximum ejection velocity that can be achieved for positive z_{abs} is given by substituting $R_{\text{crit}} = (1+z_{\text{em}})$ in this relation:

$$\frac{v_{\text{ejection}}(z_{\text{abs}} > 0)}{c} \leq \frac{(1+z_{\text{em}})^2 - 1}{(1+z_{\text{em}})^2 + 1} \quad (4)$$

For 3C 273, equation (4) yields $v_{\text{ejection}} < 0.15c$ for $z_{\text{abs}} > 0$. Thus for nearby quasars like 3C 273, the intrinsic hypothesis implies that many or most of the absorption lines (all with $v_{\text{ejection}} \geq 0.2c$) should be blueshifted!

The decision between the intrinsic and cosmological hypotheses can be made definitively with high-resolution, far ultraviolet observations of nearby quasars using the Space Telescope High Resolution Spectrograph. An appropriate complete sample can be defined as follows: all 3CR quasars with $z_{\text{em}} < 0.4$, $m_V < 18^m$, $\delta > -5^\circ$, and with intrinsic brightnesses one magnitude or more brighter than the brightest cluster galaxy (with $q_0 = 0$ evaluated at $\lambda_0 = 2500 \text{ \AA}$). There are six members of this sample: 3C 48, 3C 249.1, 3C 273, 3C 277.1, 3C 323.1 and 3C 351.

A search for Lyman-alpha halos can provide a different test for the origin of quasar absorption lines. The basis for this test has been discussed by Goldreich and Sargent (1976), Davidson (1977), Sargent and Boroson (1977), and Davidson (1979); these authors have also presented observational results on the absence of halos for some large redshift quasars.

The basic idea may be stated simply. Many high-redshift quasars show appreciable absorption of the Lyman continuum (see Osmer 1979), often at the redshift corresponding to an absorption system. If the absorption occurs locally (i.e., the absorption is "intrinsic"), then of the order of one

Lyman-alpha photon will be reemitted for each absorbed Lyman continuum photon. These reemitted photons may be detected as a "halo" if the absorbing clouds are located at observable distances from the quasar. Estimates of the expected fluxes are given in the above-cited references.

Abortive searches for Lyman-alpha halos have been carried out for several large redshift quasars on distance scales that correspond to between 10 kpc and 500 kpc at the quasar. Space Telescope observations will allow much smaller radii, r_0 , to be explored:

$$r_0 \approx 0.46 \left(\frac{\theta}{0.1''} \right) \left(\frac{z_{\text{QSO}}}{0.16} \right) h_{50} \text{ kpc} . \quad (5)$$

The relatively small sky-correction will represent an additional advantage (for this problem) of ST observations over ground-based experiments.

It will be particularly interesting to observe at the smallest possible distances, r_0 , quasars that have broad absorption lines (analogous to PHL 5200 and Q 1246-057), which most observers have interpreted in terms of material flowing out of the quasar.

The crucial instrumental requirement will be appropriate interference filters for the cameras so that redshifted Lyman-alpha lines can be observed.

5. ABSORPTION SPECTROSCOPY

Distant sources of ultraviolet radiation can be used as continuum probes to search for gas in known relatively - nearby systems. If any appreciable amount of gas is present (column density of $\text{HI} \gtrsim 10^{13} \text{ cm}^{-2}$), absorption lines will be produced by the resonant transitions listed in Table II and will be observable in the ultraviolet with ST spectrographs. I discuss next several classes of objects whose gaseous content we would very much like to study in this way.

5.1 Clusters of Galaxies

Rich Abell clusters may have halos with radii as large as 10 Mpc and a local number density of order $6 \times 10^{-7} \text{ Mpc}^{-3}$ (N. Bahcall, 1977). Thus the product $R^2 N(0)$ may be as big for Abell clusters as it is for the postulated large galactic halos (cf. equation 2b). Independent of the contribution of clusters of galaxies to the known large-redshift absorption line systems, (see section 2 for a discussion of this possibility), one would like to study the distribution, compos:

tion, extent, and physical characteristics of moderate-temperature gas in clusters of galaxies.

Lists of quasars behind clusters of galaxies have been compiled, for this purpose, by Bahcall (1969a,b). More recently, Peterson (1978) has searched unsuccessfully for 21 cm absorption in the radio spectra of quasars behind Abell clusters. ST observations should permit searches for Ly- α lines that are of order 10^7 times more sensitive than the 21 cm studies. Moreover, one can also investigate the presence of moderately-ionized heavy elements using the lines listed in Table II.

5.2 Large Galactic Halos

Quasars can be used also to study the gaseous content of large (≥ 100 kpc) galactic halos of nearby galaxies. There are many galaxies within 10 Mpc distance of our Galaxy for which the postulated large galactic halos would subtend at earth full angles of several degrees or more. It will be easy therefore to locate by standard techniques relatively bright quasars behind the supposed large galactic halos and test for the present existence of gas in these halos. The strong ultraviolet lines listed in Table II will produce observable absorption lines at the redshifts of the nearby galaxies if the corresponding ions are, as postulated (Bahcall and Spitzer 1969), present in large halos.

The galactic halos that may be observed in nearby galaxies might be different in size, chemical composition, and ionization characteristics from the corresponding galactic halos at large redshifts. For example, the evolution of massive stars may have polluted the nearby halos. Also, the recombination time at the illustrative temperatures and densities considered by Bahcall (1975) is less than the Hubble time. In the model proposed by Sarazin (1979), supernovae remnants produced during the formation of a galaxy, absorption systems are much more likely at large redshift than small redshift.

Fortunately, the study of the gaseous content of large halos of nearby galaxies is interesting in its own right, irrespective of its possible connection with the observed absorption lines in large redshift quasars. The physical conditions in the gas of the halos may be an important clue in the study of galaxy formation. The composition of the gas will indicate to what extent stellar evolution and supernova explosions have contributed processed material to the halos.

5.3 Ly- α Systems

The ST spectrographs can be used to study the absorption

systems shortward of the Ly- α emission line in relatively bright, small (emission-line) redshift quasars. The observed spectra may be somewhat less crowded than for large redshift quasars.

It should be possible to test directly the Lynds' (1971) interpretation of large redshift spectra (in terms of Ly- α lines) by searching for the other members of the Lyman series in the spectra of relatively bright quasars (e.g., 3C 273). It will also be important to test whether or not the observed Ly- α lines are "split" into subsystems separated by $\sim 10^2$ to 10^3 km/sec.

The Ly- α clouds may correspond to objects with observable radio or optical counterparts. Sensitive radio and optical studies of small-redshift Ly- α absorption systems will be of great diagnostic value.

6. SPECIAL PROJECTS

In this section, I will discuss five special projects, each (I believe) of great interest.

6.1 The D/H - ratio

The D/H - ratio is of cosmological importance (see Wagoner 1973) if it can be demonstrated that the observed ratio is a constant (or the variation can be understood in terms of local environmental effects). The conventional Big Bang cosmology predicts that D/H is independent of redshift for all measurable redshifts.

It should be possible to observe the D/H ratio at absorption redshifts that are sufficiently large so that several Lyman lines are observable (for consistency checks). Thus for $z_{\text{abs}} \geq 0.15$, Lyman lines through Ly- δ are redshifted into the region accessible with ST spectrographs ($\lambda \geq 1100$ Å). The separation of the Lyman lines for deuterium and hydrogen is $\Delta\lambda_{\text{rest}} \approx 0.3$ Å. In principle, it is possible and important to try to measure the D/H ratio with ground-based observations at large z_{abs} , but small z_{abs} offer advantages that include the possibility of using brighter sources and less crowded spectra.

The small z_{abs} analogues of the Ly- α systems observed at large z_{abs} may be especially suited to the determination of D/H. For these systems, the saturation of the Lyman lines, the contamination by other lines, and the disentanglement of the separate cloud complexes may produce relatively few complications. One will want also to try to measure the D/H - ratio

in gas within clusters of galaxies and in large galactic halos.

Many of the appropriate procedures and complications have already been discussed by Vidal-Madjor et al. (1977) and Rogerson and York (1973) in connection with their determinations of D/H in interstellar gas illuminated by nearby bright stars.

6.2 He/H

In large redshift quasars, the helium resonance lines will be observable, He I $\lambda\lambda$ 584.3, 537.0, 522.2 Å at $z \geq 1.1$ and He II λ 303.9 Å (and 256.4 Å) at $z \geq 2.6$ (and 3.3). It may be possible, therefore, to determine the helium to hydrogen ratio in some large- z objects by studying absorption systems that show He I and He II absorption as well as several of the hydrogen Lyman lines. The ionization of hydrogen can be estimated approximately from the relative strengths of observed lines from other elements, e.g. lines from O I, O II, and O III (see Tables 2 and 3) or N I λ 1134.6 Å and N II 1084 Å. Studies of systems with $z_{\text{abs}} \geq 2.6$ will be especially interesting since for them one may be able to measure the strengths (or upperlimits) of lines from H I, He II, O I, O II, and O III (as well as N I and N II).

6.3 Other Short Wavelength Lines in Large z_{abs} Systems

Table III suggests a number of other important projects that can be accomplished by studying the very short-wavelength lines in large z_{abs} systems. The C IV resonance line at 312.4 Å is of special interest. C IV doublets at $\lambda\lambda = 1548.2$ Å, 1550.8 Å have been used as the basis for identifying many of the absorption systems containing metals in known large redshift quasars. The line at 312.4 Å is the 25 to 3 p transition corresponding to the 25 to 2 p doublet at 1549 Å (the 312.4 line is actually a doublet with a splitting of 0.04 Å). Searches for the C IV line at 312 Å in large redshift quasars ($z_{\text{em}} > 2.5$) will be of great importance in testing the validity of the many identifications based on the longer-wavelength C IV doublet.

Note also that one will be able to study the detailed ionization structure of several important elements by combining observations of the lines in Tables 2 and 3. In large z_{abs} systems, this will be possible by observing lines in Table II with ground-based instruments and lines in Table III with ST spectrographs. Of special interest are systems containing N I - N V, O I - O VI, and Ne I - Ne V/II.

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Table III. Some Shortwavelength ($300 \text{ \AA} < \lambda < 950 \text{ \AA}$)
Absorption Lines That Are Expected To Be Strong

Ion	$\lambda_{\text{vacuum}} (\text{\AA})$	Ion	$\lambda_{\text{vacuum}} (\text{\AA})$
He I	584.33, 537.03, 522.21	Ne IV	543.88, 42.08, 541.12
He II	303.80	Ne V	586.42, 480.41, 357.196
C IV	312.43		(+ ex. f.s.)
N II	915.60, 644.62	Ne VI	558.59, 433.18, 411.14, 399.82, (+ ex. f.s.)
N III	989.79, 763.34, 685.00, 451.87, 374.20	Ne VII	465.22
	(+ ex. f.s.)	Ne VIII	770.40, 780.32
N IV	765.14	Na II	376.38, 372.07
O II	834.46, 833.33, 832.75, 539.09, 529.55, 539.85, 430.1	Na III	378.14
		Na IV	410.37, 408.68
		Na V	463.3, 461.05, 451.9
O III	832.93, 702.33, 507.39, 305.60	Na VI	489.57, 414.35, 311.93
	(+ ex. f.s.)	Mg IV	321 (+ ex. f.s.)
O IV	787.71, 608.40, 554.07, 553.33	Mg V	353.09, 351.09
	(+ ex. f.s.)	Mg VI	403.32, 400.68, 399.29
O V	629.73	S V	786.48
Ne I	743.70, 735.89	Fe V	536.4 (+ ex. f.s.)
Ne II	460.73		
	(+ ex. f.s.)		
Ne III	489.50, 488.10, 313.05 (+ ex. f.s.)		

6.4 Astrophysical Analyses

ST observations will make possible detailed studies of the characteristics of the gas that produces the known absorption systems, as well as the gas that will (hopefully) be identified with the large halos of galaxies and clusters of galaxies. The wide range of elements and ion states that are accessible to ST spectrographs is evident from the lists given in Tables II and III.

Chemical abundances, ionization conditions, densities, and column densities can all be derived by standard models of analysis. New insights into the evolution of galaxies and clusters of galaxies should result from the study of gas that (I expect) will be discovered in the halos of galaxies and clusters of galaxies. The techniques that have proven valuable in the study of interstellar gas in the Galaxy will

be of great importance for studies of the intergalactic gas accessible to ST. The existence of "splitting" among known redshift systems suggests that multi-cloud models of the absorption systems will be necessary in the analysis. An exemplary multi-cloud study has been described recently by Boksenberg, Carswell, and Sargent (1979), in their analysis of (necessarily limited) ground-based observations of a $z = 0.4$ absorption system in the spectrum of Pks 0735 + 178.

There may well be molecular hydrogen bands (Lyman bands $\sim 1108 \text{ \AA}$ and Werner bands $\sim 1008 \text{ \AA}$), or dust absorption features in some cooler absorption systems. It will be important to search for H_2 and dust features in order to delimit further the physical processes and conditions.

6.5 Evolution of Absorption Systems

The evolution of absorption systems can be measured by comparing the spectra of a representative sample of large-redshift quasars observed in the visible with ground-based telescopes to the spectra of a similar sample of small-redshift quasars observed in the ultraviolet with ST. The observations should be carried out by observing for both the small and large redshift samples the same lines at the same resolution and sensitivity in equivalent width in the rest frame of the quasars. These studies will provide unique information about the evolution of the gas revealed by quasar absorption studies.

VII. A SAMPLE OBSERVING PROGRAM

An illustrative observing program based on the discussions of § 5 and § 6 is shown in Table IV. In compiling Table IV, I have assumed that all spectroscopic observations were carried out at a resolution of $R = \lambda/\Delta\lambda = 2 \times 10^3$, unless specified otherwise. At this resolution, it will take (see Bahcall and O'Dell 1979 and references quoted there) of order 20 minutes to obtain a spectrum of a $V = 17^m$ object, with $F_\nu \propto \nu^{-1}$, at a signal to noise ratio of 10. The total telescope time required to complete the initial phases of all the projects listed is of order 17 days, if the time spent integrating on an astronomical object is of order one-third the allocated time on the telescope. Most of the time would be spent using the HRS. A resolution of $R = 2 \times 10^3$ for a small z_{em} object corresponds to resolution in quasar frame of order 1.8 \AA . This is to be compared with the highest-resolution ground based studies, which are typically 1 \AA in the observed frame or of order 0.3 \AA in the quasar's frame. Thus the best FOS resolution, $R = 1.2 \times 10^3$, is not sufficient for a number of the projects that I have described.

Table IV. A Sample Observing Proposal

(Telescope time = $3 \times$ Observing Time, $l = 2$ hr. for $V = 17^m$, $R = 2 \times 10^3$, $S/N = 10$)

Observation	Instrument	Initial Number of Objects	Total Telescope Time (days)
Number of Absorption Systems in Small z emission Spectra	HRS (FOS)	6	1 1/2
Lyman- α Halos	FOC	10	6
Halos of Cluster of Galaxies	HRS, FOS	15	4 1/2
Galactic Halos	HRS	20	6
Ly- α Systems	HRS, FOS	3	3
Other Lines Splitting	HPS ($R = 2 \times 10^4$)	3	12
D/H	HRS ($R = 2 \times 10^4$)	5	48
He/H	FOS, HRS	5	3
Astrophysical Analyses	HRS ($R = 2 \times 10^4$)	3	12
<u>Evolution</u>	FOS, HRS	5	<u>3</u>
Total			99

My own guess is that the above estimate of the total required telescope time is probably optimistic by a factor of two or more. I have not taken account of the fact that, among other things, many instruments perform in space less well than their design specifications.

Nevertheless, the amount of important science that potentially can be performed in a few months of telescope time using the Space Telescope is awesome.

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DISCUSSION

Boksenberg (Discussion leader): I would like to make some supporting comments to Bahcall's excellent presentation.

First, we may distinguish between the absorption systems which clearly are intrinsic to the QSO or Seyfert galaxy and the others. The intrinsic systems are either very broad in velocity profile (PHL 5200 and Q1246-057 are interesting examples of this class) or show narrow-lined absorption from metastable levels which may also be variable (Markarian 231, NGC 3516 and particularly NGC 4151 - note these are all Seyferts). In no QSO yet observed is there absorption other than from levels of the ground state and in no case is variability observed. Again, unlike the bulk of the narrow-lined QSO absorption systems, these intrinsic systems are relatively close to the parent objects and there is no problem of enormous mass or energy requirements to explain their presence.

Next, we may identify those of the other systems which clearly are not intrinsic to the QSOs. Such a case is the absorption system observed in 3C232 at the same redshift as the nearby galaxy NGC 3067 in the plane of the sky. This system contains not only hydrogen (21-cm observations) but CaII (optical observations) and MgII, FeII (UV observations with IUE). The fact that the line of sight passes far outside the optical extent of the galaxy demonstrates that the effective cross-section of galaxies as manifested by absorption lines in QSO spectra is very large and indeed this is consistent with the observed frequency of such systems. That another similar case has now been observed (PKS 2020-370 and galaxies in Klemola 31) considerably strengthens this case. Yet another case of very direct support for this comes from the observation of an absorption system due to an intervening galaxy in the IUE spectrum of 3C273. In this case, the galaxy is our own. What is particularly interesting, and indicative, is that no other absorption lines are observed than those at zero redshift and that CIV is strong. The latter fact and the deduction that the absorption must be produced in the outer galactic halo, is then in conformity with the common observation of CIV in QSO spectra because the relatively large cross-section presented by such haloes of galaxies in line to the QSOs would give strong emphasis to its detection (CIV is not observed to be strong in the disc of the Galaxy).

Finally, I would like to touch on the question of the Lyman- α absorption lines. In the work by Sargent et al. described by Bahcall in his talk, we find a clear distinction between those absorption systems containing heavy elements and those showing only hydrogen lines. The heavy element systems show fine velocity structure, generally up to a few 100 km s⁻¹ as might be expected for galactic haloes, but the "pure" hydrogen systems do not. We also find that the hydrogen systems are

identical in their properties among all QSOs we have studied and show no evidence at all of clustering such as is demonstrated for galaxies. We conclude that these hydrogen systems, in contrast to the heavy element systems, represent cosmologically distributed primordial material, unassociated with intervening galaxies and are probably intergalactic clouds.

Savage: Our high resolution IUE observations of bright stars in the Magellanic clouds enable us to study the details of the absorption lines produced in the Galactic halo with 70 times the spectral resolution of the IUE spectrum of 3C273. We find broad strong absorption components having velocities $0 \lesssim v \lesssim 150 \text{ km s}^{-1}$ associated with ions of low (OI, SiII, CII) and high (SiIV, CIV) ionisation. NV absorption with the same profile has not been observed. These absorption features bear a remarkable resemblance to what one sees in QSO absorption spectra.

Burbidge: The OI absorption is very strong in those spectra, much stronger relative to CIV, for example, than in any QSO spectrum I've seen. Is it equally strong in all your Magellanic Cloud stellar spectra? In QSO absorption spectra at high redshifts, CIV is the most characteristic and most frequently seen feature.

Savage: All stars we have looked at in the Magellanic Clouds show strong OI. Our interpretation of the coexistence of the different stages of ionisation is that there is a hot medium embedded in which there are clouds of cooler material.

Sargent: A possible explanation of the point noted by Dr Burbidge is that at large redshifts, the haloes of galaxies are more highly ionised than they are at the present epoch because of the very much greater intergalactic flux of ionising radiation due to quasars. The increase in ionising flux is roughly $(1+z)^9$, 6 powers for the evolution of the quasar population and three powers for the volume factor. Thus, haloes are expected to be much more highly ionised at redshifts of 2 than they are now.

Burbidge: I shall not present any results or describe any programs underway with ground-based telescopes because I'd like to mention two specific kinds of observations needing ST. I'll not get into the discussion of location and origin of absorption features in QSO spectra because I'd rather hear Ray Weymann say something about the results of the survey by Weymann, Williams, Peterson, and Turnshek. This survey contains many objects, with homogeneous material.

The first ST observation I'd like to mention is to observe Ly α absorption in the lower-redshift lower-ionization systems showing MgII and FeII from the ground, where Ly α is only reachable by ST, and where Arthur Wolfe and colleagues are searching for 21-cm absorption.

Comparison of the strengths of Ly α and 21-cm can yield the spin temperature of the absorbing cloud, and hence bear on its location with respect to the energy source. The only case so far where he's been able to detect 21-cm absorption in such a system is 1331+170, and the spin temperature is high, 1000 K. I'd like this to be done for as many of the MgII/FeII absorption systems as possible.

Second, I'd like to comment on the QSOs with supernova-like absorptions, very broad, which Alex Boksenberg referred to. These are turning out to be more frequent than thought previously. They are characteristically high ionization systems; in the prototype PHL 5200 the continuum drops right down to essentially zero shortward of Ly α absorption, yet somewhere the continuum must pick up and provide high-energy photons, if photoionization is the mechanism. With ST we can follow these out into the UV, and also look to see what happens at the HeI resonance line.

Weymann: It seems very clear to me now that we are dealing with several different classes of absorption lines. Which class dominates depends upon the spectral and redshift ranges in which one looks. I identify 4 classes of absorption systems: (i) The supernova-type of absorption profile which is characterised by the absorption troughs seen in PHL 5200, (ii) halo-type absorption systems which are characterised by the presence of metal-enriched material, (iii) "primordial" Lyman- α absorption systems which appear to be relatively uncontaminated by heavy elements and (iv) absorption systems with small blue and redshifts with respect to the redshift of the quasar. This last class is most often seen as absorption features superimposed on the CIV emission line. These features are seen just as often to the red as to the blue of the line centre. i.e. literally interpreted the material is just as likely to fall in as be ejected from the quasar. My preferred explanation is that these absorption systems are clouds moving backwards and forwards with velocity dispersion which can be measured from the observations. Typically velocity dispersions of 700-1000 km s⁻¹ are found which are typical of rich clusters of galaxies and not of small groups and this is a difficulty. One would like now to measure these features in low redshift quasars, to measure the very much weaker CII lines as well and directly see if we can see these features in objects which are close enough to make direct studies of their environments.

Mortola: How many cases are there where halo absorption of QSO radiation at either 21 cm or CaII H and K has been searched for and not found ?

Boksenberg: I have been involved in searches in the spectra of 3 QSOs and we have had success in two cases. The third case is not yet fully analysed.

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RADIO ASTRONOMERS, X-RAY ASTRONOMERS AND THE SPACE TELESCOPE

M.S. Longair
Mullard Radio Astronomy Observatory,
Cavendish Laboratory, Cambridge, England.

My original brief was to cover all non-optical observations of all objects in the Universe but I have limited the scope of this presentation to the radio and optical wavebands and within them mostly to the study of extragalactic objects. The paper is in two parts. Sections 1, 2 and 3 contain some general remarks about the use of the Space Telescope and the study of objects in the radio and X-ray wavebands. The remaining sections outline the scientific objectives of a number of projects which involve observations with the Space Telescope.

1. INTRODUCTION

Every time a new waveband has been opened up, the astronomers working in this band do as much as they can using information specific to that waveband. The principal examples of this phenomenon are the early histories of radio and X-ray astronomy. For example, the large scale distribution of sources on the celestial sphere may indicate whether the objects are Galactic or extragalactic, source counts provide information about their distribution in depth and so on. In some cases, the information obtained may be sufficient to study the detailed astrophysics of the objects. Radio pulsars are an example in which the astrophysics is studied almost exclusively through their radio properties. Similarly, much can be learned from the observation of X-ray emission and absorption lines from all types of X-ray source.

It is generally true, however, that following this initial phase, the non-optical astronomer is heavily dependent upon optical observations for much of the information which is crucial in studying the new astrophysical problems which arise from his observations. The obvious questions are: What sorts of objects are the sources associated with, how are their optical counterparts different from other similar objects, how common are these objects in the Universe, what are their distances and so on. Generally speaking these are questions which can only be answered by making observations in the optical waveband.

