ULTRAVIOLET, VISIBLE, and GRAVITY ASTROPHYSICS
A Plan for the 1990s

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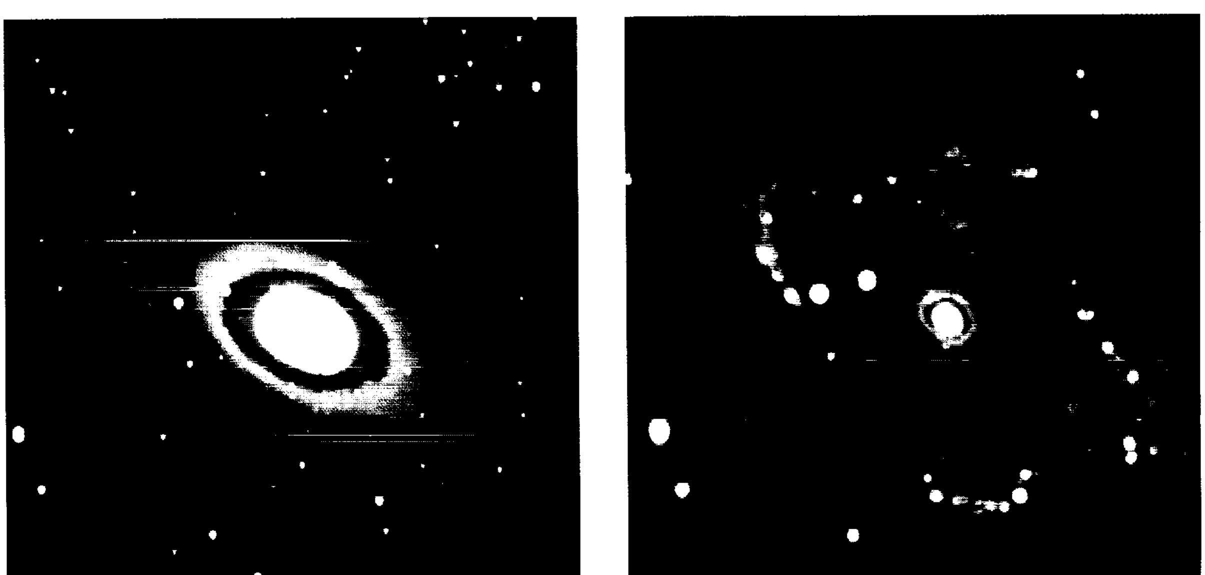
Foreword

NASA's Office of Space Science and Applications (OSSA) receives advice on scientific strategy and priorities from the U.S. National Academy of Sciences. Guidance to the OSSA Astrophysics Division, in particular, is provided by dedicated Academy committees, *ad hoc* study groups and, at 10-year intervals, by broadly mandated astronomy and astrophysics survey committees charged with making recommendations for the coming decade.

Many of the Academy's recommendations have important implications for the conduct of ultraviolet and visible-light astronomy from space. Moreover, these areas are now poised for an era of rapid growth. Through technological progress, ultraviolet astronomy has already risen from a novel observational technique four decades ago to the mainstream of astronomical research today. Recent developments in space technology and instrumentation have the potential to generate comparably dramatic strides in observational astronomy within the next 10 years.

In 1989, the Ultraviolet and Visible Astrophysics Branch of the OSSA Astrophysics Division recognized the need for a new, long-range plan that would implement the Academy's recommendations in a way that yielded the most advantageous use of new technology. NASA's Ultraviolet, Visible, and Gravity Astrophysics Management Operations Working Group was asked to develop such a plan for the 1990s. Since the Branch holds programmatic responsibility for space research in gravitational physics and relativity, as well as for ultraviolet and visible-light astrophysics, missions in those areas were also included.

The Working Group met throughout 1989 and 1990 to survey current astrophysical problems, assess the potential of new technologies, examine prior Academy recommendations, and develop the implementation plan. The present report is the product of those deliberations. A companion report by the Ad Hoc Committee on Gravity Astrophysics Technology describes the technology developments needed to support future space missions in gravitational physics and relativity.



THE SPIRAL GALAXY MESSIER 81 is about 12 million light years away in the constellation Ursa Major. The best ground-based image of M 81, recorded in red light (excluding Hα) by a CCD camera at the Kitt Peak National Observatory (left), is dominated by old, red stars in the nuclear region. A satellite image of the same galaxy was recorded in ultraviolet light by the ASTRO-1 Ultraviolet Imaging Telescope aboard the Space Shuttle in December 1990 (right, also shown on cover); extremely hot, young stars, invisible on the ground-based image, gleam from star-forming regions in the spiral arms.