This is not a one way process in which the non-optical astronomer requires his optical colleague to perform a service function. The optical astronomer reaps the benefit of making important discoveries. Probably the most striking example of this was the discovery of quasars which arose directly out of optical identification programmes of extragalactic radio sources. Significant contributions to the detailed understanding of high energy astrophysical objects have been made in many fields. For example, observations of the primary stars in X-ray binary systems, the discovery of the optical counterpart of the pulsar in the Crab Nebula and the discovery of significant differences in the spectroscopic properties of radio galaxies and other active systems.

It is therefore evident that there will be considerable demand for Space Telescope observing time from non-optical astronomers. It should be noted that many of these programmes will be at the forefront of important areas of research and thus they are likely to be rated highly when the final allocation of time is made. It should also be noted that, in many cases, the driving force for making observations will come from the radio and X-ray astronomers so that the pool of potential Space Telescope observers will be significantly increased.

My task is to predict what these demands are likely to be. Plainly, this is a task even more impossible than those of other speakers at this colloquium. A field in which my information is based on rumour and hearsay is the new data from the Einstein X-ray observatory (HEAO-2). I hope that the HEAO 2 observers present will be able to describe what they foresee as the new demands stimulated by their magnificent X-ray observatory. In excuplation of this lacuna in my knowledge, I believe that many of the optical demands will be similar to those of radio astronomers with which I am much more familiar.

2. PRELIMINARY REMARKS

As everyone is aware, there will be considerable pressure to carry out programmes which make the fullest use of the unique capabilities of the Space Telescope. To oversimplify grossly, these unique features are:

- (a) the observation of all objects at the diffraction limit of a 2.4 metre telescope, i.e., with angular resolution $\lesssim 0.1$ arcsec;
- (b) photography and spectroscopy of all objects in the ultraviolet waveband, $110 < \lambda < 320$ nm, with very high sensitivity.

In devising observing programmes, the following points should be borne in mind.

- (i) Despite these unique capabilities, there are many types of astronomy which are not appropriate for the Space Telescope and are better executed from the ground. For example, there is relatively little advantage in studying extended objects such as diffuse galaxies

or the optical emission from the lobes of radio galaxies if there is little fine structure on angular scales $\theta \lesssim 1$ arcsec. Intermediate and high resolution spectroscopy in the optical waveband demands sheer photon collecting power and thus a large ground-based telescope is to be preferred. Another example is the problem of measuring the spectra of normal galaxies at large redshifts to which I will return later. The specification of the Faint Object Spectrograph is such that it has relatively low sensitivity at wavelengths $\lambda \gtrsim 600$ nm. Another important restriction is that programmes requiring fields of view much larger than 3 arcmin make rather inefficient use of the Space Telescope since a mosaic of many Wide Field Camera frames would be required. There is thus much essential complementary optical work to be done from the ground.

(ii) The quality of Space Telescope observations will be consistently very high. All the data will come back in digital form, will be rapidly calibrated and presented to the observer in a form ready for scientific analysis. There are two related problems. First, do data of corresponding quality exist for complementary ground based observations? I know of many fields where this may well not be the case particularly in the field of photography. Second, it will be important to have access to detectors of similar quality to those to be flown on the Space Telescope for ground-based observations. In the case of spectroscopy, there already exists a wealth of ground-based experience with Digicon detectors and Image Photon Counting System. However, the CCD detectors and the two dimensional imaging mode of the IPCS are only now becoming available and then only at a few observatories. I will show later some examples of what can be done with these detectors in the field of the optical identification of radio sources. Many programmes which appear to be possible only from space are in fact possible from the ground. Scarce Space Telescope observing time can be very significantly saved if these high sensitivity detectors become generally available soon. In the case of X-ray astronomy, the pressures are even greater because the Einstein observatory is generating vast amounts of high quality material which will require large amounts of ground based observing time. There is not much time left before the first round of requests for observing proposals with Space Telescope will be issued.

(iii) The capability of taking deep photographs in the far ultraviolet will surely lead to discoveries and new understanding of all types of object in the Universe. Observing programmes must be flexible enough to capitalise on these discoveries. For example, the far ultraviolet morphology of galaxies in clusters will provide clues to their dynamical state and the role of intracluster gas in determining the morphological types of the galaxies.

A final preliminary remark concerns what I call the astronomical mode of use of the Space Telescope. There are three modes which I term the Astrophysical mode, the "Look and see" mode and the Serendipity mode. The astrophysical objectives of the observations are

monotonically less well defined along this sequence. The first mode has well defined astrophysical objectives, for example the determination of the physical conditions in and around an active nucleus. The "look and see" mode refers mainly to the use of the cameras with the highest possible angular resolution. The experience of radio astronomy indicates how dramatic an improvement of a factor of 10 in angular resolution is. The sort of result which may be found in the optical waveband is exemplified by observations using the 6-metre telescope of the Special Astrophysical Observatory which have shown that the nuclei of a number of active Markarian galaxies are multiple. Such a result can only be found from observations of an exploratory character. The serendipity mode is well-known - these observations will be of more or less random regions of sky which happen to fall within the fields of view of the cameras when another instrument is prime.

It is very important that the proper balance be maintained between the astrophysical and the look and see modes. The former provides the bread-and-butter of the observatory whilst the latter is likely to produce the most unexpected results.

3. THE SKY AT RADIO AND X-RAY WAVELENGTHS

There are significant methodological differences in the ways in which radio and X-ray astronomers select their targets for study as compared with optical astronomers. At optical wavelengths it has always been easy to observe the sky with high angular resolution and high sensitivity and millions of objects can be seen with small telescopes. In contrast, at radio and X-ray wavelengths, it is not easy to detect sources and telescopes have developed from relatively low resolution survey instruments with relatively poor sensitivity to the present generation of instruments which now have angular resolving powers similar to those of large optical telescopes and high sensitivity. In the former category one may include the 3CR and Parkes surveys of radio sources and the UHURU and Ariel V X-ray surveys. The present generation of telescopes in the latter category include instruments such as the Westerbork Synthesis Radio Telescope, the Cambridge 5-km telescope and the VLA at radio wavelengths and the Einstein observatory at X-ray wavelengths.

The total number of objects observed in these wavebands is very much smaller than those in the optical waveband and this means that it is much more feasible to undertake systematic studies of significant fractions of all known objects. It is also much easier to be confident about completeness limits because initially sources are discovered in surveys with low angular resolution and thus integrated flux densities are relatively easy to measure. For example, in the radio waveband at high flux densities at low frequencies, $S_{408} \geq 10$ Jy, there are only ~ 35 sources sr^{-1} in directions away from the Galactic plane. At a high frequency, say 5 GHz, the corresponding figure at 1 Jy is ~ 50 sources sr^{-1} . For the X-ray sky, the corresponding figures are ~ 15 sources sr^{-1} at a limiting flux density of 1 UHURU unit. When surveys

of very much higher sensitivity are performed, much larger surface densities are naturally found but even so it is only feasible to survey relatively small areas of sky. For example a typical 5C radio survey has limiting flux density 0.01 Jy at 408 MHz and the surface density of sources is $\sim 10^5 \text{ sr}^{-1}$. However, the typical survey area contains only about 250 sources. In the same way, a deep survey with the Einstein X-ray observatory has limiting flux density about 0.01 UHURU units but only a small area of sky is surveyed and typically about 20-30 sources are observed.

Much of the complementary optical work is thus concerned with relatively small samples of objects which are selected in an unbiased manner and consequently suitable for statistical analyses. This situation contrasts with the case of, say, galaxy counts which are plagued by all sorts of nasty selection effects which vary from one class of galaxy to another. The statistical properties of the optical objects found by radio and X-ray astronomers are correspondingly much easier to handle.

The significance of these remarks is best understood in the context of studies of the radio source population. I will consider this case first and show how the Space Telescope can play an important role in elucidating some of the central problems of extragalactic astronomy and cosmology.

4. EXTRAGALACTIC RADIO SOURCES

There are two separate aspects to the study of extragalactic radio sources, the astrophysics of individual objects and their distribution in space. The evidence on their spatial distribution will be presented first in order to define the cosmological problems which arise. How feasible it will be to pursue these studies using the Space Telescope is determined by consideration of the astrophysical properties of individual objects which will be given in the following sub-section along with other programmes of astrophysical importance.

4.1 The spatial distribution of extragalactic radio sources

The counts of extragalactic radio sources disagree with the predictions of all cosmological models in which it is assumed that the distribution of sources is uniform (Figure 1a and b). All uniform models predict a monotonically decreasing value of $\Delta N/\Delta N_0$ with decreasing flux density whereas at high flux densities $\Delta N/\Delta N_0$ increases with decreasing flux density. Even a value $\Delta N/\Delta N_0 = \text{constant}$ which is the case at the highest frequencies ($\nu = 5 \text{ GHz}$) is inconsistent with a uniform world model. A similar result has been inferred for quasars by application of the V/V_{max} test to samples selected according to strict criteria. In both cases it is inferred that there has been strong evolution of the average properties of sources with cosmological epoch in the sense that their comoving space densities were much greater in the past, i.e., radio sources and quasars were relatively much

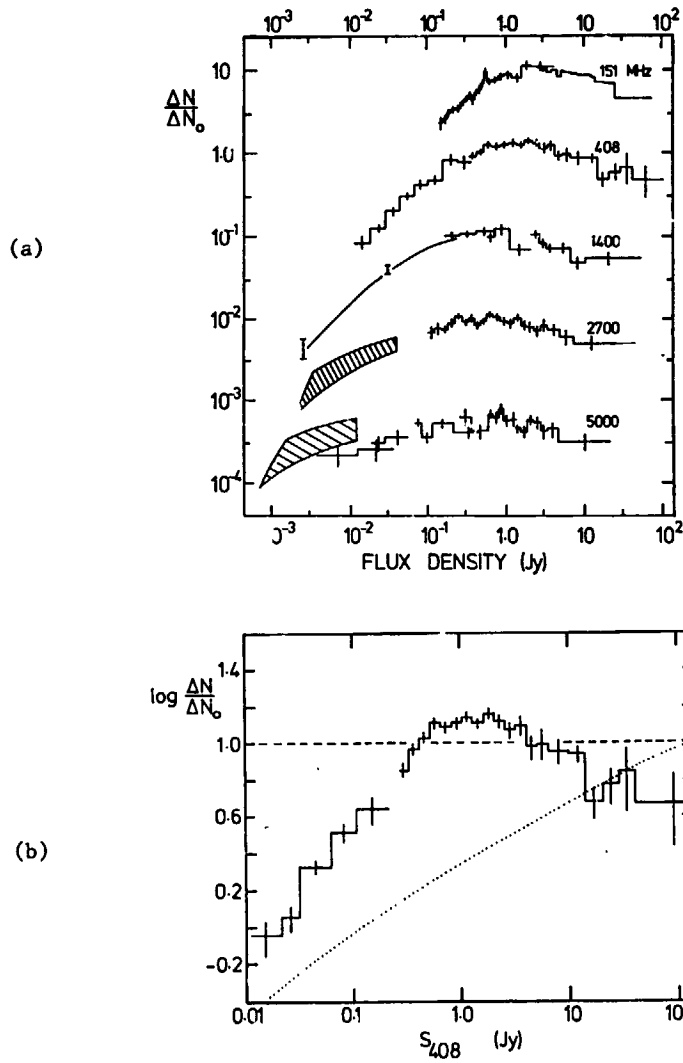


Figure 1 (a) Counts of radio sources at five frequencies in differential form. ΔN is the number of sources in the flux density interval S to $S+\Delta S$ and ΔN_0 is the expected number in a Universe in which $N(> S) \propto S^{-1.5}$ (Wall 1979).

(b) The differential source counts at 408 MHz compared with the law $N(> S) \propto S^{-1.5}$ (dashed line) and the expected relation for a Friedmann world model having $\Omega = 1$ assuming the sources are uniformly distributed (dotted line). (Wall 1979).

more common phenomena at earlier epochs.

The problems of understanding these results may be understood by considering the optical identification content and redshift distribution for a sample of 3CR radio galaxies which has been studied particularly intensively over the last 8 years. This sample is selected at high flux densities, $S_{178} \geq 10$ Jy, and includes the range of flux densities over which the anomalies in the source counts are observed. This work was only completed last week using results which will be described below and the sample is now effectively 100% completely identified (Figure 2a).

The identification situation is therefore very encouraging but redshifts are generally only available for objects with apparent magnitudes less than about 19.5. The redshifts are essential in a complete analysis because they determine how space is filled up with these objects. In this sample, the redshifts range from zero to about 2, all those with redshifts greater than 0.8 being quasars (Figure 2b). It is the combination of these data from the highest flux density samples plus the detailed knowledge of the source counts which lead to models of how the radio source population has evolved with cosmological epoch. The types of model which can account for all the data at low radio frequencies, 408 MHz, are shown in Figures 3a and b as contour plots of enhancement factors in a plane showing radio luminosity against redshift. Notice that the evolution is restricted to the highest radio luminosities i.e. to the classical double radio sources and quasars and that the enhancement factors are greater than 1000 in some regions of the diagram. This is exactly the sort of evolution which quasars alone are known to exhibit. The interpretation of this result is that at epochs in the relatively recent past, there was very much more high energy astrophysical activity than there is at the present epoch. All the models require the evolution to flatten off at redshifts $z \sim 2$ to 3 and some of them have cut-offs at redshifts $z \sim 3 - 4$. These results have important astrophysical consequences and it is important to make the models much more precise by incorporating information on larger samples of sources at lower flux densities.

The problem of extending these optical identification programmes to lower flux densities can be understood from Figure 2. Even at the highest flux densities, many of the objects are very faint optically and thus in deeper samples of radio sources extending to values about 1000 times fainter than the above sample, the optical counterparts of these radio sources will be very faint indeed. This has been found to be the case in the detailed studies of deep radio surveys. The deepest optical identification surveys at 408 and 1400 MHz have been able to achieve a success rate of at best 40% (de Ruiter et al. 1977, Perryman 1979). So far only optical identifications and colours have been available for these sources because they are mostly very faint.

The picture is somewhat different at high radio frequencies, 2.7 and 5 GHz, where a much larger fraction of sources with flat radio

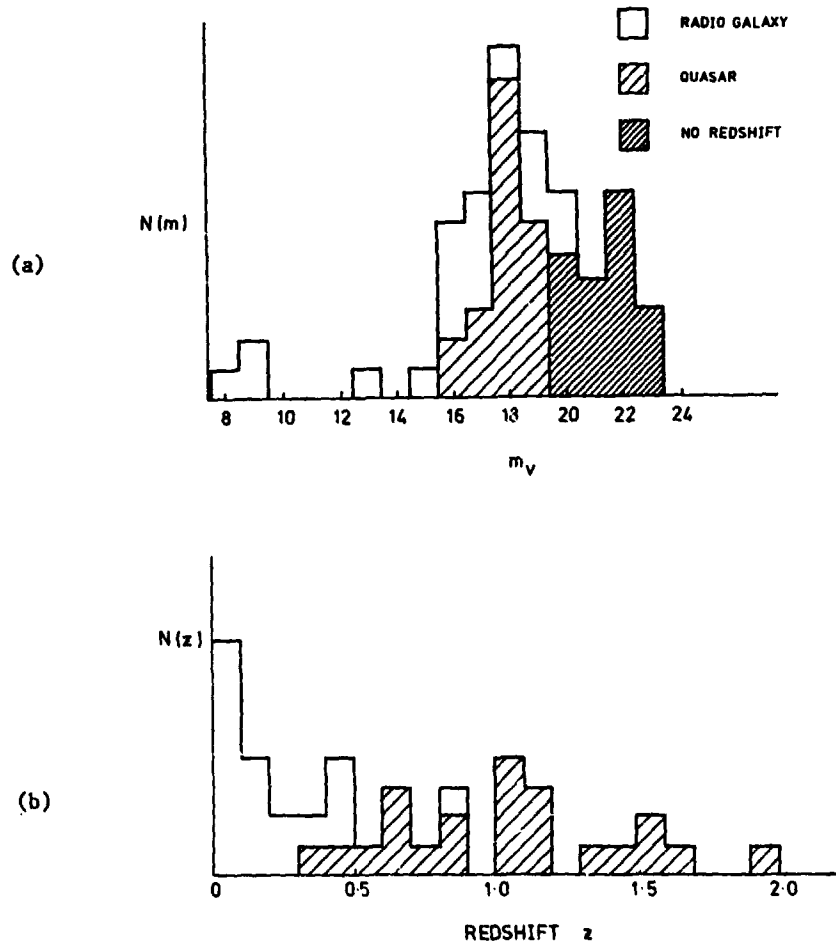


Figure 2 (a) The apparent magnitude distribution for a complete sample of 60 3CR radio sources all of which now have optical identifications (Gunn et al. 1980)

(b) The redshift distribution for the sample of 60 3CR radio sources. Redshifts are only available for 41 of these, the apparent magnitudes of those without redshifts being indicated in Figure 2(a).

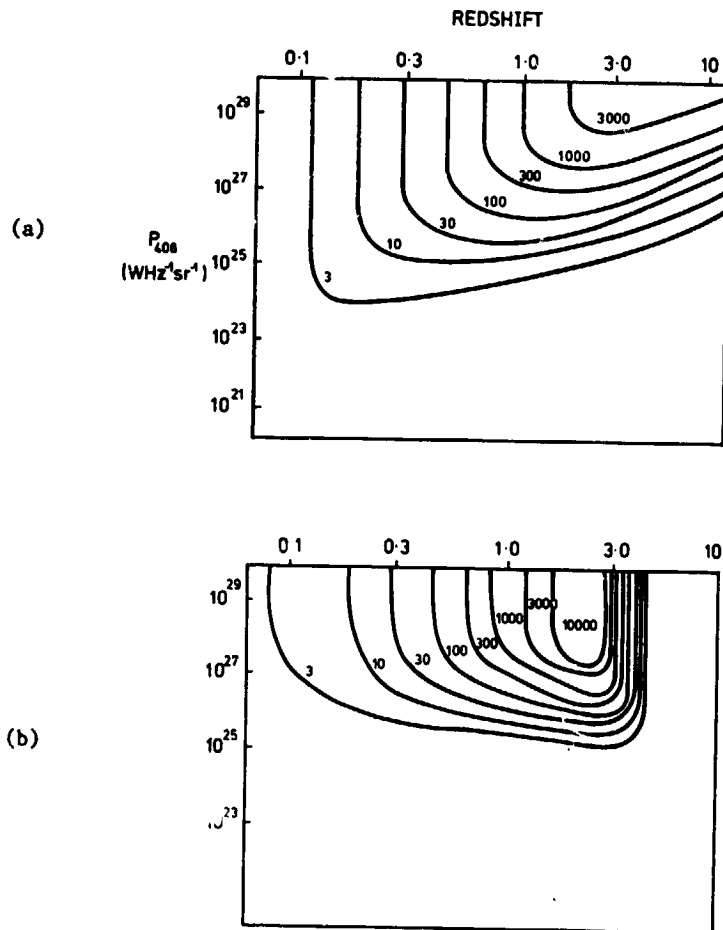


Figure 3 Two models for the evolution of the radio source population as a function of cosmic epoch (or redshift z) and radio luminosity. These models which are designed to account for the source counts at 408 MHz are models 5 and 4b (Figures 3a and 3b respectively) of Wall et al. (1977). The lines are contours of equal "enhancement factors" $f(P, z)$. For radio quasars at low frequencies $f(P, z) = \exp(M(t_0 - t)/t_0)$ where $M \approx 10-12$ and t is cosmic epoch.

spectra are observed. At high flux densities more than 50% of sources have flat radio spectra and a large fraction of these are quasars. The sources with steep spectra, similar to those found in low frequency survey, have source counts which are consistent with those of sources at low frequencies but the flat spectrum sources have a significantly flatter source count. If the counts are interpreted in terms of exponential evolution models of the form $f(z) = \exp \{M(t_0 - t)/t_0\}$ where t is cosmic time and t_0 the present epoch, the exponent $M \approx 10 - 12$ for sources with steep spectra but only $\approx 3 - 4$ for the flat spectrum sources. This result is again in agreement with the results of surveys of flat spectrum quasars using the V/V_{\max} technique (for detailed discussion, see Wall 1979).

There is thus a requirement for optical identifications, colours and spectra for statistical samples of sources at different flux densities at a wide range of frequencies to pin down exactly how the radio source population has evolved with cosmological epoch. Eventually, one might hope that one would understand why it has occurred as well, directly from the observational data. The question to be addressed is to what extent observations with the Space Telescope will help this programme. I believe that there are good grounds for believing that substantial advances will be made.

Before looking into that question, it is important to assess how much can be done from the ground. Our recent experience provides an important moral for all potential users of Space Telescope. For the last 7 years, Jim Gunn and I have been making systematic observations of the fields of 3CR radio sources. Up till this year, we have made observations with the Hale 5-metre telescope using IIIaJ plates with an image intensifier. We had considerable success in this programme but up till the beginning of this year, about 10 - 15% of 3CR sources remained stubbornly unidentified at our plate limits. This year, we were able to use the prototype CCD detector developed by JPL as part of the development programme for the Wide Field/Planetary Camera of Space Telescope. In a region of about 2 sr, there were 12 sources which were either unidentified or for which a very faint optical object required confirmation. With the CCD camera, we have obtained 100% success. Of these 6 are new identifications and 6 are confirmations. Figure 4 shows an example of the quality of the CCD images as compared with the 48-inch Palomar Sky Survey.

The moral is that if you can gain access to these advanced detectors, you may well be able to do from the ground programmes which initially look accessible only with the Space Telescope. Obviously, it is in the interests of all prospective Space Telescope users to have access to these devices. This will undoubtedly save a large amount of Space Telescope observing time.

4.2 The optical properties of extragalactic radio sources

The characteristic properties of the optical objects associated

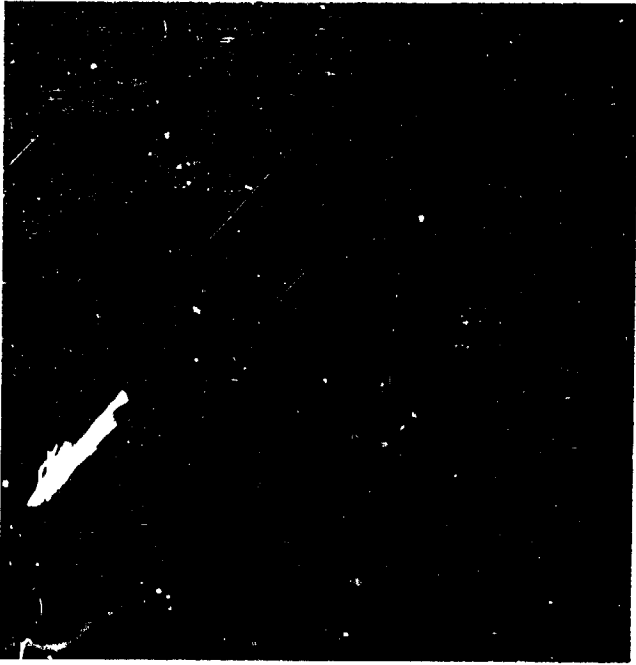
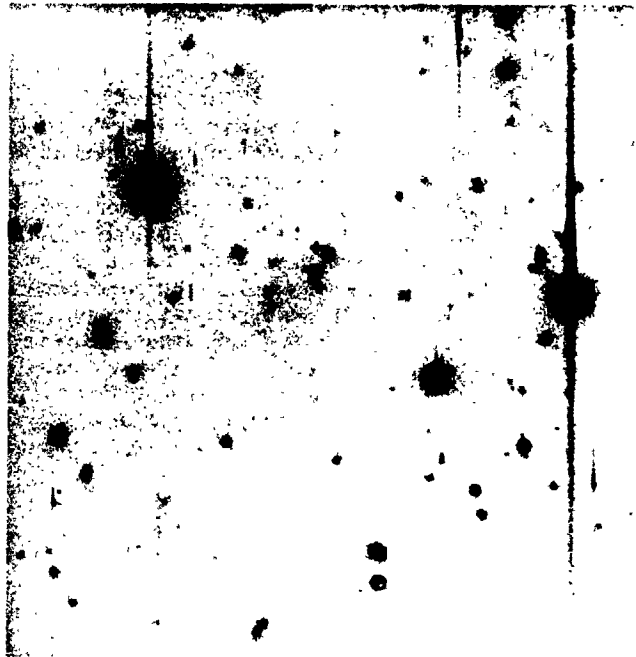


Figure 4. Comparison of the optical field of 3C 280 on the red print of the Palomar National Geographic Society Sky Survey and the CCD image of the area within the black square. The crosses on the latter picture indicate the maxima of the radio brightness distribution (Gunn et al. 1980).

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with extragalactic radio sources may be summarised under the following headings.

(i) The morphology of the optical identification. Of sources in high flux density samples at low frequencies, about 20 - 25% are quasars, the remainder being radio galaxies. In the samples studied to date, the quasars have a relatively uniform distribution of apparent magnitudes between about 16 and 20, with very few candidates for identification with quasars at fainter magnitudes. In contrast, most of the identifications with objects fainter than $m = 20$ are galaxies, although it becomes difficult to distinguish stars from galaxies at the very faintest magnitudes studied. At high frequencies, quasars form a very much larger fraction of the total, mainly because of the much higher proportion of sources with flat spectra. For the steep spectrum quasars, the percentage is the same as in the low frequency samples but for flat spectrum objects about 60% are quasars (Peacock and Wall 1980). The N-galaxies form a significant fraction of all radio galaxies, about 10 - 20% of the radio galaxies in high flux density samples being of this type.

(ii) Correlations with intrinsic optical magnitude. The majority of radio galaxies observed in high flux density samples have absolute optical magnitudes similar to those of the brightest galaxies in clusters. At low radio luminosities, $P_{178} \lesssim 10^{24} \text{ W Hz}^{-1} \text{ sr}^{-1}$ there is a weak correlation between the radio and optical luminosities of radio galaxies so that the weakest radio emitters are of lower absolute optical magnitude, e.g., Auriemma et al. (1977). Those radio galaxies which have strong compact central components in their nuclei in addition to the extended radio structure generally possess significant non-thermal optical emission from the nucleus. Indeed the total optical luminosity of radio galaxies can be synthesised by adding to the standard luminosity of a giant elliptical galaxy a non-thermal optical component. As the relative strength of the non-thermal optical component increases, N-galaxies and quasars may be accommodated within the model.

Many of the most powerful radio sources are associated with quasars indicating an overall correlation between non-thermal radio and optical emission but there exist radio galaxies which are as strong radio emitters as quasars but which possess only weak or undetectable optical non-thermal emission. The most famous examples of the latter are Cygnus A and 3C 295. There must therefore be a wide dispersion in the relation between total radio luminosity and optical luminosity.

A significantly stronger correlation is found if only the central non-thermal and optical luminosities are considered. Those sources which possess the strongest central radio components also have the strongest non-thermal optical emission and almost invariably those with no central radio component turn out to be associated with radio galaxies with no evidence of a central optical component. The quasars fall naturally into this sequence.

(iii) Correlation of optical spectral type with radio luminosity.

The proportion of radio galaxies with strong emission line spectra increases with increasing radio luminosity. For very weak radio galaxies $P_{178} < 10^{24} \text{ W Hz}^{-1} \text{ sr}^{-1}$, only about 10% of radio galaxies possess strong emission line spectra, the remainder showing either weak emission lines or a pure absorption spectrum. With increasing radio luminosity, the percentage of sources with strong emission line spectra increases. For the highest radio luminosity classes, the percentage is about 70%, there remaining a significant fraction which have no strong emission lines. These conclusions are based upon detailed studies of all the radio galaxies in the 3CR catalogue with measured spectra (Hine and Longair 1979). This is an important result because the radio luminosities of the faintest identified radio galaxies are inferred to be large and thus there is a good chance that many of them will possess strong emission line spectra which makes the determination of their redshifts much easier.

We have also found that the sources with strong emission line spectra are almost exclusively classical double radio sources in which the maxima of the radio brightness distribution lie towards the leading edge of the radio source structure. Since these are invariably sources of high radio luminosity, it is possible to predict those sources whose redshifts are likely to be measurable.

(iv) Broad and narrow line radio galaxies. Osterbrock and his colleagues (e.g. Osterbrock 1977) have shown that the radio galaxies with strong emission line spectra can be divided into two classes similar to the distinction between Seyfert I and II galaxies; they are known as broad line and narrow line radio galaxies (BLRG and NLRG). The NLRGs are apparently indistinguishable from Seyfert II galaxies. There are however, significant differences between the BLRGs and Seyfert I galaxies, the radio galaxies having weaker FeII emission lines, stronger lines of O^{++} and steeper $H\alpha/H\beta/H\gamma$ ratios. We find that there is a correlation between the breadth of the emission lines and the luminosity of the central radio component. Again, it appears that this correlation extends to the quasars studied by Miller and Miley (1979). The latter authors also found a significant difference between the line profiles of those radio galaxies which possess extended radio structure and those which do not. The extended radio sources possess significantly broader and more complex line profiles than do the compact radio sources.

(v) Clustering of galaxies about extragalactic radio sources.

There has been considerable debate about the differences between radio galaxies inside and outside clusters of galaxies, the main observational problem being finding comparable sets of sources with comparable radio luminosities and morphologies. In a recent analysis of the clustering of galaxies about 3CR radio galaxies, we have used cross-correlation functions to describe objectively the degree of clustering about the radio source (Longair and Seldner 1979). For a complete sample of 3CR radio galaxies which have redshifts $z < 0.1$, we measured their cross correlation with the Lick counts of galaxies. The diffuse radio sources

with no prominent emission lines in the optical spectrum of the galaxy belong to associations of galaxies intermediate in strength between objects selected at random in the Universe and rich clusters of galaxies. On the other hand, the classical double sources belong at best to very weak associations. In fact, so far as their cross-correlation with galaxies in general is concerned, the classical double sources are indistinguishable from galaxies selected at random in the Universe. We have interpreted this result as meaning that on average, the galaxies which can become strong classical double sources must be essentially isolated galaxies - or rather galaxies which dominate the nearby intergalactic environment. If this result is confirmed by further observations, it suggests a way of finding galaxies as bright as the brightest members of clusters but without the cluster round about them. If used as standard candles there will be no corrections for dynamical friction or cannibalism. This result is similar to that of the quasars which are all classical double radio sources when observed in low frequency samples. They are very rarely found in rich clusters of galaxies. We believe the same physical processes are operating in both cases.

5. OBSERVATIONS WITH THE SPACE TELESCOPE

There are a number of distinct ways in which Space Telescope observations will advance these studies.

5.1 The optical identification of very distant radio sources

The Space Telescope is obviously the ideal instrument for studying the most distant quasars since its sensitivity is greatest for starlike objects. The technique of optically identifying radio sources provides one answer to the question "How do you find the most distant quasars?". In principle, those quasars with redshifts as large as 10 or even greater should be observable by Space Telescope if they exist. Unidentified radio sources which turn out to be very faint quasars when studied with the Space Telescope are prime candidates for "the most distant quasar". The best approach is to study complete samples of radio sources selected at flux densities considerably smaller than those studied in detail optically to date. Equally, at high frequencies, where a larger proportion of the sources are quasars, there is great incentive to extend the surveys to fainter flux densities. To pursue these studies, it is essential that high quality radio observations of these samples of sources are available and that all the complementary optical work has been completed from the ground. I expect these observations to give information about the reality of the cut-off at large redshifts or otherwise.

For radio galaxies, the gain in using Space Telescope might appear to be less because they are extended objects. Even at the most pessimistic level, it is worthwhile exploring these fields because the sky background is significantly fainter from space. Probably the standard giant elliptical galaxy will be observable out to redshifts $z \sim 1 - 1.5$. This provides a direct method for discovering giant elliptical galaxies

at large redshifts and may prove useful in studies of the redshift-magnitude relation. However, I believe the prospects of identifying distant radio galaxies are somewhat better than this might suggest because of the known facts about the optical properties of radio galaxies listed above. According to the models of the evolution of the radio source population, a significant fraction of sources in the flux density interval $10 > S_{408} > 0.1$ Jy are distant powerful radio galaxies. These are objects which on average have stronger non-thermal optical nuclei and strong emission line spectra. Thus there is evidence that these distant radio galaxies should be similar to the N-galaxies which should be identified to redshifts of 2 or more.

5.2 Are quasars really massive galaxies with hyperactive nuclei?

All the astrophysical evidence described above shows that the properties of quasars are continuous with those of strong radio galaxies which are giant ellipticals. It is very important to find out directly by observation of quasars with the highest angular resolution whether this is indeed true.

5.3 The redshifts of distant galaxies and quasars

For quasars, there should be little problem in measuring their redshifts because of their strong emission lines. Equally for those radio galaxies with strong emission line spectra, there should be little problem. One of the most intriguing questions about Space Telescope to which I believe there is no definite answer yet is how well it will be possible to measure the redshifts for distant galaxies. The problem is greatest for those galaxies with no prominent emission lines and only a pure absorption spectrum. At wavelengths $\lambda > 600$ nm, the sensitivity of the Faint Object Spectrograph is low and measurements of the spectra of faint galaxies in this spectral region will not be feasible. It is not clear that the transmission grating-diffraction prism in the Wide Field Camera will be able to measure low resolution spectra of galaxies in the red and infrared spectral regions and it is not clear what the limiting magnitude of these observations would be. How successful the measurement of redshifts by narrow band multicolour photometry with the Wide Field Camera will be is not yet known. It may be that in the end this programme will have to be carried out from the ground with long exposures using CCD detectors attached to spectrographs. The alternative would be to design a "distant galaxy" spectrograph for the next generation of instruments for Space Telescope.

5.4 The astrophysics of the nuclear regions of radio galaxies and quasars

This topic will undoubtedly be discussed in detail by other speakers at this colloquium. There are however distinct problems posed by spectroscopic observations of radio galaxies and the ultra-violet region of the spectrum remains more or less unexplored. The IUE satellite observatory has had considerable success in studying the

brightest quasars but this is only the tip of the iceberg. There is vast amounts to be done with the Faint Object Spectrograph on the bulk of known quasars which fall in the range of apparent magnitude $16 < m < 20$ which will all be readily observable in the ultraviolet with Space Telescope.

The problem of studying radio galaxies has proved very difficult and only in a few cases have successful observations been obtained with IUE so far. Only the brightest and strongest emission line objects have been readily observable. For example, we have recently had success in obtaining a good ultraviolet spectrum of 3C 390.3 which is a classical double radio source associated with an N-galaxy (Ferland et al. 1979). It has proved particularly interesting because the spectrum contains both broad and narrow line components and they can be easily separated. The Ly α to H β ratios are different in the two regions, being normal for the narrow line region and anomalous in the usual sense for the broad line region. We have also observed 3C 382 which shows evidence for major structural changes in the emission line profile of Ly α over a time scale of a year. However, these are very time consuming programmes with IUE. We have devoted 20 hours of observation in order to measure a good spectrum of 3C 390.3 and each short wavelength exposure of 3C 382 requires 6 hours of observation. With the Space Telescope these observations should take only about a twentieth of the time. This means that it will be feasible to study large samples of narrow and broad line radio galaxies in the ultraviolet for the first time.

5.5 Clustering of galaxies about radio sources

It would be very important if the clustering of galaxies about distant radio sources could be measured with the cameras on board the Space Telescope. As indicated above, the samples suitable for study so far are restricted to small redshifts. By going to faint samples of galaxies, one is investigating the clustering about the most powerful sources for which the evidence to date is fragmentary. The problem is that the fields of view of the cameras are small. Thus at cosmological distances, the physical size of the field observed by the Wide Field Camera is about 1.6 Mpc which is not large enough to measure the background of galaxies away from the cluster core. Some information will be obtainable about the clustering of galaxies about sources but ideally much larger fields are required.

5.6 The "look and see" mode and radio sources

As a matter of principle, I am sure that it will prove very revealing to look at a sample of brighter objects with the highest possible resolution to see what these optical objects look like. It may be that it will be possible to find non-thermal nuclear components in all strong radio galaxies. Other radio galaxies may possess compact non-thermal optical knots as in M87. There is recent evidence from the Westerbork workers that the colours of the faintest identifi-

cations which they have made are bluer than the normal colours of radio galaxies (Katgert et al. 1979). This may suggest significant colour evolution of these radio galaxies at comparatively recent cosmological epochs. This evidence is similar to the evidence on the colours of distant clusters and of the counts of galaxies where one reasonable interpretation is that the colour properties of galaxies change remarkably rapidly with redshift. If this is so, it can be readily checked by studies with Space Telescopes and will have substantial implications for the study of distant radio galaxies.

6. CONCLUDING REMARKS

I believe the sorts of observational demands which observers from non-optical wavebands will make upon the Space Telescope are similar to those described above for the radio waveband. These are optical identifications, the determinations of distances, the physical conditions in the objects derived from the optical and ultraviolet waveband, the comparison with other types of object of the same optical morphological types and so on.

Table 1

Topics of Central Importance to Radio and X-ray Astronomers discussed
in Other Lectures presented at the Colloquium

	<u>Radio</u>	<u>X-ray</u>
Planets	✓	
Supernovae	✓	✓
HII regions Planetary Nebulae }	✓	
Interstellar medium	✓	✓
Globular clusters		✓
Normal galaxies	✓	✓
Their evolution	✓	✓
Active nuclei	✓	✓
Absorption lines in quasars	✓ (HI)	
Clusters of galaxies	✓	✓
Cosmology	✓	✓

Taking a broader astronomical view of the subject, it is interesting that essentially all the invited lectures at this symposium are of great importance to the interests of non-optical astronomers. In Table 1, I have indicated those areas which are particularly significant for radio and X-ray astronomers. Observations of relevance to the high-energy astrophysics of all these classes of object have been made in the radio and X-ray wavebands and consequently will have an important bearing on observations with Space Telescope.

We should also be prepared for more speculative types of proposals. For example, the high resolution imaging of gravitational lens. There is the one possible example which has already been mentioned but of course many more quasars will be discovered by Space Telescope and the probabilities are not so small of finding a few examples. If there is optical emission associated with the superluminal expansions of compact radio sources, do we observe the centre of gravity of the optical image jittering on the scale of 1 - 10 m arcsec? The most exciting examples will be those that we have not thought about.

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DISCUSSION

Burbidge: This is a comment on the urgent need for ground-based work in preparation for observing with the ST and also a comment on a remark by Dr. Spinrad after Dr. Groth's talk in the session on ST instruments. Spinrad asked if the DOT were considering all the difficulties encountered by ground-based observers in working on really faint objects - putting the invisible object down the hole, making on-the-spot decisions etc. It is, of course, a very important problem for the FOS, and it is a software problem - to think of all the options and alternatives, and have pre-programmed choices which the observer can make. For the FOS Hollard Ford is the DOT team member and he is working on this, also Greg Schmidt at UCSD and co-investigator Bruce Margon. The programs ought to be thoroughly tested on the ground.

Van der Laan (Discussion leader): Our experience of nine years operation of the Westerbork Synthesis Telescope is that virtually no project in radio astronomy can be completed astrophysically without the use of complementary information from other wavebands, in particular optical, X-ray and UV data. In particular, as illustrated by the previous lecture, radio astronomers are addressing themselves particularly to the relation between the activity observed at radio wavelengths and the optical properties of the related objects.

I will give three examples from our current research programmes which illustrate these points and which will benefit from observations with the Space Telescope.

- (i) Is the optical jet in M87 unique? Van Breugel, Miley and Butcher have searched for optical jets in four radio galaxies which possess strong radio jets. In the cases of 3C66B and 3C31 they have found optical knots coincident with the local maxima in the radio jets. In addition, unresolved optical cores in the galactic nuclei have been discovered. These observations are at the limit of the 4-metre telescope and there will be advantages in pursuing these studies with the FOC and WFC of the Space Telescope. These observations provide important information about the processes of energy transport and transformation in radio galaxies.
- (ii) As mentioned in the previous lecture, we have found that radio galaxies at redshifts $z \gtrsim 0.5$ are excessively blue. The blue excess appears to be associated with extended objects but its nature is not at all clear. Is the light dominated by a non-thermal nuclear component or is the blue light associated with the stellar population?
- (iii) At Westerbork, we have been making complementary radio

observations to the deep X-ray survey fields observed with the Einstein X-ray observatory. Those objects which are simultaneously bright radio and X-ray sources are obviously important examples of high-energy astrophysical phenomena. This programme leads to much complementary optical work, first of all identification and cross-correlation of the radio and X-ray data and then optical spectrophotometry.

These programmes illustrate the importance of complementary optical work for radio and X-ray astronomy.

Burke: When the VLA is completed, it will consist of a Y-shaped array of 27 antennas, each 25-metres in diameter. The operating frequencies are 1.3, 2, 6 and 21 cms and provide maximum resolution ranging from 0.1 to 2 arcsec. The maximum sensitivity to faint objects is at 6 cms where the angular resolution will be 0.5 arcsec. Thus the angular resolution will be similar to that of the Space Telescope. At present, approximately half of the array is working and we can attain 0.8 arcsec resolution at λ 6 cm. In about a year the whole array will be completed and subsequently spectral-line facilities will become available. The sensitivity is currently a few tenths of a mJy with ultimate sensitivity limit about 0.1 mJy. The angular accuracy for astrometric work will be ~ 1 marcsec.

VLBI observations will also continue throughout the era of the Space Telescope, the current maximum angular resolution being 0.2 marcsec. Perhaps one day we will be able to do ten times better. There will also be other large powerful telescopes in operation throughout this era - the 1000-ft Arecibo dish, the 36-ft Kitt Peak millimetre telescope, the Westerbork Synthesis Telescope and the Cambridge 5-km telescope. All of these instruments will provide information supplementary to that provided by ST.

The types of astronomy to be done with these instruments is huge. One class of observation which has not been mentioned so far is that of stars. It was predicted theoretically that the thermal radio emission associated with mass loss from stars would be observable by radio means and this has indeed turned out to be the case. It has the advantage of being independent of temperature.

A major problem will be the oversubscription of observing time. Already the VLA in its incomplete state is oversubscribed by about a factor of 3. Cooperative programmes will have to be developed just as it proved to be essential for VLBI. The system must also be responsive to new discoveries. A good example is the recent discovery of the binary pulsar. It was possible to schedule "quick look" observations with the VLA which required in total only 42 minutes of observation. The subsequent cleaned maps showed radio components of roughly equal

intensities associated with each quasar but one of them also showed extended structure, not dissimilar from that of a typical radio galaxy and quasar. The observations are thus at present inconclusive. What is now required is a proper set of observations with much more complete filling of the aperture plane and this will be carried out in a more leisurely fashion as part of the normal observing programme.

Hemenway: The aim of the Texas radio survey is to provide large sky coverage for very large numbers of radio sources. Accurate radio positions (± 1 arcsec) are derived from interferometric observations at 335, 365 and 380 MHz for sources in the range $+70^\circ > \delta > -36^\circ$. The flux density limit will be about 0.25 Jy and we expect to observe more than 50,000 sources. We already have about 6700 sources in a 10° declination strip centred on $+18^\circ$. Optical identifications are being sought for all survey sources on glass copies of the O and E plates of the Palomar-National Geographic Society Sky Survey. The relative accuracy of the radio and optical positions should be 0.7 arcsec for all sources. We intend publishing finding pictures, radio positions, flux densities and other relevant information.

Vidal - Madjar: I wish to draw attention to the importance of a very restricted spectral range which will not be accessible to Space Telescope, i.e. the 900-1100 Å wavelength range. The observation of interstellar absorption lines in this wavelength range can provide important information which will supplement that obtained with the Space Telescope. Absorption lines due to many important ions and atoms fall in this wavelength range, including N, O, F, P, Cl, Ar, Zn for which depletion factors of 1 are found and Mg, Al, Si and Fe for which depletion factors $D \sim 0.1$ are observed, these figures reflecting the observational situation for slightly reddened stars. There are many important aspects of such studies but I draw attention to only a few of them.

- (i) The deuterium line can be observed only below 1100 Å and therefore this very important determination can only be achieved in this specific wavelength range.
- (ii) Above 1100 Å, the only available HI line is Ly α which is strongly saturated and which may lead to erroneous HI abundances especially if high velocity clouds are present along the line of sight. The observation of the other Lyman lines below 1100 Å provide crucial complementary information on which to base accurate determinations of the atomic hydrogen abundances.
- (iii) For NI, many unsaturated lines are available below 1100 Å whilst above 1100 Å the lines are most often saturated. It is important to obtain both sets of data in order to determine the structure along the line of sight. As illustrated by our recent work on the γ Cas line of sight (Ferlet, Laurent,

Vidal-Madjar and York, Ap. J., Jan 15, 1980) the weak lines allow the main components to be determined and the saturated lines show that some other weak components also exist along the line of sight. The combination of all NI lines leads to a structure along the line of sight involving 4 clouds.

Finally, we would like to know the total hydrogen abundance and for this we need to determine both HI and H₂ abundances. To determine the latter, it is necessary to determine abundances of H₂ from the different rotational levels. Most of these lines are below 1100 Å, a few of them being around 1100 Å.

Brandt: There will certainly be some response shortward of 1100 Å on the HRS, 25 perhaps even 50 and we should see some lines of H₂ and other important lines. It is not yet clear how well we can do this.

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PRECISE DETERMINATION OF THE DISTANCES OF GALAXIES

G. A. Tammann
Hale Observatories*,
Astronomisches Institut der Universität Basel,
and European Southern Observatory, Geneva

ABSTRACT

The Space Telescope shall be useful to check the local extragalactic distance scale to within 10-15 percent. It opens up the opportunity to determine relative distances of cosmic standard candles, viz. brightest M-supergiants and SNe I in E galaxies. The M-supergiants shall map the velocity field out to $v_0 \approx 3000 \text{ km s}^{-1}$ thus providing (1) a firm basis for the determination of H_0 (global) from local distances; (2) the possibility to derive precise distances of all nearby field galaxies from their recession velocities; and (3) in combination with the density profile of the Virgo complex an accurate value of the density parameter $\Omega/\Omega_{\text{crit}}$. Photometry of the SNe I out to $z = 0.5$ shall lead to a direct determination of q_0 via the Hubble diagram, and the form of their light curves offers a fundamental test on the nature of redshifts. The independent determination of $\Omega/\Omega_{\text{crit}}$ and q_0 shall give an estimate of the smoothly distributed, invisible matter in the universe and test the assumption $\Lambda = 0$.

1. INTRODUCTION

Except for the nearest galaxies, where the brightest stars (Cepheids, early and M-type supergiants, RR Lyr stars, etc.) can be resolved, there exists no single field spiral galaxy whose distance would be better known than within ~25 percent; and for early-type galaxies (E, S0, Sa) there is actually no way to determine their absolute distances.

It is therefore evident that the best distances to an

*Operated jointly by the Carnegie Institution of Washington and the California Institute of Technology

unlimited number of individual galaxies (and aggregates of galaxies) shall come from their (mean) recession velocities v_0 , corrected for all possible deviations from an ideal Hubble flow, in combination with the global value of H_0 . The deviations from an ideal Hubble flow can be mapped using relative distances only, and once this is achieved, the value of H_0 can be determined with much better accuracy than the distance to any individual galaxy, because H_0 is found from the mean of the ratios r/v_0 (corrected) for all galaxies for which estimates of the distance r are available.

After a short discussion of the status quo of H_0 (Section 2), the reasons are exposed why H_0 can presently not be obtained to an accuracy of better than 10-15 percent, and it is shown that several of these problems shall not be solved by the Space Telescope (Section 3), at least not with a direct attack. In Section 4 the possibilities of the Space Telescope are considered of checking the extragalactic distance scale within the before-mentioned accuracy out to ~ 10 Mpc using RR Lyr stars and especially Cepheids. The highly promising potentials of the Space Telescope to map the local velocity field by means of the brightest M-supergiants are developed in Section 5. Finally, it is shown in Section 6 that the search for and photometry of supernovae of Type I out to redshifts of $z = 0.5$ is feasible with the Space Telescope, and that the Hubble diagram of these objects offers a unique chance for the determination of q_0 .