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Executive Summary

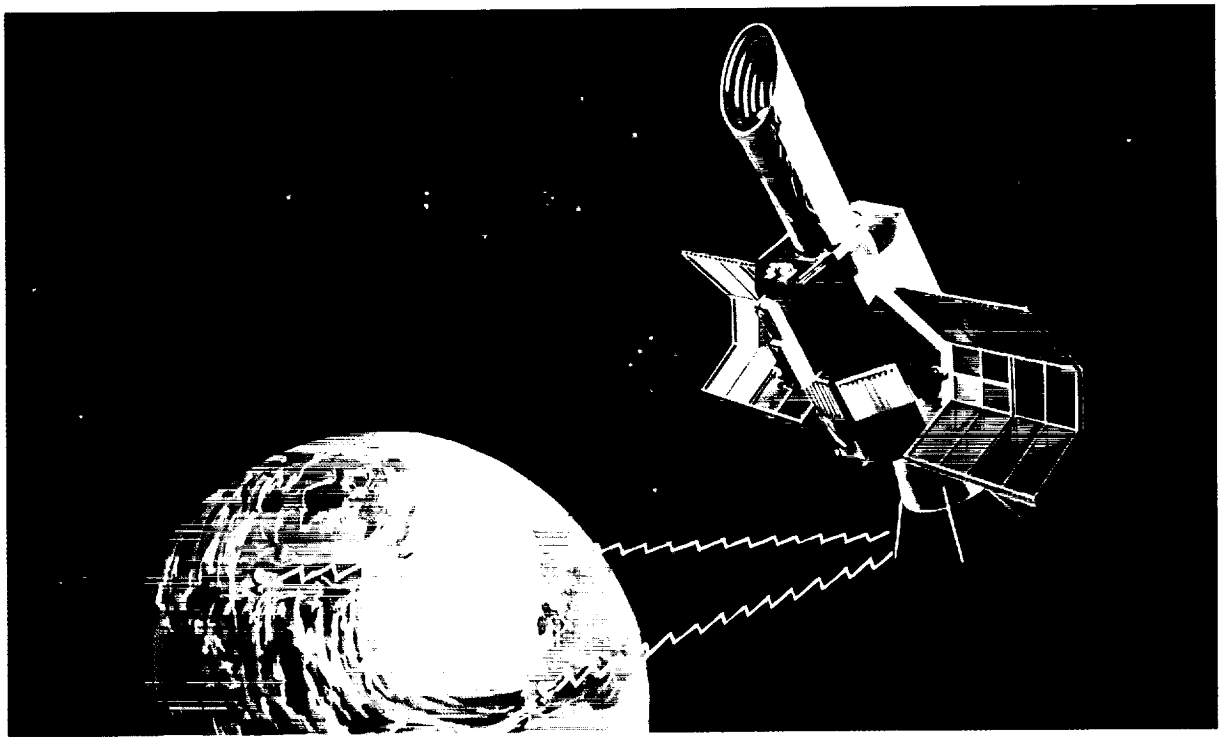

Figure 1. THE INTERNATIONAL ULTRAVIOLET EXPLORER (IUE) satellite, launched in 1978 to address a broad range of astrophysical questions, is well into its second decade of operation. The geosynchronous orbit, providing continuous, 24-hour contact with ground stations in the United States and Spain, permits an unusually efficient observing schedule.

Modern astronomy has been built upon millennia of ground-based observations made at visible wavelengths of light—the wavelengths transmitted through the Earth's atmosphere.

Direct observations of astronomical objects from space, by contrast, are less than 40 years old. They began with the flight of instruments sensitive to ultraviolet (UV) radiation carried aboard suborbital sounding rockets. Since nearly all UV radiation is blocked by the Earth's atmosphere, UV observations must be made from space.

These pioneering rocket flights provided only brief, 5-minute glimpses of how the sky would look if we ourselves had eyes sensitive to ultraviolet light—yet they were sufficient to force major revisions in our concepts of hot stars and the interstellar medium. In only four decades, we have moved from these primitive beginnings of UV astronomy to the sophistication and scientific power of the Hubble Space Telescope (HST), launched in April 1990 as the first of NASA's "Great Observatories."

One reason that UV astronomy has been so scientifically productive is that it can be used to diagnose the physical conditions of astronomical phenomena whose temperatures range from a few degrees Kelvin (K) to nearly 10^7 K. The UV is the only portion of the electromagnetic spectrum for which this is true.

It is therefore not surprising that the range of scientific discoveries attributed to UV observations has been so broad. With the advent of HST, it is now possible to extend these observations to much fainter, and hence more distant, objects than was previously possible, allowing us, for the first time, to examine the UV properties of large numbers of extragalactic objects.

Studies at visible and infrared wavelengths also benefit dramatically from satellite observations. In the visible region of the spectrum, space telescopes can provide much higher angular resolution than ground-based telescopes, since the blurring effect of atmospheric turbulence is eliminated. Moreover, a telescope in space can study fainter objects than the same telescope on the ground because of the reduction in sky-background noise.