2. H_0 FROM GROUND-BASED OBSERVATIONS

Probably the most objective picture of the present knowledge of H_0 comes from a comparison of the two most divergent views presently in the literature. Of these distance scales the one is proposed by Sandage and Tammann (1976 and references therein; hereafter referred to as the ST scale), the other one by de Vaucouleurs (1979 and references therein, hereafter referred to as the V scale).

As can be seen from Table 1, the distances of the V scale are on the average 18 percent smaller. There is a tendency of the differences to increase with distance: from 16 percent in the Local Group to 26 percent at the Virgo cluster. (Surprisingly the agreement of the mean distance of the M81 group --irrespective if this group is considered a physical entity or not--is almost perfect.)

The overall agreement is not too bad, indeed, and there is reason to believe that the discrepancies can be narrowed

Table 1: Comparison of ST and V Scales

Object	(m-M)° (ST)	(m-M)° (V)	(ST - V)
Within Local Group (n = 6)	---	---	0.32
M81 Group (n = 6)	27.56	27.54*	0.02
M101 Group	29.30	28.70*	0.60
Virgo Cluster	31.50	31.00*	0.50

*The published values are still based on a CSC-law of galactic absorption as derived from galaxy counts. Since it is now known that galaxy counts cannot yield the absorption at the poles (Noonan 1971; Heiles 1976) and that the galactic polar caps are essentially absorption-free (Sandage 1973, 1975, 1976a; Sandage and Visvanathan 1978; Burstein and Heiles, 1978), all moduli are reduced here to zero-absorption at the poles.

down in the near future. For instance, a great leap forward has recently been made with the Cepheids in LMC by Martin et al. (1979); they included infrared magnitudes of galactic and LMC Cepheids to control metallicity effects, and they based their zero-point not only on the Hyades modulus but also on purely physically derived distances from the Baade-Wesselink method. The resulting LMC modulus is 0.38 larger than that of the V scale, and since LMC is a fundamental local calibrator, the change shall perpetuate through the whole V scale with considerable weight. In addition, at the distance of M101 the V scale cannot explain why Cepheids have so far escaped detection, and the brightest blue stars in M101--now spectroscopically confirmed by Humphreys (1979a)--would be fainter than the brightest stars in the solar neighborhood, which seems unacceptable. Finally, there is a strong suspicion that the V scale suffers from a Malmquist-type bias at the distance of M101, which increases with increasing distance--exactly in the sense in which the Malmquist effect is known to act.

To illustrate this point it must be stated that the V scale implies an increase of H_0 beyond the Virgo cluster:

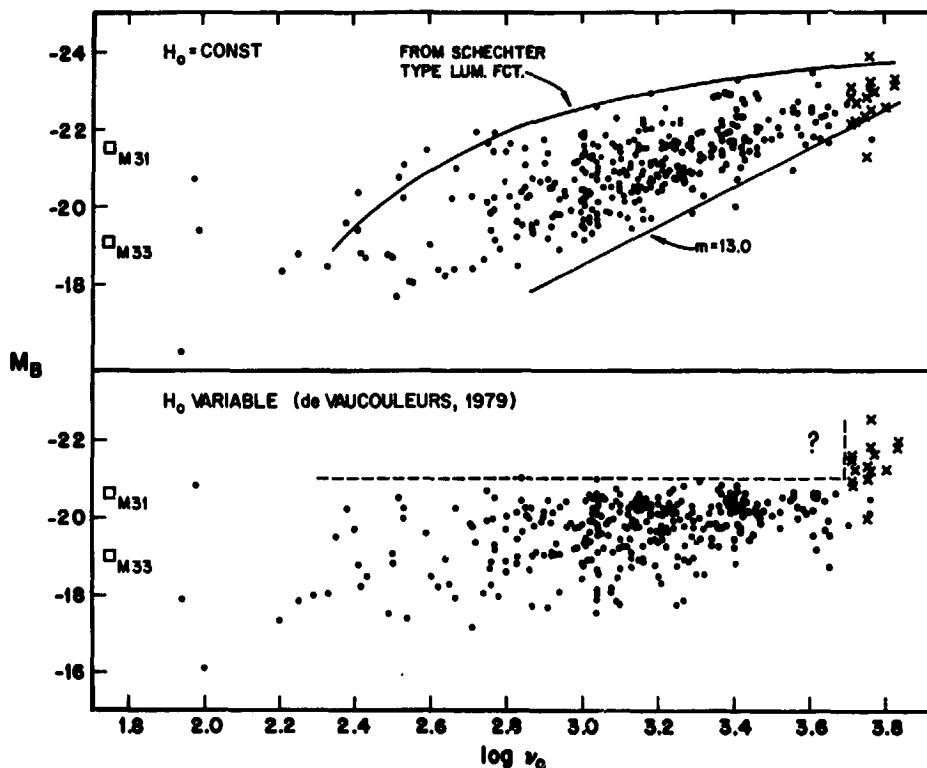


Fig. 1. Upper panel: The dependence of absolute magnitude M_B on $\log v_0$ for 327 spiral galaxies from de Vaucouleurs' (1979) list. The values M_B are derived assuming a uniform value of H_0 (here $H_0 = 50$). The point distribution is well bound by an upper envelope calculated from a Schechter-type luminosity function. The Shapley-Ames spiral galaxies with $v_0 > 5000 \text{ km s}^{-1}$ are also plotted (crosses); they fit smoothly to the upper boundary. — Lower panel: The same galaxies are plotted, but this time using de Vaucouleurs' (1979) individual distances and $H_0 = 90$ beyond $v_0 = 5000 \text{ km s}^{-1}$. The flat upper boundary and the jump in M_B at $v_0 \approx 5000 \text{ km s}^{-1}$ requires a strange luminosity function with a pronounced discontinuity at $M_B = -21^m$.

while it requires $H_0 \approx 70 \text{ [km s}^{-1} \text{ Mpc}^{-1}]$ at Virgo, it suggests $H_0 \approx 82$ at $v_0 \approx 3000 \text{ km s}^{-1}$ (these values hold after the above-mentioned absorption correction). It can easily be

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shown that this apparently modest change of $H_0(\text{local})/H_0(\text{global}) = 0.85$ already leads to unacceptable consequences. The V scale out to larger distances is defined by 327 spiral galaxies, which are drawn from an essentially *magnitude-limited* sample of galaxies and which are proclaimed to be somewhat biased toward *high-luminosity* galaxies; for these galaxies distances were determined by at least four different equations (de Vaucouleurs 1979; Table 1). Their implied absolute magnitudes are plotted against $\log v_0$ in Figure 1 (lower panel). The striking result is that the absolute magnitudes have a sharp upper bound at $M_B = -21^m$. This can only be explained if one assumes that spiral galaxies have a well-defined upper luminosity cutoff, because even the very large volumes surveyed at large v_0 do not provide any bright galaxies. However, if one uses the global value of H_0 of the V scale, i.e., $H_0 = 50$ (before galactic absorption correction in order to achieve consistency in Fig. 1), to determine the absolute magnitudes of all additional Shapley-Ames galaxies with $v_0 \geq 5000 \text{ km s}^{-1}$, one finds that most of them are much brighter than -21^m ! This result is equivalent to a very pronounced discontinuity of the galaxian luminosity function.

It was recently shown that the upper envelope in an M versus $\log v_0$ plot for an apparent-magnitude-limited sample of galaxies can be used to determine the galaxian luminosity function (Sandage et al. 1979). Instead of deriving the highly strange luminosity function from the lower panel of Figure 1, I have replotted the same 327 galaxies in the upper panel of Figure 1, this time using a *constant* value of H_0 (here $H_0 = 50$). In addition, an upper envelope was calculated from a Schechter luminosity function, using appropriate parameters for spiral galaxies (Tammann et al. 1979) and an appropriate normalization (Yahil et al. 1980). The good agreement of the *form* of the calculated envelope with the point distribution is strong support for the assumption that spiral galaxies have a normal Schechter-type luminosity function, if only one uses a correct distance scale, i.e., a uniform expansion field. That spiral galaxies conform indeed with the Schechter function is independently evidenced by the spiral members of the Virgo cluster (Tammann and Kraan 1972). (Note, the form of the luminosity function does not depend on the adopted value of H_0 , only on its constancy. Note also that the apparent excess of nearby bright galaxies in the upper panel of Fig. 1 is expected because of the local density anomaly due to the Local Supergalaxy.)

There are other observations which restrict the size of any peculiar streaming motions of galaxies, and hence of any variation of H_0 . The most stringent limits on such motions

are set by three *independent* methods, using relative distance indicators only:

(1) A comparison of field galaxies with known redshifts and Virgo cluster galaxies provides a predicted Virgo cluster velocity. Using surface photometry (Kormendy 1977), the color-luminosity relation of E and S0 galaxies (Visvanathan and Sandage 1977), and the apparent luminosity function of Shapley-Ames galaxies (Tammann *et al.* 1979a) predicts a mean Virgo cluster velocity of $1098 \pm 60 \text{ km s}^{-1}$ (Tammann *et al.* 1979b).

(2) On the reasonable assumption that the mean velocity of the Coma cluster of 6890 km s^{-1} reflects the cosmic expansion velocity to better than 90 percent, one can predict the Virgo velocity from the distance modulus *difference* of the two clusters. This difference is found to be $\Delta(m-M)^{\circ} = 3.88 \pm 12$ (Tammann *et al.* 1979b) using brightest cluster members (Sandage and Hardy 1973), the ten brightest cluster members (Weedman 1976), the color-luminosity relation of E and S0 galaxies (Visvanathan and Sandage 1977; data from Persson *et al.* 1979), and Type I supernovae at maximum light (Tammann 1978). The corresponding ratio of linear distance is 5.97 ± 0.34 , which requires a Virgo velocity of $1154 \pm 65 \text{ km s}^{-1}$.

The *observed* mean recession velocity of the Virgo cluster is $950 \pm 50 \text{ km s}^{-1}$ (Kraan-Korteweg 1979); this and the combined evidence from (1) and (2) indicates then that the Local Group has a peculiar motion toward the Virgo cluster of $174 \pm 74 \text{ km s}^{-1}$.

(3) An analysis of the magnitudes and velocities of the galaxies of the Revised Shapley-Ames Catalog (Sandage and Tammann 1980), making proper allowance for selection effects and all possible density fluctuations, yields a peculiar Local Group motion of $100 < v_{\text{pec}} < 200 \text{ km s}^{-1}$ in the direction of Virgo (Yahil *et al.* 1979); this result is derived by *excluding* the galaxies in the Virgo direction, and it is therefore fully independent of (1) and (2).

The small peculiar motion toward Virgo and the requirement of a reasonable luminosity function as well as other constraints (cf. Tammann *et al.* 1979) exclude the possibility of variations of H_0 of the size proposed by the V scale. These arguments disprove also other claims of peculiar motions of the Local Group of the order of 500 km s^{-1} , either away from Virgo (Gudehus 1978) or toward Virgo (Machra 1979). These claims are based on unreliable distance indicators, viz the "knee" of the galaxian luminosity function and the width of the 21 cm-line, respectively.

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In accordance with the only slightly disturbed local expansion field, the ST scale found nearly the same values for H_0 (local) and H_0 (global), i.e., $H_0 = 55$. (This value is almost automatically decreased to $H_0 = 50$ if van Bueren's Hyades modulus of 3.03 has to be increased by ~ 0.2 .) The V scale requires $H_0 = 70$ within the Local Supercluster, and because it can be demonstrated by the arguments given above that H_0 does not appreciably increase beyond the Virgo cluster, the possible range of the global value of H_0 lies between 50 and 70. The higher value, as preferred by the V scale, comes already into the above-mentioned difficulty with recent data on the Cepheids in LMC and with the brightest stars in M101.

One can therefore be confident that with some more ground-based work the uncertainty of H_0 can be confined to $\sim \pm 15$ percent. Much of this work shall be concerned with the galactic absorption, the calibration and application of the period-luminosity-color relation of Cepheids, and an improved understanding of the biases of galaxy samples. The character of these problems does not make it evident how the Space Telescope could be used effectively for their solution.

3. PRESENT LIMITATIONS ON THE ACCURACY OF H_0

In the previous section it was argued that it is possible to determine H_0 (local) from the ground within $\sim \pm 15$ percent, and since stringent limits can be set on any large-scale non-linearity of the expansion field, the value of H_0 (global) can be obtained to almost the same accuracy.

Therefore if the Space Telescope is to be used for the determination of H_0 , there must be justified hope that it can do considerably better, i.e., it must obtain H_0 to less than ± 10 percent.

Unfortunately there are intrinsic limitations to the accuracy with which H_0 can be determined. These limitations are largely controlled by the following three factors:

(1) Uncertainty of the local calibration: Because the Hyades modulus, on which essentially the whole Population I distance scale rests, is still uncertain at the 10 percent level, derived extragalactic distances cannot have smaller zero-point errors. The same error holds also for the Population II distance scale which is illustrated by the fact that presently quoted errors of the absolute magnitude of RR Lyr stars amount to ± 0.2 (Sandage 1970; Hemenway 1975; Heck and Lakaye 1978; Pel and Lub 1978).

(2) Intrinsic scatter and instability of distance indicators used: The absolute magnitudes of known distance indicators have random variations of ≥ 0.2 (an exception are the mean absolute magnitudes of RR Lyr stars and Cepheid luminosities derived from the period-luminosity-color relation), and the variation of standard diameters (H II regions) is even larger. In addition, some distance indicators are known to be unstable against changes in chemical composition.

(3) Random motions of field galaxies: The random motions of galaxies in the field can amount up to 50 km s^{-1} in the mean (cf. Tammann et al. 1979b), which immediately introduces at least a 10 percent uncertainty to H_0 derived from the most accessible, nearby galaxies ($v_0 \leq 500 \text{ km s}^{-1}$).

The Space Telescope shall eventually help to improve the situation with problem (1). Problems (2) (at least in part), and (3) can be solved by averaging over many galaxies. But this requires very much observing time, which is further increased by the necessity to control the patchiness of the galactic absorption below $|b| \sim 40^\circ$ (cf. Sandage 1976b) and within the parent galaxy.

There is hope that the Baade-Wesselink method applied to supernovae shall eventually yield distances to galaxies within ≤ 10 percent. Present results are encouraging (Kirshner and Kwan 1974; Branch 1977; Schurmann et al. 1979). But to derive H_0 one shall turn to galaxies with $v_0 \leq 5000 \text{ km s}^{-1}$, which is clearly a task for ground-based work.

These views on the possibilities of the Space Telescope to improve the accuracy of H_0 in a single program may be overly pessimistic. However, there is no question that it would be highly desirable to check the accuracy of the present distance scale with the Space Telescope. To this end two feasible programs are described in the following.

4. A CHECK ON THE DISTANCES OF NEARBY GALAXIES

The Space Telescope shall offer the opportunity to observe primary distance indicators to about ten times larger distances than previously possible. Two particularly important applications of this ability shall be briefly described.

4.1. RR Lyr Stars in M31

Except for a few dwarf spheroidal galaxies, extragalactic RR Lyr stars have been observed only in LMC (Graham 1973) and SMC (Graham 1975). At the apparent distance modulus of M31

$(m-M)_{AV} = 24.64$ (Baade and Swope 1963; Sandage and Tammann 1971), RR Lyr stars with a mean absolute magnitude of $\langle M_V \rangle = 0.5$ shall appear at $m_V = 25.14$ or at minimum light at ≤ 26.0 . At this magnitude the Wide Field Camera (WFC) yields an accuracy of 0.06 within 1000 sec of integration. (The technical specifications of the WFC are taken from Westphal et al. 1978).

The search field should be placed along the minor axis on the far side of the galaxy and hardly nearer than 10 kpc from the nucleus; this is to guard against absorption effects and to stay outside the main image of the galaxy. Our Galaxy has at this radial distance ~ 1 RR Lyr star kpc^{-3} (Kinman 1972). If this is taken as representative for M31, one calculates an order-of-magnitude expectation of 8 RR Lyr per 0.27 kpc^2 , corresponding to the field of the WFC at the distance of M31.

In principle it is not necessary to obtain periods of the RR Lyr stars because there is hardly a correlation between $\langle M \rangle$ and period. The detection of the variables and the establishment of their character would then require only ~ 5 exposures. However, to obtain some information on their Osterhoff type and metallicity, one still needs light curves and hence periods, perhaps even colors at minimum light. This requires at least 15 exposures well spaced in time.

The distressingly small number of variables in the WFC field makes it doubtful whether one search field is sufficient. It may be necessary to search 2-6 fields, say ~ 3 .

The total observing time required becomes then $\sim 45,000$ sec, or 22×2000 sec. A principal reason why this project is so expensive is, of course, the large angular extension of M31 and the relative scarcity of RR Lyr stars. For this reason the following program should be given higher priority.

4.2 Cepheids in M101

The distance of M101 is of fundamental interest for two reasons: (1) it is a member of a bona-fide group (Sandage and Tammann 1974b); therefore the mean group recession velocity of $368 \pm 23 \text{ km s}^{-1}$ (Tammann and Kraan 1978) should be essentially free of random peculiar motions, and it therefore provides a zero-point calibration of the local velocity field derived from relative distances only (cf. Section 5); (2) M101 is the brightest nearby Sc spiral; the reasonable requirement that the brightest corresponding Virgo cluster members must reach at least this luminosity, sets a lower limit to the cluster distance; in addition, the necessity of some distant

field Sc's being brighter than M101 (cf. Section 2) yields immediately a maximum value of H_0 (global).

Ground-based photometry down to $m_B = 22^m$ of 20 Cepheids in an outlying, nearly absorption-free field in M31 has reached to an apparent distance modulus of $(m-M)_{AB} = 24^m.8$ (Baade and Swope 1963).

An equally suitable field in M101, at a distance modulus of $(m-M)_{AB} = (m-M)^{\circ} = 29^m.3$, requires then photometry down to $26^m.5$ (corresponding to minimum light of the Cepheids). Scaling the frequency of Cepheids in M31 to a field of 14 kpc^2 , corresponding to the WFC field at M101, gives a sufficient number of ~ 16 Cepheids. An accuracy of 0.1 at minimum light would be satisfactory; this corresponds to an integration time of 720 sec.

In order to determine the widely different periods of Cepheids at least 25 B-exposures are needed. Because the period-luminosity-color relation requires additional color information, 10 V-exposures are also necessary.

The total observing time required is then found to be 26,000 sec, or 13×2000 sec. It is surprising that this program is almost certainly less demanding than the RR Lyr stars in M31.

From the case of M101 it is clear that the Cepheids in the Virgo cluster, still 2.2 more distant, lie at the very limit of the Space Telescope. For three reasons the result could not possibly excel in accuracy: (1) Only m_B (max) can be hoped for, and therefore the relation of period and D_{max} has to be used (cf. Tammann and Sandage 1968); (2) the apparent advantage of larger numbers of Cepheids per exposure is offset by absorption and crowding effects; and (3) the mean Virgo cluster velocity has an inherent error of $\pm 50 \text{ km s}^{-1}$ to which is to be added the error of our infall motion toward Virgo. For this reason alone any value of H_0 derived from the cluster is inseparably inflicted with an error of ~ 10 percent.

5. THE MAPPING OF THE LOCAL VELOCITY FIELD

It was stated above (Section 2) that it is of paramount importance to map the local velocity field with relative distance indicators if one wants to transform one or several known values of H_0 (local) into H_0 (global). Since our local peculiar motion of $150 \pm \sim 50 \text{ km s}^{-1}$ toward Virgo is almost

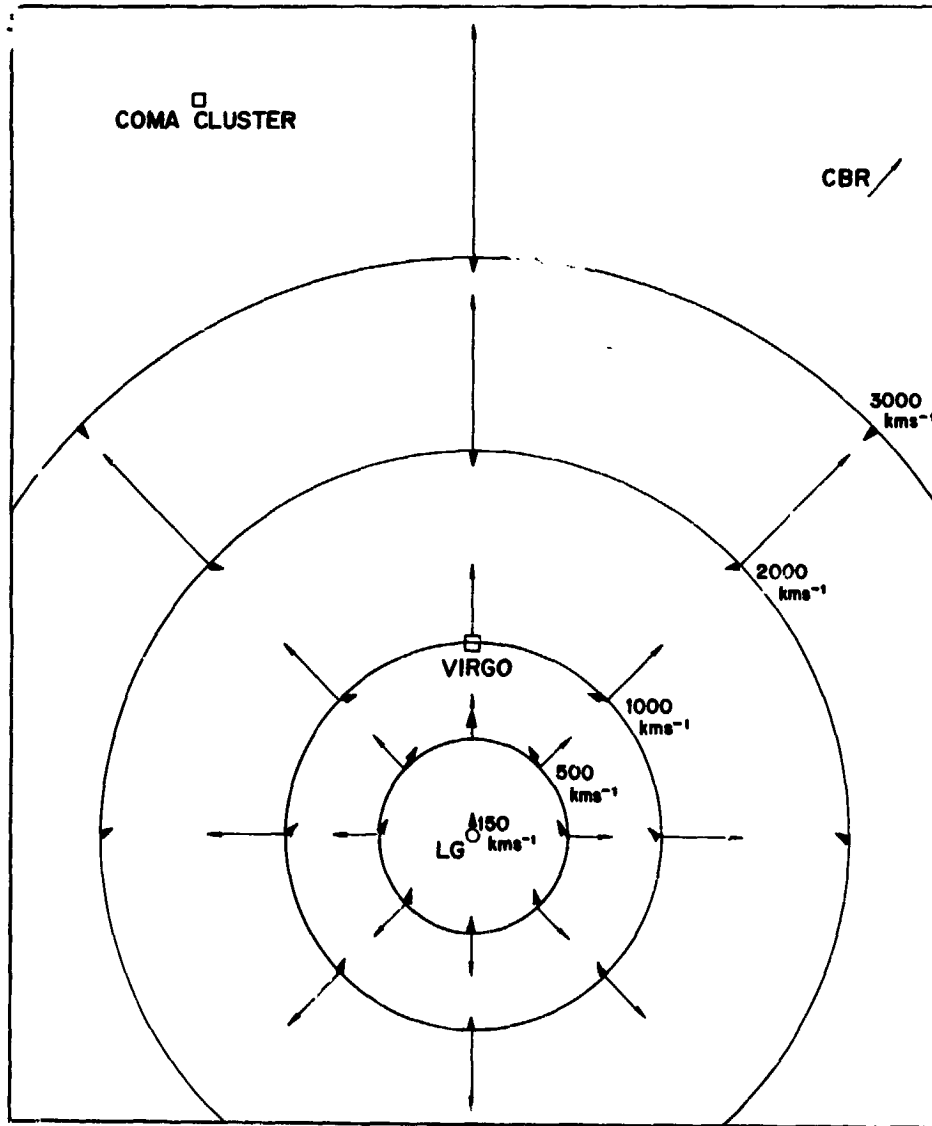


Fig. 2. Schematic presentation of the local velocity field in the Supergalactic plane. Thin arrows symbolize the ideal Hubble flow. Heavy arrows represent the overlaying Virgo-centric flow; their length is calculated assuming a Local Group infall velocity of 150 km s^{-1} and a density profile of the Virgo cluster complex decreasing with r^{-2} . The random peculiar motions of individual field galaxies, $\leq 50 \text{ km s}^{-1}$,

C-4

certainly not the residuum of a large primordial turbulence, one can construct a self-consistent dynamical flow model on the rather more likely assumption that the peculiar motion is the result of the mass density excess around the Virgo cluster (Yahil et al. 1979). With this assumption and the known density profile of the Virgo complex (Yahil et al. 1980) one can calculate the Virgocentric peculiar motion of any galaxy; a visualization of the result is given in Figure 2. The peculiar velocity field causes that local galaxies shall have a non-Hubble component in their recession velocities--or in other words that at a fixed observed velocity v_0 a galaxy shall appear too near or too distant depending on the angle between that galaxy and the Virgo center. This effect expressed in $\Delta(m-M)$ is shown in Figure 3 for galaxies near the Supergalactic plane.

The assumption of a self-consistent dynamical Virgocentric flow model must be tested using suitable standard candles. It seems that for this purpose the brightest M-supergiants in later-type spirals are ideally suited in combination with the Space Telescope. There is good evidence that these stars have a well defined maximum brightness near $M_V = -8.0$ (Sandage and Tammann 1974a). This upper luminosity limit, which is independent of galaxy size (very much in contrast to the brightest blue stars), is probably the result of mass loss, which funnels the most massive, evolved stars below a threshold luminosity (Sandage and Humphreys 1979). The brightness of the brightest M stars is presently known in 10 galaxies of widely different size (cf. Table 2). Further details are given by Humphreys (1979c).

The high luminosity of M-supergiants, their extreme colors, $(B-V) \geq 2.0$, and the fact that they are probably all variable, makes their identification and distinction from foreground stars easy. The variability has, however, the disadvantage that at any given moment no star may lie at the upper luminosity boundary. It may therefore be cautious to take a minimum of three exposures of each galaxy at different epochs. It is to be expected that the magnitude of the upper boundary defined in this way has better statistical stability than the momentary brightness of the brightest star. Multiple exposures have also the advantage of giving a higher

are too small to be shown to scale. The distance to the Coma cluster is not to scale; it is shown only as an available reference point which is likely to reflect the cosmic expansion to within less than 10 percent. The 600 km s^{-1} velocity inferred from the anisotropy of the Cosmic Background Radiation (CBR) must comprise the whole volume shown.

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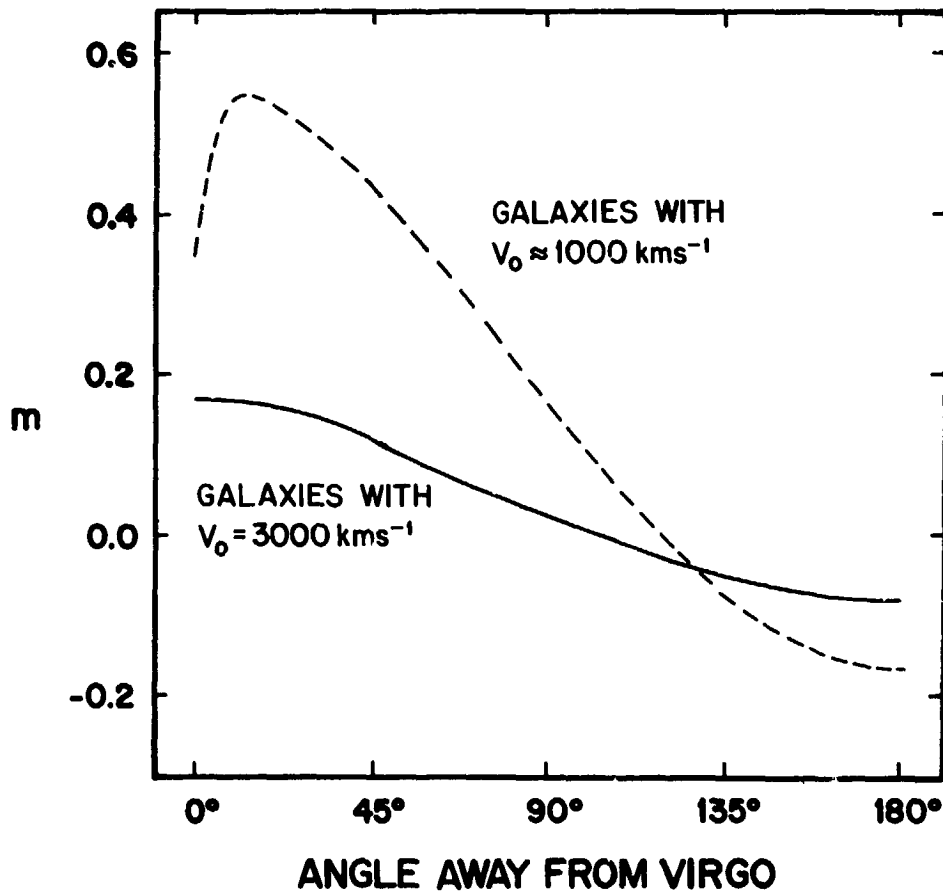


Fig. 3. The variation of apparent distance modulus in the Supergalactic plane for a fixed observed recession velocity. The values $\Delta(m-M)$ are roughly estimated from the Virgocentric flow model described in the text. The actual calculation shows that $\Delta(m-M)$ is multi-valued at small distances from the Virgo cluster.

Table 2: Brightest M-Supergiants

Galaxy	M_V (max)	Source
Galaxy (μ Cep)	-8.2	2
LMC	-8.1	1,3
SMC	-8.2	1,7
M33	-8.1	4
NGC 6822	-7.8	1
IC 1613	-8.03	1,5
WLM	-7.8:	6
NGC 2403	-7.8	1
IC 2574	-7.8:	1
Ho II	-7.4:	1

$$-7.9 \pm 0.1, \sigma \approx 0.25$$

Sources: 1, Sandage and Tammann 1974a; 2, Humphreys 1978; 3, Humphreys 1979b; 4, Sandage and Humphreys 1979; 5, Sandage and Katem 1976a; 6, Sandage and Katem 1976b; 7, Humphreys 1979a.

chance to the subsample of stars with small intrinsic absorption to appear at maximum; this is important because individual absorption corrections would pose additional problems.

The values in Table 2 were essentially derived without intrinsic absorption corrections. They come in addition from data with widely different time coverage. It can therefore be assumed that the upper luminosity shall be determined with only a few exposures to within ~ 0.2 . This makes the M-supergiants clearly powerful distance indicators.

At a velocity of $v_0 = 3250 \text{ km s}^{-1}$ the M-supergiants appear at $V = 26^m$ and $B \approx 28^m$. Good V-photometry (± 0.06) can be obtained in 1000 sec of integration, and since the B-magnitude is only needed to ensure that $(B-V) \geq 2.0$, about 2000 sec of integration in B are sufficient. The WFC covers at that distance the inner 25 kpc, i.e., essentially the whole optical spiral structure of even a large spiral galaxy and therefore almost the entire population of M-supergiants. This makes evident that these stars are ideally suited for the WFC: they are still accessible at distances where whole spiral galaxies can be sampled.

With 3 V- and a minimum of 1 B-exposures a galaxy at $v_0 \approx 3000 \text{ km s}^{-1}$ requires therefore 5000 sec. The expense for a galaxy at $v_0 \approx 1000 \text{ km s}^{-1}$ is about the same, because

shorter integration times are compensated by the necessity of several frames (unless one chooses intrinsically smaller galaxies).

A program of 50 galaxies at $v_0 \approx 3000 \text{ km s}^{-1}$ and 10 galaxies at $v_0 = 1000 \text{ km s}^{-1}$, well distributed over the sky, needs $150 \times 2000 \text{ sec}$ of integration time, which corresponds roughly to 14 days of the life of the Space Telescope. The obvious yield would be 10 percent limits on the random peculiar velocity components of individual galaxies, but because the random noise of their radial velocities is almost certainly $\leq 50 \text{ km s}^{-1}$, large-scale streaming motions down to $\sim 50 \text{ km s}^{-1}$ could be detected. This shall give a unique possibility to improve the local Virgocentric motion, to test the assumption of a general Virgocentric flow model, to detect deviations from this simple model, and to determine the density parameter $\Omega/\Omega_{\text{crit}}$ (cf. Yahil et al. 1979). It shall also set stringent limits on what fraction of the observed cosmic background anisotropy (cf. Smooth 1979; Wilkinson 1979) could be due to local shear motions. Finally it should be repeated that the mapping of the local velocity field is a prerequisite for a high-accuracy determination of H_0 (global) from local distances.

The above considerations are somewhat pessimistic because M-supergiants were used only as relative distance indicators. Actually their maximum absolute magnitude is rather well determined, i.e., $\langle M_V(\text{max}) \rangle = -7.9$. Making reasonable assumption on the systematic errors, the external uncertainty of this value is ≤ 0.3 . With this information on their absolute luminosity, a number of them at $v_0 = 3000 \text{ km s}^{-1}$ will directly lead to an estimate of H_0 (global) to certainly better than 20 percent.

6. SUPERNOVAE AS STANDARD CANDLES

Present data suggest that SNe of Type I in E (and S0) galaxies are at maximum light very good standard candles. The observed magnitude dispersion amounts to $\sigma(m_{\text{pg}}) = 0.4$, but the true dispersion is certainly smaller and possibly vanishingly small (Tammann 1978). SNe I in other types of galaxies suffer from internal absorption, as do SNe II, and they exhibit therefore a much wider luminosity scatter at maximum (cf. also Branch and Bettis 1978).

The properties of brightest cluster galaxies are known to change with cosmic time which disqualifies them for the determination of q_0 . Their role as standard candles could be

taken over by SNe I in E/S0 galaxies, because the explosion of a Type I SN, whatever its origin may be, seems to be a physically well defined event, which is not expected to vary with time. However, SNe I are 3^m fainter at maximum than brightest cluster galaxies, and it is this property which makes them ideal objects for the Space Telescope.

The potentials of SNe as cosmological probes are apparent from Table 3, where some of their relevant properties are compared with those of brightest cluster galaxies.

Before pursuing the main line of our argument further, it is important to investigate if sufficient SNe I in E/S0 galaxies can be found at cosmologically useful distances, say at $z = 0.5$.

6.1 The SN Search

The faintest SN found so far from the ground has $\sim 20^m$. From this it is clear that SNe at 23^m , corresponding to the maximum magnitude at $z = 0.5$, must be searched with the Space Telescope! In that case one has to ask where the highest SN I frequency per (arcmin)² can be expected. This is clearly in rich clusters. These clusters have in addition the most welcome property of providing almost exclusively the subtype of SNe of interest here: with essentially only E and S0 galaxies these clusters cannot yield anything but absorption-free SNe I. There is yet another advantage to concentrate on clusters: if the parent galaxy of a SN happens to be too faint to obtain its redshift--from the ground or from the Space Telescope--the cluster redshift can also be obtained from the brightest cluster members. Moreover, the clusters and hence the SNe can be preselected according to redshift.

At $z = 0.5$ the field of the WFC corresponds to a circle of 0.64 Mpc radius ($q_0 = 0$). Within that radius a cluster like Coma contains $5 \cdot 10^{12} L_{\odot}$ (Abell 1975; Rood et al. 1972; King 1972). The SN frequency in E/S0 galaxies is $0.16 \text{ SNe } (10^{10} L_{\odot})^{-1} (100 \text{ yr})^{-1} (1+z)^{-1}$ (Tammann 1978) or 0.5 SNe I per year per cluster at $z = 0.5$ (with the reasonable assumption that the SN I frequency has remained essentially the same during the last few billion years). A Space Telescope survey of 50 Coma-like clusters at $z = 0.5$ (admittedly a sample size which is presently not available) would therefore yield 25 SNe I per year with an estimated uncertainty of a factor 2.

From the standard B-light curve of SNe I (Barbon et al. 1973), one finds that a SN remains within 1^m of its maximum

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Table 3: First-Ranked Cluster Galaxies and SNe I
in E/S0 Galaxies as Standard Candles

	First-ranked gal. SNe I (in E/S0)	
difficulty of photometry of extended obj.	yes	no
luminosity evolution	yes!	no (?)
dynamical evolution	yes	no
selection effects (Malmquist bias)	yes (?)	controllable ¹⁾
imperfect imaging of a realistic universe ²⁾	yes	little
intergalactic absorption	yes	yes
$M_V(\text{max})$	-23. ⁰	-19. ⁷
$\sigma(M_V)$	0. ³	0. ⁴
$(B-V)_{\text{max}}$	1. ⁰	-0. ¹⁵
at $z = 0.25$		
$m_V(\text{max})$	17. ⁶	21. ¹ ³⁾
$(B-V)_{\text{max}}$	1. ⁶	0. ⁰ ³⁾
at $z = 0.5$		
$m_V(\text{max})$	20. ⁵	22. ⁹ ³⁾
$(B-V)_{\text{max}}$	1. ³	+0. ¹⁵ ³⁾

¹⁾ At least in principle a comparison between expected and observed SN numbers yields the influence of any possible magnitude bias. In addition the search is planned here to detect all SNe I.

²⁾ Cf. Zeldovich 1964; Kantowski 1969; Dyer and Roeder 1973; Refsdal 1970. In the absence of background the effect on the photometry of point sources is smaller.

³⁾ Assuming $q_0 = 0$, the approximate K-correction is calculated assuming an energy distribution of a black-body of 10,000 K. Due to cooling the K-correction increases strongly after maximum: 15 days after maximum (~ 8000 K) a SN at $z = 0.5$ shall therefore decrease not by 1.⁰, but rather by 1.⁴, and it shall have $(B-V) \approx 0.³$.

brightness for 25 (1 + z) days, i.e., at $z = 0.5$ it is brighter than 24^m for 38 days. About 40% of all SNe I with $m_B < 25^m$ discovered at $z = 0.5$ shall be at pre-maximum; for the remaining 60% the maximum B-magnitude can be restored within $\sim 0.2^m$ from the standard light curve. It is therefore sufficient if each cluster is searched--yielding ample margin--down to 25^m once per month. Because of the high temperature of SNe at maximum and because of the background light of the parent galaxy, it is advantageous to conduct the search in blue light.

A 25^m object can be detected with the WFC with a signal-to-noise ratio of 7 within 100 sec of integration. The background noise of the parent galaxy shall reduce the photometric accuracy, especially in the inner regions, but it shall hardly affect the discovery chance. Therefore 12 100 sec-exposures of each of the 50 clusters, resulting in 25 sufficiently fresh SNe I, will require 30 x 2000 sec of actual observing time, which corresponds roughly to 4 days of telescope time. This is indeed a modest price for the goals described in the following.

6.2 The Hubble Diagram of SNe I

The apparent magnitude of standard candles at $z = 0.5$ differs by 0.25^m for the case $q_0 = 0$ and $q_0 = 0.5$ (Sandage 1961). If the intrinsic magnitude dispersion of SNe I at maximum is 0.2^m , then it is possible to distinguish with only six SNe between a Euclidean and an open universe at the 3σ level. Even if the intrinsic dispersion were as high as 0.4^m the same result could be obtained from 25 SNe.

It should be noted that the determination of q_0 from the Hubble diagram requires only apparent magnitudes (in addition to redshifts) and that it is therefore independent of H_0 . However, it is not sufficient to have a number of SNe at $z = 0.5$ to determine the curvature of the Hubble line. Rather a number of SNe at small and intermediate redshifts with uniform photometry are needed in addition. The search for these additional SNe I in E/S0 galaxies shall turn out to be quite time-consuming, regardless if performed from the ground or with the Space Telescope. The presently known 14 SNe I with $m(\max)$, which occurred in E/S0 galaxies, define the zero-point of the Hubble line only to within $\sim 0.2^m$ (Tammann 1978). The details of an optimum observing programme are still to be devised.

A minor difficulty is that at present the time-variable K-correction of SNe is not known. It would be important to

obtain the ultraviolet spectra, possibly with IUE, of a nearby Type I SN during an interval of ~ 25 days around maximum light. This would also be important for the determination of the optimum wavelength of the precision photometry which must follow the discovery. This photometry, possibly performed with the Faint Object Camera, is necessary to determine the exact phase and to inter- or extrapolate the maximum brightness.

6.3 SNe I as Non-Standard Candles

The increasing potentials of the Baade-Wesselink method applied to SNe have been mentioned above (Section 3). The application of this method of SNe at higher redshifts has most recently been discussed by Oke (1979) and Wagoner (1979).

Suffice it to mention that two spectra with resolution 10^3 could be obtained with the Faint Object Spectrograph of a SN I at $z = 0.5$ about a week after maximum (23:5) within 2×12^h .

The principal difference of this approach toward q_0 and the route via the Hubble diagram is that the Baade-Wesselink method gives a proper-motion distance and hence a value for q_0 for every single SN, and that in addition the assumption of SNe I being standard candles can be dropped. The price for this is, of course, a full understanding of SN atmospheres and long integration times of the spectrograms.

7. CONCLUSIONS

The Space Telescope shall eventually improve the Galactic distance scale which shall influence also the calibration of extragalactic distances. It should observe RR Lyr stars in M31 and more importantly Cepheids in M101 to check the present distance scale at the ~ 15 percent level.

The brightest M-supergiants, which can be observed with the Space Telescope out to $v_0 \approx 3000 \text{ km s}^{-1}$, shall provide an excellent relative mapping of the local velocity field. Knowledge of this field is important to determine H_0 (global) as function of position and H_0 (local); but it is not clear, whether the Space Telescope shall play a decisive role in providing an improved zero-point calibration of the expansion. However, the relative velocity field shall also yield an accurate determination of the density parameter $\Omega/\Omega_{\text{crit}}$.

A unique chance to determine q_0 from the Hubble diagram of SNe I out to $z = 0.5$ is offered by the Space Telescope.

If, however, the expectation that SNe I in E galaxies are nearly perfect standard candles should prove wrong, q_0 could still be obtained via the Baade-Wesselink method applied to SNe. The photometry of SNe I at $z = 0.5$ at the rest-wavelength of the B-filter would, in addition, yield a fundamental test on the Doppler nature of redshifts (Tammann 1979).

Since the Space Telescope shall improve the determination of Ω and measure q_0 , it affords a comparison of these parameters which shall set limits on the smoothly distributed invisible mass in the universe or/and on the cosmological constant Λ .

These notes were written while the author was a guest at the Hale Observatories. He thanks the Director, Dr. M. Schmidt, and the Staff for their hospitality. He thanks Dr. A. Sandage for many stimulating discussions. He acknowledges support from the Swiss National Science Foundation.

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DISCUSSION

van Woerden: 1. In the derivation of the infall of the Local Group towards the Virgo Cluster, you assume that the properties of galaxies in the field and in the Virgo and Coma Clusters are the same. Should one not expect that these properties will depend on the environment ?

2. You accept a sharp cutoff at $M = -8.0$ for red supergiants, but reject a cutoff in the absolute magnitudes of galaxies in your comparison of the Sandage-Tammann and the Vaucouleurs distance scales. To what extent is this justified ?

Tammann: 1. Yes. However, we have made very careful comparisons of the properties of E and SO galaxies in these clusters. In particular the luminosity functions of the E and SO galaxies follow exactly the same Schechter luminosity function.

2. M supergiant stars are good distance indicators because there are good physical reasons why they cannot be brighter than $M = -8$. Mass loss prevents it.

Spinrad: If you measure the light curves of supernovae well enough, you can find a redshift from the time dilation.

Tammann: Yes. This also provides a direct test of the nature of redshifts.

Oke (Discussion leader): I will discuss the Raade-Wesselink method of distance determination which avoids the various steps discussed by Dr. Tammann in his presentation. The method was first applied to Cepheids: you have to measure three things, the velocity of the expanding atmosphere or envelope and the flux per cm^2 at two different times through the surface of the star. If the atmosphere of the expanding envelope is understood, the change in flux is related to the change in radius of the star and consequently its distance can be found. This has already been attempted for supernovae with encouraging results. However, the method needs to be perfected and I will discuss some of the problems.

The expansion velocity of the envelope is determined from the emission lines in the optical spectrum. The lines are broad and have characteristic P-Cygni profiles. To interpret them in terms of expansion velocities needs good model atmospheres. Type II supernovae are good in this respect because their spectra are reasonably well understood. The spectra of Type I supernovae are less well understood. It may be possible to make UV observations from IUE or ST to use the $\text{MgII } 2800 \text{ \AA}$ line which may be free of blends.

To evaluate the surface flux, one works out the effective temperature and uses a model atmosphere to find the total emitted flux. So far the visible and near infrared wavebands have been used to measure the spectra and the energy distributions are similar to black bodies. In the UV, the recent Type II supernova in M100 was observed by IUE and the UV spectrum agreed well with a black body model atmosphere. For Type I supernovae further observations will be necessary with IUE and ST to find out how well the model atmospheres can account for the observations. Good model atmospheres for these expanding envelopes will be needed.

Dr Wagoner will describe more details of this technique.

Wagoner: I would like to discuss briefly why the space telescope could allow us to make full use of the advantages of supernovae as distance indicators. The basic idea was introduced by Walter Baade in 1926, and its application to supernovae was first suggested by Leonard Searle. Estimates of the Hubble constant were first obtained from Type I supernovae (SNI) by Branch and Patchett in 1973, and from Type II supernovae (SNII) by Kirshner and Kwan in 1974.

There are two basic advantages to the use of supernovae as probes of the Universe. First, they may be physically simpler systems than galaxies. Second, this kinematical method of determining distance avoids the need to invoke assumptions about the intrinsic properties of the probe (such as its luminosity or size) which can only be indirectly tested by observation.

The main assumption involved in this method is that the nature of the photosphere is understood in terms of a model atmosphere. In particular, if the photosphere is spherically symmetric and sharp (optical depth $\tau \approx r^{-n}$, $n \gg 1$), the (proper motion) distance to the SN is given by

$$d_M = (c/H_0)Z[1 - 0.5(1+q_0)Z + O(Z^2)] = v_*(d\theta/dt)^{-1}.$$

The photospheric velocity v_* is determined from the line profiles, and the effective angular size θ from the ratio of observed to emitted flux. Since the P Cygni type lines are better identified and the continuum is better defined in SNII, the method is most easily applied to them. In any case, the assumed model atmosphere is tested by a) the detailed frequency dependence of the observed flux, and b) the predicted constancy of $v_*(t)(d\theta/dt)^{-1}$. In fact, from (b) it is known that the assumption of a sharp photosphere breaks down about one month after maximum brightness. Therefore, absolute spectrophotometry of the supernova is required at least once a week before that time.

It might be thought that the use of SNI would have the advantage that a) they are 1-2 magnitudes brighter at maximum, and since they

occur in elliptical galaxies. b) less absorption is expected and c) the search of rich clusters with the wide-field camera on the space telescope (at redshifts $Z \gtrsim 0.3$) would preferentially find them. However, SNI and SNII are equally bright ($M_B \sim -17$) after a few weeks, when observations are still required, so that (a) is only relevant to discovery. Secondly, there are indications that a significant fraction of SNII may have little absorption, and this can be determined from good spectra. Finally, the results of Butcher and Oemler indicate that distant rich clusters may have a higher fraction of galaxies in which SNII are expected.

The space telescope becomes absolutely essential in determining q_0 by this method. The basic reason is the fact that for redshifts $Z \gtrsim 0.1$, resolutions less than 1 arcsec are required to exclude the galactic background flux. At a redshift $Z = 0.3$, a SNI or SNII with little absorption will have reached $m_v \sim 23$ after a few weeks. This corresponds to the limiting magnitude of the space telescope faint object spectrograph with wavelength resolution $\lambda/\Delta\lambda = 10^3$ and $S/N \sim 10$ for 5 orbits of observation.

The detection of SN of redshift $Z < 0.3$ may best be carried out from the ground. The rate of occurrence of either type with redshifts $< Z$ in a Schmidt field ($6^\circ \times 6^\circ$) should be $dN/dt \sim 100 Z^3$ per week for $Z \ll 1$. Plate scanners and digitizers such as those being developed by Ed. Kibblewhite could detect the changes in luminosity and/or shape of a galaxy due to a SN event at such redshifts. It is a fortunate coincidence that the relatively small field of the wide field camera on the space telescope can however encompass a rich cluster of galaxies at redshifts $Z \gtrsim 0.3$.

The implementation of this program to use supernovae as distance indicators should proceed in three stages :

- 1) More theoretical study and construction of model supernova atmospheres. Ground-based observations of SNII with redshifts $Z \lesssim 0.01$ to test the model atmosphere.
- 2) Ground-based (and/or space telescope ?) observations at redshifts $0.01 \lesssim Z \lesssim 0.1$ to determine H_0 .
- 3) Space telescope observations at redshifts $Z \gtrsim 0.1$ to determine q_0 .

A vital part of this program is the initiation of systematic searches for supernovae of the required redshifts. It would appear to be worth the effort, since this method involves no evolutionary effects, selection effects, or the need for many objects.

A more detailed discussion of this approach to the determination of

cosmological distances will be published in Comments on Astrophysics and the Proceedings of the 1979 Les Houches Summer School on Physical Cosmology.

Kirschner: In addition to being tools for cosmology, supernovae are of interest and importance in their own right. Particularly interesting will be observing them to their very faint later stages where we may learn something about what is inside them. In addition UV observations of both Types of supernovae will be very interesting. The IUE observations by the European observers show how much of importance about the supernova atmosphere can be learned and this should be extended to Type I supernovae with IUE and ST.

Macchetto: It is true that the continuum radiation of the supernova in M100 agreed with a black body according to our IUE observations but there are problems. The UV lines gave initially velocities of about 4000 km s^{-1} but when the optical lines developed the velocities were twice this value. This means that supernovae of Type II are not simple objects and better models are needed. It also illustrates the importance of ST because IUE can only observe the very brightest extragalactic supernovae whilst ST can go to very much fainter magnitudes. Also UV observations of the CIV as well as the MgII lines will prove important diagnostic tools for velocities of expansion.

Humphreys. In their recent series of papers on the determination of the Hubble constant, Sandage and Tammann found that the luminosities of the brightest blue stars are dependent upon the luminosity of the parent galaxy - the more luminous the galaxy, the more luminous the brightest star. Their preliminary results for the red stars suggested that they may have a maximum luminosity near $M_v \approx -7^m.9$ which is independent of galaxy type, contrary to the results for the brightest blue stars. Consequently, the M supergiants might be useful as distance indicators.

I have been observing the individual brightest stars of all spectral types in nearby galaxies. The emphasis of this program is on the calibration of these most luminous stars as extragalactic distance indicators and on the physical characteristics and evolution of the most massive stars in galaxies of different types. Spectra for classification and photometry have been obtained for candidate supergiants in the Local Group galaxies, M33, M31, IC 1613, NGC 6822, the LMC and SMC, and the Milky Way. Most recently spectra have been taken of the brightest blue stars in M 101 and NGC 2403.

When I began these observations, the only known (spectroscopically) M supergiants were in our own galaxy. For that reason, much of the observing program has concentrated on the confirmation of the M supergiants and the determination of their luminosities in a variety of different galaxies.

The results for the M supergiants, in all of the Local Group galaxies studied, show that the brightest red stars will be excellent distance indicators.

The supergiants in the solar neighborhood were first surveyed to provide a reference population for comparison with the results for other galaxies. The luminosities of the brightest stars in our galaxy are determined from their membership in associations and clusters.

Although a large body of data already exists in the literature for the early-type supergiants in the LMC, very little was known about the red supergiants. Spectra and photometry were obtained for a large number of red stars in the LMC; 54 were confirmed spectroscopically to be M supergiants.

Spectra and photometry have also been obtained for the much fainter suspected M supergiants in the more distant Local Group galaxies - M33, IC 1613, NGC 6822. The brightest red stars have photographic magnitudes of $B \approx 19^m - 19^m.5$. Because the exposure times are long (4-m KPNO) fewer stars have been observed in these galaxies.

	# red stars observed	confirmed M supergiants
M33	33	12
IC 1613	3 (all variables)	3
NGC 6822	16	8

The observed magnitudes of all of the M supergiants were corrected for interstellar extinction and combined with the true distance moduli (from Cepheids) of the galaxies to derive their luminosities. The brightest red stars have maximum visual luminosities of $M_V \approx -9^m$ which is independent of galaxy type or the luminosity of the galaxy.

My observations in the SMC are not yet complete, but the preliminary results also suggest that the brightest red stars will be near $M_V = -8^m$.

Summary of Calibration for M Supergiants

	<u>First Brightest</u>	<u>Three Brightest</u>
Galaxy	-8.2	-8.0 ± 0.2
LMC	-8.1	-8.0 ± 0.1
M33	-8.4	-8.2 ± 0.2
NGC 6822	-8.0	--
IC 1613	-8.1	--

These results for the M supergiants in different types of galaxies

with a wide range of luminosities yield a very tight luminosity calibration for the brightest M supergiants of $M_V = -8 \pm 0.2$. There also appears to be little or no dependence on the metal abundance of the galaxy (LMC and SMC).

On the basis of these results I suggest that the brightest M supergiants will be excellent distance indicators for spiral and irregular galaxies for the following reasons :

- 1) $M_V = -8^m$ is very tight; no dependence on galaxy type, no dependence on metallicity.
- 2) They are easily identified -- very red color (two-color photometry helps, B-V + V-R or B-V + V-I). Also most are variable which helps identification.
- 3) They are 2 magnitudes brighter than brightest Cepheids.

With the space telescope the M supergiants should be especially useful as distance indicators. With imaging to $V \approx 28^m$ the M supergiants could be identified in galaxies as distant as $(m-M)_V \approx 35^m$ (100 Mpc). With the faint object spectrograph spectra would even be possible to distance moduli of $(m-M)_V \approx 10^m$ (10 Mpc) which would include M 101.

In a collaborative program with Steve and Karen Strom to study the stellar content of M 101, we have tentatively identified the M supergiants. The brightest candidates have V magnitudes of $\approx 21^m$ which with $M_V \approx -8^m$ gives a distance modulus of $+29^{m.0}$ for M 101.

In addition to the red stars, the brightest blue stars have also been observed in these same galaxies. The spectra and photometry for these stars confirm the Sandage and Tammann result that the luminosity of the brightest blue star depends on the luminosity of the galaxy. Because of this dependence on the luminosity (or type) of the galaxy the brightest blue stars are not as good distance indicators as the red stars.

It is worth mentioning that the visually brightest blue supergiant is a late B or early A-type star in all of these galaxies.

I recently obtained spectra of the brightest blue star candidates in the more distant spiral galaxies M 101 and NGC 2403. These are the first spectra of individual stars outside our Local Group. Four stars in NGC 2403 and three in M 101 are confirmed to be members. The visually brightest stars in both galaxies are A-type supergiants, and their spectral characteristics are consistent with the luminosities derived from their membership in M 101 and NGC 2403. The visual

luminosities of the A-type supergiants are -9.4 for the one in NGC 2403 and -10.3 and -10.1 for the two in M 101. These two supergiants in M 101 are the visually brightest normal stars yet known in any galaxy.

Huchra: I'd like to talk about some work that throws a monkey wrench into the relatively smooth, undisturbed picture of the Hubble flow.

The Tully-Fisher relation is essentially the correlation between the absolute luminosity of a spiral galaxy and the width of its 21-cm neutral hydrogen profile. This correlation is strong and was used by the above authors to derive a distance to the Virgo cluster relative to local group galaxies. Its physical bases are the connection between the mass of a spiral galaxy and its maximum rotational velocity plus a relative constancy of the mass to light ratio.

After its initial application using blue luminosities, a number of objections were raised by other galaxy distance measurers, notably Sandage and Tammann, concerning problems of internal absorption corrections to the luminosities and differences of stellar content in spirals. A year ago my co-workers, M. Aaronson and J. Mould and I decided to see if these problems could be minimized by using infrared (1.6μ) magnitudes instead of blue magnitudes. This worked exceedingly well (Ap. J., 226, 1, 1979) - the infrared colors of almost all galaxies are very similar, so the population measured is similar, and the extinction in the 1.6μ band is only 0.07 of that in the blue, substantially reducing absorption corrections to the luminosities of edge-on galaxies. Note that edge-on systems are preferred for measuring 21-cm profile widths because the inclination corrections become negligible. The scatter in the relation was reduced to 0.3 magnitudes, making the infrared Tully-Fisher relation an ideal method for determining distances to galaxies and clusters of galaxies. We derived initial values of 67 and 58 $\text{km s}^{-1} \text{Mpc}^{-1}$ for the Hubble constant using the Virgo and Ursa Major galaxy complexes, in good agreement with Sandage and Tammann.

In the past year we have improved the precision of the local calibration with large aperture photometry of nearby galaxies with the KPNO 0.075 m and obtained additional data for Virgo. Our distance moduli for galaxies in the M81, M101 and Sculptor groups - based on the Sandage and Tammann (hereafter ST) zero point for M31 and M33 agree exceedingly well with theirs, and our recalibration of the Virgo modulus with double the number of galaxies gives a Hubble constant of $62 \pm 5 \text{ km s}^{-1} \text{Mpc}^{-1}$, in very substantial agreement with the ST value of $55 \text{ km s}^{-1} \text{Mpc}^{-1}$.

The problem arises with values derived for more distance clusters. Using radio data for six clusters at velocities of $4\text{-}7000 \text{ km s}^{-1}$ from Sullivan and Schommer and from Chincarini and collaborators, we have derived a mean value of the Hubble constant of $\sim 90 \text{ km s}^{-1} \text{Mpc}^{-1}$. These clusters are scattered around the sky and are of a variety of

morphological types. We have considered the possible systematic measuring effects and these cannot explain the discrepancy. The simplest hypothesis is that we are falling towards the Virgo complex with a peculiar velocity of 400-500 km s⁻¹ - a velocity comparable to that seen in the recent microwave background anisotropy experiments, but substantially larger than the 175 km s⁻¹ seen in the local galaxy samples by Sandage, Tammann and Yahil. Thus, I think the problem of the local motion appears not to be as simple as Tammann has just stated.

In closing, I would like to point out that although Space Telescope will not be useful for the measurement of global galaxy properties used here, its superb capability in the IR and near IR can substantially aid in the reduction of systematic errors in the local distance scale derived from stellar (Cepheid, RR Lyrae and Red Giant) calibrations by reducing the effects of both interstellar absorption and metallicity on the derived magnitudes of the calibrating stars.

Freeman: The Fisher-Tully relation in the Aaronson et al. form is $L \sim V^4$ which means constant mean surface density Σ from galaxy to galaxy. If this constant Σ changes from local calibrators to one cluster sample to another sample, then the zero point of the F-T relationship will change, and the luminosities derived will be systematically in error. For example, if the cluster spirals are systematically 0.5 mag different in Σ (compared to the calibrators), then the corresponding cluster distance will be wrong by 25%. Someone (I can't recall who!) has recently suggested that the Virgo spirals are systematically higher in surface brightness than spirals in the field. If the cluster environment, or anything else, affects the mean surface density of its spirals, then the F-T method will not be a reliable way to measure even relative distances for clusters.

Huchra: I think that the fact that we observe clusters of different morphology (concentration), some of which are very close to each other, and get approximately the same answer for all indicates that this problem may not be important.

Gunn: There are some spiral galaxies with rotation curves which seem to go on and on at roughly 230 km s⁻¹ to 60 to 80 kpc. Have you looked into what these galaxies do to the Tully-Fisher relation?

Rubin: The answer seems to be that if you stick to a single Hubble type, everything is all right. I would like to make two other comments. First, I would like to repeat a comment I made in 1961 at the Santa Barbara galaxy conference. Velocities in the S.A. catalogue can have errors as large as ± 300 km s⁻¹. Some velocities come from a single plate by Sinclair Smith at 1000 Å mm⁻¹. I hope before space telescope observations are undertaken that velocities of nearby galaxies will be available to higher accuracy.

Second, evidence that the expansion of the universe is smooth comes mostly from adopting as the distance of a galaxy the value v/H . The opportunity to discover a possible irregularity may depend upon a very special circumstance. Possibly one such circumstance is the Perseus cluster of galaxies, with a string of galaxies with $\langle V \rangle$ near 5000 km s^{-1} extending west from NGC 1275 (Perseus A), and a tighter group of galaxies with v near 8000 km s^{-1} to the NE of NGC 1275. At NGC 1275, we see both velocities, 5000 to 8000 km s^{-1} , with evidence from the 21-cm absorption line that the 8000 km s^{-1} gas is in front of the 5000 km s^{-1} gas. Could we be seeing 2 clusters, with the $V = 8000 \text{ km s}^{-1}$ cluster in front of the $V = 5000 \text{ km s}^{-1}$ cluster? I don't know, but we ought to be alert to the possibility.

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THE PROBLEMS OF COSMOLOGY

P.J.E. Peebles
Joseph Henry Laboratories
Princeton University

The business of modern cosmology is the search for the main constituents of the universe, the pattern of their distribution and motion, the relation to the geometry of space-time, and the way the whole arrangement is evolving with time. This leads us to a rich list of research problems. I describe here three examples that illustrate the expected role of space telescope in the endeavour.

I. THE DISTRIBUTION OF GLOBULAR STAR CLUSTERS

In Ostriker's (1977) cannibalism scenario giant elliptical galaxies grow by capturing neighbors. If the growth by capture and violent relaxation had proceeded through several generations it would have tended to produce a fixed ratio of globular clusters to starlight. This is not observed in the Virgo cluster: the galaxy M87 has an unusually large abundance of clusters for its luminosity in comparison to other large ellipticals (Harris and Petrie 1978). The distribution of clusters within M87 is similar to the distribution of starlight at $\theta \leq 20'$, corresponding to $r \leq 100$ kpc (Harris and Smith 1976). It would be of considerable interest to know whether the halo of light extending beyond $20'$ around M87 is matched by a similar halo of globular star clusters.

A test from the ground is not practical because of the problem of telling the globular clusters from the foreground stars and background galaxies. Space telescope observations will readily settle the question because the clusters will be resolved ($\theta \sim 0.3''$). If clusters are not present in the extended halos of giant ellipticals and cD galaxies we will have the interesting puzzle of understanding how a sea of stars spread through the halo without bringing clusters with it. The mass-to-light ratio of the matter in halos is thought to be considerably larger than in the central parts of galaxies, as is

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required to account for the remarkably flat rotation curves in some spirals and the dynamics of groups and clusters of galaxies (eg. Ostriker, Peebles and Yahil 1974; Rubin 1979). If globular clusters were distributed in proportion to mass the abundance of clusters relative to starlight would increase going into the halo. That does not happen in our galaxy, but it is a single and perhaps not representative case. With space telescope observations it should be possible to determine the general pattern of the distribution of globular clusters around spiral and elliptical galaxies and then decide whether a similar pattern in the mass distribution could account for the dynamics of galaxy pairs, groups and clusters.

Could intergalactic globular clusters be common (Peebles and Dicke 1968)? We know from limits on the possible contribution to the light of the night sky that the mean luminosity density due to clusters could not exceed about $10^8 L_{\odot} \text{Mpc}^{-3}$, comparable to that of galaxies (Dube, Wickes and Wilkinson 1977). With $M_V = -8$ this gives space density $n \leq 10^3 \text{Mpc}^{-3}$. At 1 Mpc a cluster diameter is $\sim 5''$, large enough to be measured from the ground but perhaps not so large that one could tell it from a distant galaxy without special study. Thus local surveys for globular clusters do not much improve the limit on n . In a $3'$ by $3'$ space telescope field the above space density gives ~ 10 globular clusters at distances ≤ 40 Mpc, diameters $\geq 0.2''$, $J \leq 25$, to be compared to ~ 100 galaxies at the same limiting magnitude (Kron 1978; Tyson and Jarvis 1979). The space telescope thus will considerably improve the tests for intergalactic globular clusters.

2. TESTS OF THE EXPANSION OF THE UNIVERSE

The general expansion of the universe is a key element of the conventional cosmology. We have strong indirect evidence of expansion from the observation that the microwave background has a spectrum close to blackbody. More direct local tests for the kinematic effects of expansion have been proposed and are well worth pursuing. Tammann (1979) noted that under the expansion hypothesis the redshift factor applies not only to the frequency of radiation but also to the observed rate of a distant event, which would not be expected in a tired light cosmology. Thus under the expansion hypothesis the light curve of a supernova observed at redshift z should have a time scale larger by the factor $1 + z$ than that of a supernova of the same type occurring nearby. Tammann points out that with the space telescope it may be possible to detect distant supernova and apply this test.

In an expanding cosmology the bolometric surface brightness of a galaxy varies with redshift as

$$\propto (1 + z)^{-4} \quad (1)$$

One power of $1 + z$ comes from the reduced energy of each photon, one from the reduced rate of reception of photons, the remaining two from aberration. In a tired light cosmology one might expect only the first effect and so the relation

$$i \propto (1 + z)^{-1} \quad (2)$$

It will be noted that these relations are independent of space curvature. Their use as a test of the expansion hypothesis was first discussed by Hubble and Tolman (1935), and the test was revived by Geller and Peebles (1972). The main observational problem is fixing the relative angular scales at which surface brightnesses of the galaxies at different redshifts are to be compared (eg. Hoffman and Crane 1977). The greatly improved angular resolution provided by the space telescope should give much more reliable measures of galaxy core radii (if they exist) and so a much better test for expansion.

A third possible test is based on galaxy counts as a function of apparent magnitude. If the universe is homogeneous we have the Robertson-Walker line element

$$ds^2 = dt^2 - \frac{a^2 dr^2}{1 - r^2 R^{-2}} - a^2 r^2 d\Omega, \quad (3)$$

where R^{-2} is a constant. In the expanding cosmology the redshift factor is

$$1 + z = a_0/a(t), \quad (4)$$

the expansion factor $a(t)$ is written as the series

$$a(t) = a_0 [1 + H(t-t_0) - \frac{1}{2}q_0 H^2(t-t_0)^2 + \dots], \quad (5)$$

and, if $\Lambda = 0$, the density parameter and space curvature parameter are

$$\begin{aligned} 2q_0 &= \Omega = 8\pi G\rho/3H^2, \\ (a_0 R)^{-2} &= H^2(\Omega-1). \end{aligned} \quad (6)$$

For purposes of comparison let us consider a tired light model with $a = \text{constant}$ in equation (3) and redshift proportional to distance,

$$dv = -vHdt, \quad v \propto e^{-Ht} \quad (7)$$

In these two models we can write the expected count of galaxies as a function of bolometric flux in the series expansion

$$\frac{dN}{df} = \Sigma \frac{n}{2} \frac{L^{3/2}}{f^{5/2}} \left[1 - \alpha \left(\frac{H^2 L}{f} \right)^{1/2} + \beta \frac{H^2 L}{f} + \dots \right]. \quad (8)$$

The sum is over the luminosity function, with L the galaxy luminosity per steradian. In the expanding model the first two coefficients in the series are

$$\alpha = 4 \quad (9)$$

$$\beta = \frac{25}{2} - \frac{5q_0}{2} + \frac{1}{2H_a^2 R^2}.$$

In the tired light model we have

$$\alpha = 2$$

$$\beta = \frac{25}{8} + \frac{1}{2H^2 R^2}. \quad (10)$$

The coefficient α is independent of the parameters in the model and so galaxy counts at $z \ll 1$ are not very sensitive as a discriminant among Friedman-Lemaitre models (Sandage 1961). That is an advantage in the test for expansion because it means the adjustable parameters are not very important. For a meaningful application of the test we would need tight control on the distribution of K-corrections from color measurements of a fair sample of the galaxies, and a reliable luminosity function from a fair sample of galaxy redshifts. Here what is needed is not space telescope but rather considerable ground-based labor. It remains to be seen whether luminosity evolution might spoil the test.

3. THE CLASSICAL COSMOLOGICAL TESTS

The theory and practice of tests meant to discriminate among Friedmann-Lemaitre models has been discussed by Sandage (1961), Gunn (1978) and other practitioners. I review here some theoretical considerations relevant to possible observations at redshifts on the order of unity.

We extract two relevant lengths from equations (3) and (4). The proper circumference of the circle described by a great circle at fixed redshift z is

$$C(z) = 2\pi a(t)r(z). \quad (11)$$

A comoving observer sees that a light pulse travelling toward us moves distance dt in the interval of cosmic time t to $t + dt$, and that distance is related to the difference of redshifts at the two events by the equation

$$dt = dz / \left[\left(\dot{a}/a \right) (1+z) \right]. \quad (12)$$

The angular size of an object with proper size d seen at redshift z is

$$\theta = 2\pi d/C(z). \quad (13)$$

In a Friedmann-Lemaitre model with $\Lambda = 0$ the ratio of expected values of θ with $\Omega = 1$ and $\Omega = 0.1$ is

$$\begin{aligned} \theta(\Omega = 1)/\theta(\Omega = 0.1) &= 1.12, & z = 0.5; \\ &= 1.24, & z = 1.0. \end{aligned} \quad (14)$$

Thus an interesting measure of Ω from observations at $z \sim 1$ requires that the systematic error in d (relative to objects at low redshift) be much less than 25 percent.

If the mass distribution is clumpy it causes fluctuations in the value of θ at fixed d and z , depending on how the tidal fields of the clumps near the line of sight affect the convergence of the light rays (eg. Dyer and Roeder 1974). However, the mean value of θ^2 is not affected because the mean solid angle per source, which is 4π divided by the number of objects in the sky, is unaffected (Weinberg 1976). If a sample of objects with small enough scatter in d were available the scatter in θ at fixed z would be an interesting measure of mass clumping (eg. Press and Gunn 1973), and we would learn even more if we had the scatter in angular sizes both for galaxies and clusters of galaxies.

The measured energy flux from a galaxy, integrated over frequencies, varies with redshift as

$$f \propto C(z)^{-2} (1+z)^{-4}. \quad (15)$$

The first factor fixes the solid angle (eq. [13]), the second factor the surface brightness (eq. [1]). Although the redshift-magnitude ($z-m$) test is equivalent to the $z-\theta$ test (in expanding cosmologies) the former has the advantage that $C(z)$ appears squared, and perhaps also that f is easier to measure than θ . We see from equations (14) that an interesting measure of Ω from observations at $z \sim 1$ requires that systematic errors of luminosities of distant galaxies relative

to nearby ones be much less than 50 percent, $\delta\langle M \rangle \ll 0.5$ magnitudes. The expected amount of evolution of M is discussed at this meeting by Tinsley.

The final test is based on counts of objects. The distribution in redshift and magnitude for objects with luminosity function ϕ is (eqs. [11] and [12])

$$\frac{\partial^2 N}{\partial z \partial m} = \frac{C(z)^2 (1+z)^2}{4\pi^2 (\dot{a}/a)} \int \frac{d\phi}{dM} (\text{type}; M=m-g(z, \text{type})). \quad (16)$$

The function g represents the redshift-magnitude relation with the K -correction appropriate to a particular spectral type. If $d\phi/dM$ is fairly narrow we have two tests for Ω . The first is the variation with m of the shape of the distribution in redshift: the z - m relation. The second is the variation in the number of objects with z , which is fixed by the factor in front of the sum. If $\Lambda = 0$ the ratio of this factor in models with $\Omega = 1$ and $\Omega = 0.1$ is

$$\begin{aligned} \frac{C^2 a/\dot{a}(\Omega = 1.0)}{C^2 a/\dot{a}(\Omega = 0.1)} &= 0.67, & z = 0.5; \\ &= 0.48, & z = 1.0. \end{aligned} \quad (17)$$

For a useful test of Ω from counts at $z \sim 1$ we would have to be sure that the comoving density of objects agrees with the local density to much better than a factor of two.

The integral of equation (16) over z yields the count-magnitude relation. At low z this N - m relation is insensitive to the parameters of the cosmological model (eq. [9]), but that is not a problem at $z \sim 1$ where the sensitivity becomes comparable to that of the other tests. The great virtue of the N - m test is that m is much easier to measure than z so the measurements can probe considerably deeper. Galaxies with redshifts on the order of unity are just about within reach of ground-based counts and well within the range of the space telescope.

The greatly improved angular resolution afforded by the space telescope may be of critical importance in helping us decide whether galaxies or clusters of galaxies might have held their shapes to within better than 25 percent accuracy since $z = 1$ and so might be useful standard lengths for the z - θ test. The possible stability of galaxies as standard candles for the z - m test has been a subject of some discussion, as is summarized by Tinsley at this conference. Again, observations of the color and appearance of galaxies at $z \sim 1$ may be expected to play an important role in the debate. The easiest observation is the N - m relation, and it will be of considerable interest to see how this goes at the depths reached by space telescope. A

full interpretation likely will await the much more difficult observation of the joint distribution in z, m and color (eq. [16]). I have the impression that the main bottleneck will be the redshift measurements and that a second generation Faint Object Spectrograph sensitive to 1μ wavelength may play a decisive role in the development of the tests.

ACKNOWLEDGMENT

This research was supported in part by the National Science Foundation.

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APPENDIX

Dr Peebles provided participants with an outline-summary entitled "The Problems of Cosmology". This summary included an indication of how the various invited lectures contribute to different aspects of these problems. Because of its pedagogic value, it is reproduced below with Dr. Peebles's permission. The abbreviations are self-explanatory (e.g., g = ground, ST = Space Telescope, etc.).

The Problems of Cosmology

I. $Z \lesssim 0.3$: THE LOCAL UNIVERSE

1. INVENTORY

a. Galaxies

- luminosity and morphology functions (Oemler)
- physical and chemical nature and evolution (Oemler, Tinsley)

b. Other objects

- constraint on abundances of luminous objects: the integrated background in the radio, infrared, optical, uv, X-ray (g, rockets, balloons, COBE, IRAS, HEAO,...)
- search for compact objects at $r \lesssim 100$ pc, $r_{\text{core}} \lesssim 10$ pc (ST)
- distributions of compact galaxies, globular star clusters in clusters of galaxies (ST)
- detecting massive dark objects in galaxies, clusters, the field (ST, ?)
- intergalactic HI, HII clouds (g, IUE, HEAO; Bahcall)
- other fossils: quasars, microwave background, extragalactic cosmic rays, quarks, magnetic monopoles, light and heavy neutrinos, other diverse particles, magnetic fields, gravitational radiation, primaeval black holes, snowballs, goblins,...

2. CLUSTERING

a. Clustering of galaxies on scales $\lesssim 10 h^{-1}$ Mpc ($H = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$)

- surveying in angular position and/or m and/or redshift: groups, clusters, cells, holes, filaments, hierarchies, clouds and superclusters (g)
- evolution of clustering (ST)

- b. Clustering on scales $10 h^{-1} \text{ Mpc} \lesssim r \lesssim cH^{-1} = 3000 h^{-1} \text{ Mpc}$
- isotropy of deep galaxy counts (g, ST)
 - distribution of galaxies in angular position - redshift space (g)
 - distributions of great clusters, quasars, radio sources (g, HEAO, ST)
 - anisotropy of radiation backgrounds (g, COBE, HEAO).

3. THE MASS PROBLEM

a. Census of the local disc and halo

- main sequence stars, degenerate H stars at $M \lesssim 0.05 M_{\odot}$, star remnants, interstellar matter (g, ST, HIPPI; Salpeter, van den Bergh)

b. M/L of stellar populations (g, ST)

c. Dynamical measures of mass, M/L

- the structure of the Milky Way galaxy (van den Bergh, Oemler)
- velocity dispersions as functions of position in elliptical galaxies and in the bulges and halos of spirals (g)
- velocities of companions and satellites - galaxies, globular clusters, HI and HII regions (g)
- peculiar velocities derived from redshift statistics (g, ST)
- tests of the inverse square law (?)

4. THE GENERAL EXPANSION

a. Evidence of expansion: distinguishing the expected kinematics of expansion from predictions of tired light cosmologies

- $\delta\lambda/\lambda$ independent of λ (g, S)
- surface brightness $\propto (1 + Z)^{-4}$ (ST)
- timing $\propto (1 + Z)$ (g, ST)
- count-magnitude-redshift relations (g, ST)
- redshift \propto distance (g, ST)

b. Time and distance scales

- astrometry (Tammann)
- Hubble's constant (Tammann)
- ages of galaxies, stars, the elements, the Solar System (Freeman, van den Bergh, Tinsley)

5. OTHER PUZZLES

- black holes; matter-antimatter; matter creation and annihilation; variations of fundamental constants; unconventional redshifts; unconventional physics

II. $0.1 \lesssim Z \lesssim 3$: THE UNIVERSE NEAR THE HORIZON

1. EVOLUTION OF STRUCTURES

a. Galaxies

- color and magnitude: K-correlation, Scott effect and evolution (Tinsley)
- morphology: details at $Z \lesssim 0.3$, gross classification of the brightest galaxies at $Z \sim 1$ (ST)
- clustering: galaxy types, gas content, cluster morphology (HEAO, ST)

b. Quasars, blank field radio sources and beyond

- abundance as a function of Z ; evolution
- clustering among themselves, around galaxies (Sargent), Bahcall, Longair)

2. THE CLASSICAL COSMOLOGICAL TESTS

- count-magnitude relation to $Z^* \sim 1$ to 2 (ST)
- count-angular size relation to $Z^* \sim 0.5$ to 1 (ST)
- redshift-magnitude relation for giant galaxies to $Z \sim 0.5$ (g, ST)
- redshift-count relation for great clusters to $Z \sim 0.5$ (g, ST)
- redshift distribution of galaxies by apparent magnitude (g, ST)

III. $Z \gtrsim 2$: THE YOUNG UNIVERSE

1. FORMATION OF GALAXIES, CLUSTERS

- a. What does the sky look like at low surface brightness: spotty due to isolated compact protogalaxies? mottled by overlapping diffuse protogalaxies?
 - radio: young active galaxies, quasars, HI clouds (g)
 - microwave: irregularities present at decoupling; perturbations by intervening protogalaxies and protoclusters (g)

- infrared: highly redshifted starlight if stars formed early (COBE, IRAS)
- optical: the light from galaxies at moderate redshift (g,S)
- uv: starlight from very active galaxies at moderate redshift (DUVS ?)
- X-ray: hot gas from collapsing protogalaxies and proto-clusters; active young objects; patchy intergalactic matter (HEAO)

b. Spectrum of the electromagnetic background

- microwave background: distortion from a Planck spectrum by departures from homogeneous isotropic expansion; absorption and emission by intervening matter (COBE)
- infrared - optical - uv - X-ray background: integrated light from early generations of objects (COBE, HEAO, S)

2. BEYOND THE FRINGE

a. Remnants of the Big Bang

- light element abundances (ST, S)
- quarks and beyond (?)

b. Origin of the Big Bang

DISCUSSION

Baum: The two distant indicators, galaxy diameter and galaxy magnitude, used in classical cosmological tests are intimately linked with one another and are not easily separable. If the luminosity profiles of individual galaxies followed a simple power law $I = I_0 r^{-n}$ with constant n , it would be impossible to distinguish a distant intrinsically bright galaxy from a nearer intrinsically faint one, and cosmology would be impossible. In the real world, n is not quite constant, and the ability to measure diameters and magnitudes correctly is dependent on that. But the luminosity profile of a galaxy departs only mildly from constant n within the portion of the profile that is feasible to measure at large distance, so in practice it is difficult to determine diameters and magnitudes correctly. Photometric imaging with the Space Telescope CCD cameras should make it possible to handle this problem better than in much earlier work.

Tinsley: The counts of faint galaxies by Richard Kron which extend to 24th magnitude disagree with the predictions of uniform world models. Thus, contrary to what might have been implied by Peebles, the counts of galaxies do not seem to be a particularly sensitive cosmological test for q_0 .

Spinrad: There is a counter-argument to what Beatrice has just said. If one has colour information and if one believes models for the colour evolution of galaxies, one can take out the evolutionary changes and find a self-consistent solution for the age of the galaxies and q_0 from the counts.

Tinsley: Kron tried to do this but was not successful.

Einasto (Discussion leader): One of the key problems of cosmology is the study the large-scale structure of the Universe. The comparison of the large scale structure at different redshifts gives us information about the physical processes which have led to the formation of this structure. In particular, it is possible to discriminate between different cosmogonic scenarios: gradual clustering of galaxies and clusters from smaller units or the formation of proto-superclusters first and galaxies thereafter as in the "pancake" theory.

The local large scale distribution of galaxies has been studied recently using large samples of redshifts (e.g. by Gregory, Thompson and Tifft; Tarenghi, Chincarini and Rood; Einasto, Joeveer and Saar). These studies have shown that galaxies and clusters are concentrated into cluster chains and more or less plane sheets in between - super-clusters of galaxies.

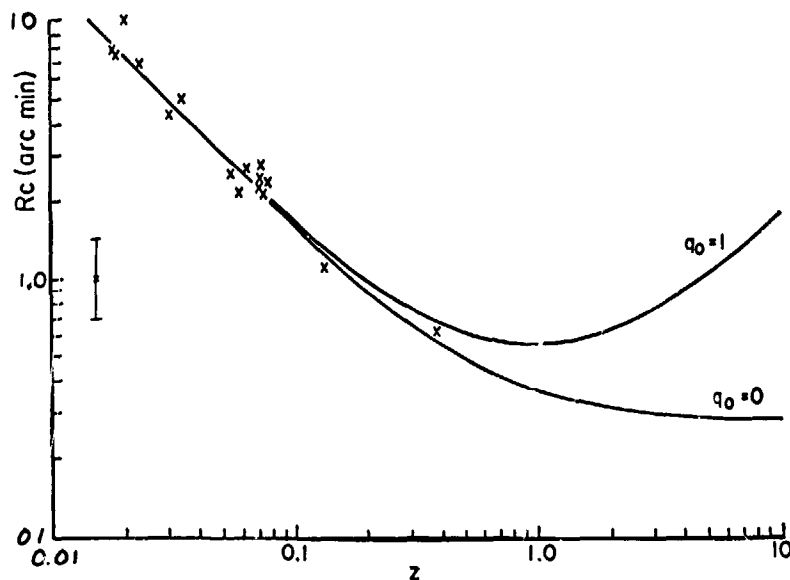
Most of the cluster chains consist of poor clusters and consequently their detection at large redshifts is impossible as is the detection of

sheets of galaxies. However, some chains, such as the Perseus chain of galaxies, are very rich and these can be detected at high redshifts and may be considered as supercluster indicators. The computer processed map of the Shane-Wirtanen counts of galaxies (Seldner, Peebles and collaborators) shows that at redshift $z \approx 0.15$, cluster chains are clearly visible. Thus supercluster chains existed at a look-back time of ~ 3 G years.

To follow the evolution of the clustering over a longer period, cluster chains should be observed at larger redshifts. To reach $z \approx 0.5$, galaxy counts to $m \approx 20.5$ should be made; counts to $m \approx 22-23$ give information about the structure at $z \approx 1$. Galaxy counts can be made with ground-based wide field telescopes. Cluster redshifts can be measured with large ground-based telescopes using CCD detectors. Radio and X-ray data are also essential because all rich clusters contain radio galaxies and are extended X-ray sources. Detailed study of the morphology of galaxies in cluster chains can only be made with ST. Local rich clusters are very rich in elliptical and SO galaxies. It is of fundamental importance to follow the evolution of the morphology of galaxies in cluster chains.

Groth: We have a major industry in Princeton working out the statistical properties of the clustering of galaxies. We are now studying deeper samples of galaxies from deep plates taken with large ground-based telescopes and we realistically expect to study the clustering of galaxies with mean redshift $z \sim 0.4$. With ST, it is feasible to study the clustering at a mean redshift $z \approx 1$. With a modest number of wide field camera frames, we should be able to obtain a sample of say, 1000, galaxies for statistical studies. We believe that the evolution of the clustering properties of galaxies on large scales with cosmic epoch should be easier to understand than the evolution of individual galaxies but we shall see.

N.A. Bahcall: The core radii of the galaxy distribution in rich compact clusters appear to be rather constant (Bahcall 1975. Ap. J., 198, 249, 1977. Ann. P. Astr. Astrophys., 15, 505). When measured for the brightest ~ 3 magnitude galaxies in a cluster, this size is found to be (Bahcall) 0.25 ± 0.05 Mpc ($H_0 = 50$). A somewhat larger value of typically ~ 0.3 Mpc is found by Dressler (1976 Ph.D. dissertation, Santa Cruz) for the distribution of much fainter galaxies. This is shown by Quintana (1979 A.J., 84, 15) and Sarazin (1979 preprint) to be partly due to a weak dependence on limiting magnitude of the measured core size. This relatively small spread in the core radius when measured in a consistent manner suggests that core radii of galaxy clusters may provide a standard-size for use in the angular-size-redshift cosmology test. The angular-size-redshift relation for a 0.25 Mpc radius is shown in the figure for two values of q_0 : 0 and ∞ . The crosses are measurements by Bahcall (1975). The Wide-Field-Camera on Space Telescope can be used to measure core radii of clusters of galaxies at large redshifts, $z = 0.5 - 2$,



($R_c < 1'$ at $z = 0.5-2$). At $z = 2$, the difference between $q_0 = 0$ and 1 models is a factor of two in measured angular size. This is a relatively large difference; a reasonable sample of distant clusters ($\sim 10-20$) may be exploited to set limits on q_0 (assuming further work from the ground for $z < 0.5$ continues to show a relatively small spread in the core-size).

The evolution of core-size with epoch may be dominated by the dynamical evolution of the clusters. Additional observational information on the structure of the X-ray emitting intracluster gas and the galactic content of clusters at high redshifts would be helpful in calculating this evolution.

Spinrad: I want to address the question of the determination of the redshifts of normal galaxies at large redshifts. From the stellar content of a galaxy we observe absorption features and from the gaseous component various emission lines. Let me deal with the absorption spectra first.

In the standard optical spectrum of a galaxy, the main absorption features are the H and K lines of CaII, the 4000 Å break and the G band absorption feature. The optical spectrum has thus two characteristic breaks which enable redshifts from 0.2 to 0.6 to be determined. At larger redshifts, there are two main problems. First, I believe the stellar populations of galaxies evolve so that there are more hot stars in distant galaxies and this decreases the amplitudes of the breaks. Second, the features are shifted to long wavelengths. With the faint object spectrograph which cuts off at $\lambda 7000 \text{ \AA}$, it will be difficult to measure redshifts beyond $z \approx 0.8$ using these features. It may be

possible to measure redshifts using multi-filter photometry provided one has some confidence that one knows what the intrinsic spectra should look like.

At shorter wavelengths, there are discontinuities of larger amplitude in the Sun and F stars at λ 2900 Å and λ 2600 Å due to line blending. This should take one out to a redshift $z \approx 1$. To measure larger redshifts, there is a silicon edge at 1600 Å but for very large redshifts, one may have to use the Lyman limit at 912 Å. We do not know what this will look like. There is of course the problem that if you observe a spectrum with a single break in it, how do you identify it? It is to be hoped that there will be other helpful features in the spectrum.

Concerning emission lines, there may be some galaxies with active nuclei and high excitation lines but in general there will only be the emission lines of HII regions heated by stars with black body temperatures of, say, 30 000 K. None of the strong emission lines observed in Seyfert nuclei will be observed. λ 3727 should be useful out to $z \approx 1$. The strength of Lyman- α is unknown but may be usable. The spectra of normal galaxies measured with IUE so far do not hold out much promise but there is an urgent need for more studies with this satellite so that it is clearer what will be possible at large redshifts.

Oke: For the last few years, Jim Gunn and I have been measuring the redshifts of the brightest galaxies in clusters which were discovered by purely optical means according to strict magnitude selection criteria. About 80 brightest cluster galaxies were measured in the magnitude interval 19 to 22. About 75 of these galaxies have $m < 21.5$ and 90% of these have normal energy distributions. Their redshifts are typically about 0.5. About 5-10% of these 75 are peculiar in the sense that they are blue and redshifts have not been determined. Thus, there is not much evidence of colour evolution in this sample of galaxies.

We have, however, 6 objects with $m \approx 22$. Three of these are normal galaxies like those at small redshifts but with redshifts $z \approx 0.55$. The three others have peculiar energy distributions and the redshifts are not certain. It is expected that they should have redshifts $z \approx 0.6-0.65$ and the red end of the spectrum would agree if they have $z \approx 0.65$. However at shorter wavelengths, there is no H and K break and the spectrum is much bluer than that of a normal galaxy. These observations suggest that the percentage of peculiar blue objects increases at $z \approx 0.6$.

The above observations were made with the multi-channel spectrometer. To go to fainter magnitudes, particularly in the red, Jim Gunn has built a low resolution CCD spectrometer with very high quantum efficiency in the red which should take us out to $z \approx 1$ and $m \approx 23.5$. For larger redshifts we will have to take UV spectra as described by Spinrad and this looks quite promising.

Gott: Local tests for the value of Ω complement the classical cosmological tests which use objects at large redshifts. Local tests include virial mass determinations in groups and clusters of galaxies and statistical virial theorem studies. These are and will continue to be essentially ground based projects. These tests measure all the mass, visible and invisible, which clusters with the galaxies. There are some theoretical difficulties with having a large fraction of the mass of the universe in a form which does not participate in this clustering (cf. Gott, Gunn, Schramm, Tinsley 1974 Ap. J., 194, 543).

The most important local test of Ω for which the Space Telescope will be of great help is the mapping of the velocity field in the Local Supercluster. The observational prospects for such a study with ST were covered by Tammann in his talk yesterday. This type of study will provide a sensitive test for the value of Ω due to the clustered component. Counts of galaxies show the Local Supercluster to be a density enhancement of a factor of several over the mean density in the universe. In the standard picture, the Local Supercluster started as a small density enhancement at recombination which because of its excess density has accelerated more than the rest of the universe. Thus we expect the current expansion rate within the Local Supercluster to be slower than outside. The value of Hubble's constant measured within the Local Supercluster (H_{IN}) should be smaller than the value measured outside (H_{OUT}) using galaxies with $V \gtrsim 3000 \text{ km s}^{-1}$. For a given local density enhancement, the ratio (H_{IN}/H_{OUT}) depends on the value of Ω . (We will assume a cosmological constant $\Lambda = 0$ throughout). The lower the value of Ω the closer the ratio (H_{IN}/H_{OUT}) is to unity. In a low density universe the overall deceleration is small and the additional deceleration produced by a density enhancement is also small.

To illustrate the sensitivity of this test for Ω let me compare as examples the values of H_{IN} , H_{OUT} reported by Tammann and Huchra yesterday.

First let me describe Tammann's results. Sandage, Tammann & Yahil (1979 private communication) have found that a sphere of radius $\sim 20 \text{ Mpc}$ centered in the Virgo cluster contains approximately 4 times the number density of galaxies as a larger surrounding region. Tammann finds $H_{OUT} = 55 \text{ km s}^{-1} \text{ Mpc}$. From distance indicators he expects the Virgo cluster to appear at redshift $V = 1100 \text{ km s}^{-1}$. Its actual velocity is 950 km s^{-1} indicating that we have a peculiar infall velocity of $\sim 150 \text{ km s}^{-1}$. This gives $H_{IN} = 47.5$. Combining H_{IN} , H_{OUT} and the enhancement factor of 4 we find $\Omega = 0.06$. Since H_{OUT} is a function of Ω we can also solve for the present age of the universe: $t_0 = 16.5 \times 10^9 \text{ yr}$. This is consistent with the age of the oldest globular cluster stars. The ages of the oldest globular cluster stars depend on the primordial Helium abundance which depends on H_0 and Ω . For the above values we find $t_g = 15 \times 10^9 \text{ yrs}$. (In fact Gunn (1978) has shown that with current

data $t_g \leq t_0$ requires $H_0 \lesssim 60 \text{ km s}^{-1} \text{ Mpc}^{-1}$). The Tammann values for H_{IN} , H_{OUT} produce a low density universe with a consistent age.

Huchra reported values of $H_{IN} \approx 62 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $H_{OUT} \approx 90 \text{ km s}^{-1} \text{ Mpc}^{-1}$. With these distance scales Huchra places the local supercluster galaxies a factor 1.25 further away relative to the distant galaxies than Tammann. The relative number density of galaxies in the supercluster is decreased by $(1.25)^3$ but each galaxy becomes more luminous by $(1.25)^2$ so the luminosity density enhancement in the Supercluster is decreased by a factor of (1.25) to a value of 3.2 times the density outside. With this value and H_{IN} , H_{OUT} we compute $\Omega = 0.35$, and $t_0 = 8.6 \times 10^9 \text{ yrs}$. Note that the ratio H_{IN} , H_{OUT} gives a sensitive test of Ω . The above value of t_0 is perhaps embarrassingly small. For fixed H_{IN} , increases in H_{OUT} shorten the age of the universe both because H_{OUT} is larger and because this produces an additional deceleration. One must also note the observational point that any Malmquist bias (cf. Tammann's discussion) will have the effect of increasing H_{OUT} relative to H_{IN} causing us to overestimate Ω .

With the Space Telescope one can map the velocities and distances of galaxies out to $V \gtrsim 3000 \text{ km s}^{-1}$. One can measure the density enhancement due to the Local Supercluster and the Hubble expansion inside and outside the supercluster. This will give us an important independent estimate for the value of Ω which will supplement those obtained from clusters and groups of galaxies and those from classical tests with galaxies at large redshifts.

Ostriker: I want to discuss dynamical effects in the evolution of galaxies and how this can be tested by observation. There are two forms of dynamical evolution. The first is tidal stripping which must be very common in the Universe and is the process by which stars are torn from the outer parts of galaxies making them fainter. The other is merging of galaxies (or cannibalism) which is very much rarer. In general merging of galaxies is not important and it is certain that most E galaxies did not form in this way. However, for galaxies in clusters and, in particular the brightest galaxies in clusters which are important for cosmology, merging is important and I want to address the question of estimating how much merging has taken place in a given cluster.

There are three dominant effects. First, with time the galaxies get brighter and bigger, the radius being conveniently measured by the parameter $\alpha = d(\log L)/d(\log r)$. Second, the magnitude - core radius relation deviates from the relation for normal galaxies. Third, brighter galaxies are redder than fainter galaxies and therefore during cannibalism, the brighter the galaxy gets, the bluer it gets rather than redder. Thus, in all three cases, the merged galaxies deviate from the normal relation.

The problem is that the "normal" relations for these quantities are not well known, in particular, core radii are very poorly known. My proposal for ST is to measure properties such as colours, core radii etc for normal galaxies and establish the normal relations. If one then sees objects deviating from the standard relations, one can correct them back to the standard relations through the theory of merging galaxies and thus eliminate this dynamical effect when one is studying the redshift-magnitude relation.

Wilkinson: Partridge and Peebles suggested two ways of searching for primaeval galaxies. The first is the search for the background light from young galaxies if there were a burst of star formation at large redshift. The problem is that the background due to zodiacal light is very high in the waveband where it is best to search and there are only upper limits on the background. The alternative is to search for individual very red extended objects which may be identified with young galaxies. We have deep observations using CCD detectors on the 4-metre Kitt Peak telescope which we are using to search for these objects at very faint magnitudes. We have not found any of these faint red extended objects in 8 fields. Using the WFC on Space Telescope, I estimate that in a single 1-hour exposure one will gain perhaps 3 to 5 magnitudes over what can be done from the ground and this is all because of the much lower sky background at $1 \mu\text{m}$ in space.

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SUMMARY OF THE CONFERENCE

James E. Gunn
Hale Observatories
California Institute of Technology

There has been presented at this conference a bewildering variety of problems for the Space Telescope, so many and so broad in scope that it is clear that the instrument in its lifetime will not be used for all of them, however able it may be to solve them and however interesting they may be.

There are several conclusions to be drawn from this state of affairs, and I wish mostly in this summary to discuss the conference in the light of those conclusions.

First, it is clear that it would be criminal to use ST for problems that can be solved from the ground, even if their solution using ground-based techniques is laborious in the extreme. I have made a list, almost certainly woefully incomplete, of problems that can probably only be attacked by ST or its like. They come mostly from the conference, and I will occasionally use my privilege of having the last word to chide my colleagues for leaving out a few important things.

In the solar system, high resolution UV spectroscopy with the HRS will allow study of atmospheric chemistry in all (but most interestingly in the outer) planets. Jupiter in particular promises a gold mine. The resolution of ST is, as we have heard, sufficient for rather detailed meteorological studies on Venus and Jupiter. The very large amounts of time required to do this problem justice may be difficult to obtain; but it would seem to me that at some point in the life of the mission some protracted study should be undertaken.

ST will not resolve the nuclei of comets, but monochromatic imagery and UV spectroscopy of the nuclear region will almost certainly yield improved understanding of the physical processes in these primitive bodies.

The understanding of the interstellar medium seems to be in a state of continuous evolution; in many respects, the HRS on ST will have the final word on several interesting problems. Copernicus has resolution which is tantalizingly close to enough, but ST will be able to resolve blends and indeed resolve the expected motions within single clouds. The aperture and resolution will allow the study of very much larger volumes of space; UV spectroscopy of stars behind moderately dense molecular clouds will yield direct probes of molecular chemistry and provide several tests of molecular formation and destruction dynamics.

IUE has already opened up a fascinating new topic which ST will be able to extend beautifully: the study of the far gaseous halo of the Galaxy, and, indeed, other galaxies. Detailed absorption line spectra of Magellanic Cloud stars and bright QSOs will elucidate the physical conditions in the halo and almost certainly answer the question of whether such structures cause the absorption line spectra of quasars.

Little attention was given to problems of star formation, which brings me to a suite of problems for ST for which few counterparts exist in ground-based astronomy. One might call them "voyeur"-problems. In the solar system, one can observe phenomena with imaging devices and see rapid changes. In galactic astronomy, the size scales and velocities and the span of human life and attention is such that, except for rapid photometric variation of essentially point sources, one observes an essentially static universe. There are, of course, exceptions - changes in nova and supernova shells and reflection nebulae are seen, and binary motion is seen - but ST will, in two areas, enormously enlarge this list. In the Taurus dark cloud, 100 pc away, stars are forming; the resolution of moderately enhanced ST pictures at this distance will resolve about 5 A.U., corresponding to dynamical times of a few years for one solar mass objects. One may be able to see matter falling into and/or flowing out of protostars and may see pre-planetary disks. The other case of "motion watching" which will be of enormous interest is the Crab Nebula, in which ground-based data whet the appetite, which ten times the resolution may or may not slake, but will be certain to be interesting.

One of the most active areas of extragalactic research at present is the study of stellar populations, a game played with considerable difficulty from the ground because of limitations in limiting magnitude, and, but also more importantly, confusion. One will reach with ST through Baade's window in the bulge of the Galaxy to well below turnoff, yielding an answer to the crucial question (in one instance, at least) of what the formation mass function is in an elliptical-like population. In M31, one will be able to reach almost to the turnoff in the oldest stellar population, and explicit removal of the bright stars will allow very

much better study of the faint population than will ever be possible from the ground. The very faint main sequence will be reachable in globular clusters and to a lesser extent in the dwarf spheroidals. There will be an enormous amount of data where now there is essentially none toward answering the questions concerning the kinds of stars that form under widely differing physical and chemical conditions in the universe, and how the formation mechanisms affect and are affected by the dynamics and morphology of the present system. It is worth being reminded that we live in a universe ninety percent of whose mass we are aware of only because it gravitates, but whose nature is entirely unknown. It is not clear that it has anything whatsoever to do with star formation, but it would be nice to know.

Stars per se also received short shrift in these proceedings, and it is interesting to note that a number of spectroscopic binaries can be resolved using ST which are close enough that complete dynamical parallaxes can be obtained using both velocity and separation information. The cosmic distance scale, which ST has long been supposed to determine accurately, can, perhaps, start very close to home.

Star formation, the interstellar medium, and gravitation together make galaxies, and it is in the high resolution study of their component parts that ST will make significant advances.

For the evolution of galaxies, it is the high resolution and the near-infrared imaging capabilities of ST which will be valuable. Counts from the ground already reach to the 24th magnitude, and ST will extend that by a couple of magnitudes, but the exciting possibility delivered by ST is the study of the morphology of external systems to the largest distances to which they are detectable. The accompanying photographs are simulations of wide field camera images of 1000 sec exposure on an Sc I and a barred spiral. The resolution and noise characteristics are based on the expected performance of the instrument, a night sky of 23^m per square arc-seconds in the visual, and a passband which remains at 4500 \AA in the galaxy rest frame and is 20% wide. The Sc I is seen at simulated redshift of 0.078, 0.180, and 0.50; the barred spiral at 0.051, 0.12, and 0.27. The last picture of the set is of the barred spiral at a redshift of 1.0, as imaged with the Planetary Camera with modest image enhancement (resolution enhanced by a factor of 1.4) with 8000 seconds of data (four 2000 sec exposures).

It is apparent that one can study structure in galaxies to very large distances indeed; the study of the evolution of galaxies reduces to the (still difficult) problem of selection: Who are whose precursors?

The exciting prospect of using supernovae as distance indicators has been rather exhaustively discussed here; even if (as seems likely) the spectroscopic task imposed by the Baade-Wesselink

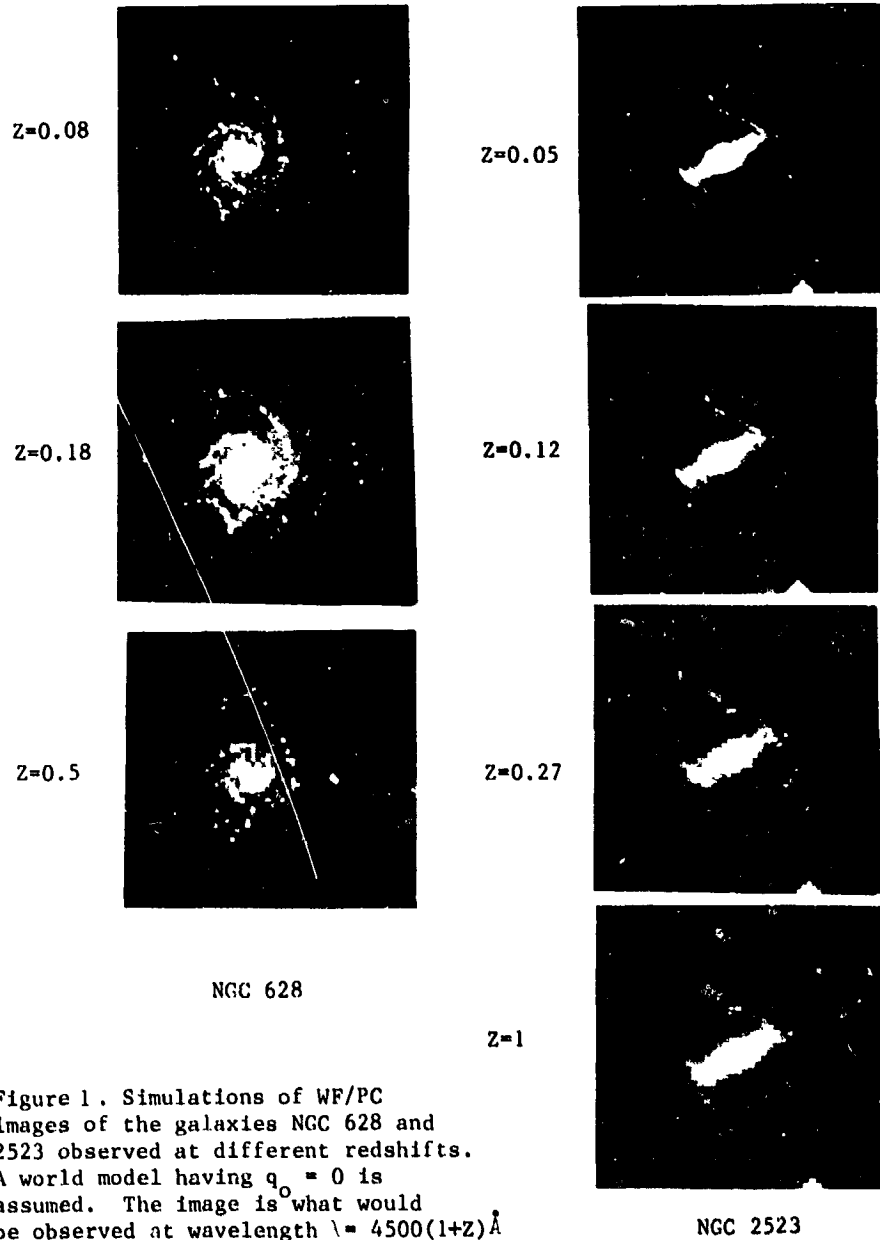


Figure 1. Simulations of WF/PC images of the galaxies NGC 628 and 2523 observed at different redshifts. A world model having $q_0 = 0$ is assumed. The image is what would be observed at wavelength $\lambda = 4500(1+z)\text{\AA}$. The simulations for all images except NGC 2523 (Z=1) are 1000 sec exposures in the WFC mode. That of NGC2523(Z=1) is a Planetary Camera image which is a composite of 4x2000-sec exposures.

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technique is beyond the capabilities of ST, purely photometric techniques appear very promising.

What ST will say about the quasar problem is not clear; we have heard a very carefully considered suite of problems concerning absorption lines which ST can address; to some extent this is almost certainly a problem concerning galaxies and/or the intergalactic medium, not QSOs themselves. The question of the association of quasars with galaxies can certainly be elucidated with ST, especially if the small-angle scattering properties of the optics are as good as they might be. To me the most exciting prospect for the QSO problem attackable with ST will come from the study of relatively nearby active systems where QSO-like things are going on on a much smaller scale. Systems like M87, 4278, 1068, are near enough that much can be learned about the dynamics and inflow of matter into whatever engine powers the nonthermal activity.

The problem of the distance scale is one about which so much has been written and said in connection with ST that it needs no comment. Suffice it to say that it is evident from the controversy still surrounding the problem that it has not been solved from the ground, and that the faint limit and high angular resolution of ST render it an incomparable tool for its solution - not that it will be easy even with ST.

The classical cosmological problem - i.e., discovering which Friedman model is the "correct" one for the universe - is, of course, just an extension of the distance scale problem, and with ST even some of the distance scale techniques can be adopted for its solution. The classical tests using galaxies can be applied in a unique way with ST, because the sizes of the galaxies at large redshifts can be resolved, and there is hope that those classical tests may yet yield a global value of the deceleration parameter which can be compared with what we hope by then will be a quite well-determined value for the density parameter from studies of nearby systems. ST's ability to study galaxies at very large distances will make it an invaluable cosmogonic tool for the study of the origin of structure in the universe, which is, perhaps, as interesting as the global questions.

The questions raised here will hopefully not be all the interesting ones when ST flies, and whether they are or not, the most exciting results will certainly be serendipitous.

This conference has dealt little with ground-based preparation for ST, and it is worth considering a little. The awesome pressures on ST can be alleviated somewhat by good homework before and during the mission. Technology, some of it directly related to ST, has made ground-based telescopes potentially enormously more powerful than they were even a couple of years ago. We recently completed a small, low-resolution CCD spectrograph and

camera for use at the prime focus of the 200-inch telescope, which has a 30% total effective throughput; a galaxy spectrum of one hour's exposure and a five-minute exposure of the cluster are shown. The redshift is 0.53 and the visual magnitude 21.8. A fifteen-minute exposure of the spectrum would easily have yielded the redshift. It is to be fervently hoped that these magnificent detectors will be produced and made available for ground-based use; the gulf separating "ordinary" astronomy on the ground and some of the capabilities of ST will, I think, be narrowed enough to significantly sharpen the effort for ST itself.

The last point I wish to discuss is a sociological/political one. Whatever problems for ST remain elusive at present, the set of more-or-less obvious ones is so large that ST cannot work on them all. Who gets to do them? Hopefully not the proposer with the earliest postmark, but that is an obvious solution. The community needs desperately to invent a mechanism to make efficient, fair use of ST in a way which will involve all capable interested parties. Problem-oriented teams are one possibility, and there may be others; it is clear that some approach must be worked out before the telescope flies.

It looks as if it will finally happen, this magnificent machine, and I would like to extend my personal thanks and, I trust, the thanks of the whole community, to those in the community who have worked for years to make it happen, and to those at NASA Headquarters and Goddard and Marshall, and at ESA who are making it happen, and perhaps especially to Lyman Spitzer whose vision it was to begin with.

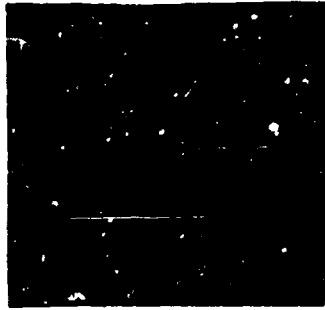


Figure 2. The cluster 160131+4254 observed with the Hale 5-meter telescope using a camera employing a 500x500 CCD developed by Texas Instruments as part of the development program for Space Telescope. The exposure was 5 minutes in a band 1000 wide centered at 6500

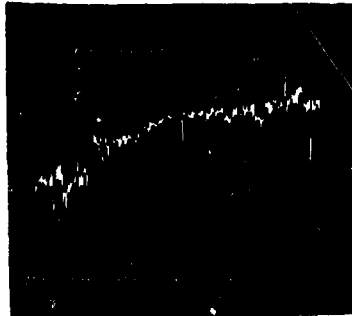


Figure 3. The spectrum of the brightest member in the distant cluster 160131+4254 taken with the CCD camera in its spectrographic mode. The exposure was 4000 sec. The r magnitude of the galaxy is 21.8, its redshift is 0.53.

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NASA IN-HOUSE ASTRONOMERS - VERSE AND CONVERSE

Noel W. Hinners
National Air and Space Museum
Washington, DC 20560

It is a particular pleasure to be here tonight, the degree of pleasure having been heightened by the unaccustomed luxury of participating, albeit rather passively, in the scientific discussions of the past days. The net result of the listening is an increased conviction that astronomy offers, along with biology, the best prospects of all the sciences for major increases both in our comprehension of nature and, simultaneously, in our awe at nature's complexities and energies. To the degree that the Space Telescope brings those prospects to fruition, it will have to rank as one of the premier astronomical tools of the 1980's and 90's. But I don't need to preach its merits to this audience. What I'd rather do is to give you some of my views on a topic commonly thought to be an "issue" and which has risen to a state of high visibility within NASA in large part on account of the Space Telescope and its operation. That "issue" revolves around the scientist who happens to work in NASA.

Most simply, the issue can be formulated as a number of statements which are thought by some non-NASA scientists to represent basic truths. To wit, the average NASA scientist:

1. Is not as "competitive," i.e. competent, as his academic counterpart, and obtains large amounts of supporting research and technology funding through an uncompetitive system;
2. Is guaranteed a job and security by dint of the "un-civil" service;

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3. Gets preferential consideration in the allocation of research funding because the salary is not paid by the R&D budget;

4. Spends full time on research without the intrusion of students and committees;

5. Exerts undue influence on NASA Headquarters concerning scientific priorities and objectives; and

6. Has access to a large engineering capability which gives a favored position when competing for flight projects.

So far, you will notice that I've not been talking specifically about astronomers but have generalized to include all NASA scientists and for good reason; that is, non-NASA astronomers are not unique in their perceptions of the internal NASA scientist and centers. In fact, when I was at NASA, it became a common topic of conversation at meetings of the Physical Sciences Committee (PSC) (later the Space Science Advisory Committee) once in a while quite vociferous but more often sotto voce. My earliest inclinations, five years ago, were to ignore the rumblings and to chalk them up to sour grapes and a lack of visibility into the workings of NASA. The persistence, however, soon became bothersome. This was exacerbated by the tone of some of the discussion surrounding the Space Telescope and its operation. Clearly, we at NASA were dealing with a new (to us) community who had very little insight into NASA and who were used to a particular type of operation and interaction with the Government, a type I lump under the rubric "NSF-mode." The community you may recognize as one we in NASA loosely referred to as the "ground-based astronomers" (you may well ask, "is that in contrast to the astronomer based in space?").

Oversimplifying, it initially seemed to me that the desire of the ground-based astronomers to operate the Space Telescope via a Space Telescope Science Institute was primarily a paranoid reaction to the perceptions of NASA listed earlier, augmented by a desire to do business in the NSF-mode and further fueled by a belief that NASA sees itself as a builder of projects to the detriment of long-term operations. It might have been relatively easy to dismiss the arguments out-of-hand, point to successful NASA-astronomer relations and operations in the Copernicus and SAS projects, later augmented by HEAO and IUE, and tell the ST proponents that we'll do it the standard NASA way, take it or leave it.

Why didn't I? Partly because I, a few others at NASA Headquarters, fewer yet at NASA centers, harbored suspicions that some of the concerns were valid and, more significant, many of the people expressing concern were obviously not cranks but respected members of the scientific community. At the same time, all considered, it also seemed necessary and desirable to clear the air of what I was convinced were, and to a large degree remain, wrong impressions about the NASA scientists. Let me work my way back now to the statements of perceptions.

You are all aware of the outcome of the deliberations about an ST Science Institute. The decision to proceed with the ST Science Institute has been viewed by some NASA scientists, particularly at the Goddard Space Flight Center, as a vote of no-confidence in their integrity and abilities, and as an explicit acceptance of the validity of the external perceptions listed earlier. Not so.

The NASA headquarters support for the ST Science Institute concept as it now exists can be attributed largely to the fact that it: (1) is what the bulk of the ST user community wants, is comfortable with, and has the potential competence to manage (I recognize, however, that one element of the user community's desire for an Institute is based upon the perceptions), (2) has real advantages as detailed in the Space Science Board study report, (3) doesn't cost appreciably more than if done totally "in-house," and (4) leaves to NASA those operational aspects which, in NASA's view, cannot or should not be "contracted out."

Although I maintain that the validity, or lack thereof, concerning the external perceptions about NASA and NASA scientists had little to do with NASA's ST Science Institute decision, the perceptions must be addressed. Let me first deal with NASA as a development-oriented agency. If one must generalize, my conclusion is that NASA in aggregate is indeed dominated by a "build-it" attitude, where the perceived challenge is mainly one of overcoming technical hurdles and of conceiving and implementing new, complex, sophisticated systems (sometimes overly so).

This has shown up in the past. For example, the decision to return to the moon after Apollo 11, largely for scientific reasons, was not uniformly popular in NASA. The predominant desire of the "Manned" space flight side was to get on with the Shuttle development. In some of the

early budget crunches, although Shuttle funding was also decreased, Apollo's 18-20 were completely deleted and Viking was delayed two years (I have no hesitation in believing that the Viking slip was a blessing).

With the end of Shuttle development in sight, there is an increasing sense of frustration in parts of NASA because there is no obvious major development goal to shoot for. Rationality is prevailing, but for awhile the desires were, on occasion, being expressed in the form of uncritical proposals for commitments to the likes of near-term space manufacturing and solar power satellites. Another related thought to ponder, as NASA is doing, is the possibility of contracting for the operation of the Space Shuttle when, and if, it becomes operationally routine -- the kind of thing that just does not require the same type of talents and interests NASA is known for and does well.

One can find examples, of course, of successful NASA long-term involvement in operations, e.g., launch vehicles Skylab, Kuiper Airborn Observatory, IUE, HEAO, Voyager, etc. but even in those systems much of the day-to-day routine effort is run by contractors.

A net result of NASA's orientation is a tendency, sometimes very subtle, to put development ahead of operations in the priorities. This is true on occasion even in Space Sciences, especially when a development project is in an overrun condition.

I conclude, not that it is wrong for NASA to be development-oriented, but that if there is a long-term high priority operational science program, an external well organized operator and advocate, such as the ST Science Institute, is a good thing.

The thrust of my talk now is to deal with the perceptions about the scientists in the hope that where they are valid the corrective action has been, or will be, taken and that where invalid the real situation can be demonstrated or at least advocated where judgment is required in place of hard fact.

1. Competitiveness and competency -- in the Office of Space Science we maintained that, all else being equal (yes, I'm aware that it usually isn't!), the science funding

should be used for the highest quality science, regardless of where the scientist is located. The most acceptable method at our disposal for ascertaining the quality of the science and of the scientist is by the proposal and peer-evaluation route. A study by the Physical Sciences Committee, published in May, 1976, was aimed at investigation among other things, of the balance between and the accountability of research projects at the NASA centers and at the universities. The Committee determined that they were satisfied, or "at least not dissatisfied" with the present balance of effort between NASA centers and universities but that the review procedure for in-house work needed to be beefed up with uniform procedures applied to both in-house and university research. That recommendation was implemented and should go a long way to assure that quality work is done across-the-board.

2. Guarantee of a job by dint of Civil Service -- there is some truth to this. However, the research money can be, and has been when warranted, cut off. The scientist still gets paid, albeit out of a different pot of money, and one can legitimately argue that taxpayer money is being wasted. Frequently, the scientist is transferred to another activity within NASA and on occasion leaves. It is not, I admit, a good system; my only retort as regards the university community, is to tell you that the tenure system suffers in the same way.

3. Preferential consideration in allocation of research funding on account of salary being paid from a non-R&D "pot" of money. The PSC and NASA agreed that in-house research appears to be about 40% less expensive than university research. The recommendation was, simply, that NASA officials in charge of research funding maintain an awareness that the appearance is deceptive and that the real costs are about equal between centers and universities.

4. Spends full time on research without the intrusion of students and committees. There undoubtedly are NASA researchers who enjoy the luxury of full-time research. Equally true, of course, of a growing number of university-associated researchers who have recently been designated the "un-faculty," a class resulting from the filling-up of the tenured positions. That aside, my experience convinces me that a sizeable fraction (I can't tell you what fraction) of NASA scientists do their fare share of penance running or participating on committees, working groups,

project reviews, and budget reviews, or serving as project scientists, post-doc advisors, thesis or research advisors to grad students from near-by universities, or teaching. At any given time, in Space Science, there are apt to be 5 to 10 serving a one year sentence at Headquarters, along with another 15-20 full time. These scientists serve an invaluable function at both the Centers and Headquarters in advocating Space Science across the board and in making it an acceptable and vigorous part of the space program. There is one very great detriment to being a NASA scientist, the ability to travel to scientific meetings and to other laboratories is now severely limited by budget, relative to that of the university scientist, and often lowest priority when compared to project-related travel.

5. Exert undue influence on NASA Headquarters regarding science priorities and objectives. I think that at one time this may have been true to the extent that in the 1960's a large number of the Explorer missions had a high proportion of NASA experimenters. How much of that was a real bias caused by proximity to the decision making and how much to the fact that NASA had a lot of the recognized experts I can't say. What I can say is that the opening of the Explorer program to the announcement-of-opportunity process in 1974 certainly cut down on the likelihood of undue influence.

It is a fact -- one of the few maybe -- that participation on working groups and advisory committees can, and in my view ought to, influence priorities and objectives. A look at the membership of the NASA-related working groups and committees, including those of the Space Science Board, shows a dearth of NASA members, in fact below what I consider to be a correct proportion if it is assumed that the prime criterion for membership is scientific expertise. This is a genuine form of reverse discrimination, provable for one internal advisory committee which prohibited NASA membership (a policy I reversed when I found out about it).

6. Access to engineering capabilities which enhances competitive position. Quite true. A major part of the NASA center activity revolves around technology development and spacecraft engineering. Proximity to those activities, along with the ability to direct manpower resources to tackling areas of frontier science, has to result in a competitive edge -- if it doesn't, something is wrong. The question is, is this good or bad?

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I maintain that it is good to the degree that the best science gets done and for the reason that there ought to be some perceived advantage to working at NASA. It is not good to the degree that an in-house, lesser quality scientist ends up on top of a technology which could be better exploited by an external scientist. The problem, then, is how to assure at least some competition for the technology and engineering resources.

This is a question of increasing concern to the university community as the cost of supporting engineering staffs become greater, for a host of reasons, and as the sophistication of the technology increasingly exceeds the capability of small university groups to understand and/or manage it.

A partial solution is to open up the technology, engineering, and research capabilities of the NASA centers to increased outside participation. This is indeed the intent of an item in Dr. Frosch's policy statement on academic involvement in the NASA R&D program. As you all know, policies are too often wonderful reading but frequently end up as nothing more than placebos. It is incumbent on both NASA and the academic community to assure that the intent of the policy is implemented. At this point, I'd like to suggest that, in view of the importance to astronomers of access to high quality facilities, and in view of the prescription on the ST Science Institute regarding internal engineering capabilities, that the management of the Institute, whoever that may be, work diligently with NASA to avail itself of the NASA capabilities, both facilities and people.

In summary, for a multitude of reasons, not all of which I've had time to adequately address, I believe that a strong NASA in-house science capability is essential to the health of the larger space science endeavor. Maintaining high quality and proper balance vis-a-vis the academic world depends upon your continued support of NASA through direct participation -- send some good graduates to work there and sweat through your share of committees and by vocal but constructive criticism when you think something is out of whack. There are many people in NASA who want to hear you.

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