The Hubble Space Telescope, for example, was designed to achieve a tenfold improvement in angular resolution by comparison with a

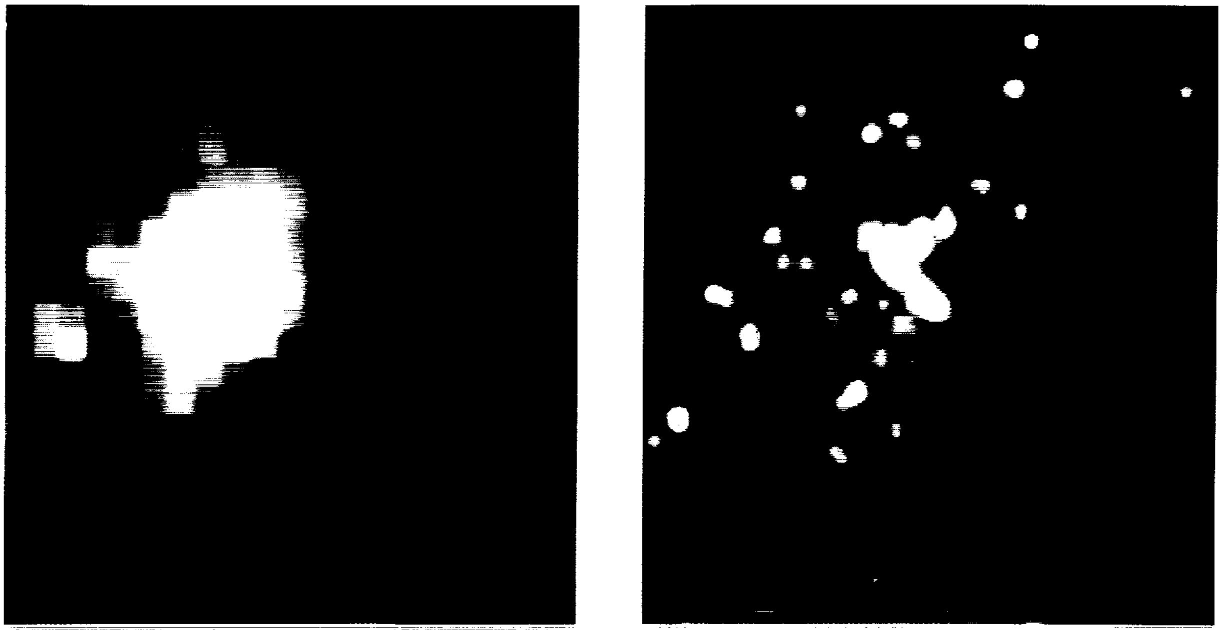

Figure 2. THE YOUNG STAR CLUSTER R136, as imaged by a large ground-based telescope (left) and the HST Faint Object Camera after computer processing (right). R136 lies within the 30 Doradus nebula in a rich, star-forming region of the Large Magellanic Cloud.

ground-based telescope and to detect objects twenty-five times fainter than can be observed from the ground. When equipped with second-generation instruments that correct for the effects of spherical aberration, HST will greatly enlarge the observable Universe at visible and UV wavelengths, increasing by orders of magnitude the number of extragalactic objects that can be studied.

Advances in ultraviolet, visible, and infrared space astronomy have gone hand in hand with advances in space technology. Some have argued that the International Ultraviolet Explorer (IUE), launched in 1978 and still operating in 1991, has already surpassed any previous satellite observatory in scientific productivity and may in fact be the most productive single astronomical instrument ever built (Figure 1). As of December 31, 1990, IUE data had been discussed in 2,083 articles published in refereed scientific journals and had in addition provided the basis for 107 Ph.D. dissertations in the United States alone. The Hubble Space Telescope can carry on this tradition for a much broader range of the electromagnetic spectrum, including the UV, visible, and infrared spectral regions (Figure 2).

The past decade brought a tremendous increase in the sophistication of space technology and instrumentation. Applied to space astronomy, these increases will lead to telescopes and interferometers of unprecedented capability. The scientific gains to be brought about by increasing the size of the observable Universe and the detail with which we can observe it will be profound. Although the most important discoveries may be those we cannot now anticipate, astronomers can already foresee the contributions of new generations of instrumentation to many fundamental and exciting areas of current research.

The NASA Ultraviolet, Visible, and Gravity Astrophysics Management Operations Working Group (MOWG) recognized in 1989 the need to systematically plan for the implementation of a space-astronomy program that builds on our current missions and knowledge to exploit this new technology.

The goal of the MOWG is to assist NASA in defining an implementation plan that will assure the continuation of the Ultraviolet, Visible, and Gravity Astrophysics program at the forefront of science, and to aid NASA in its implementation. The plan presented in this report, the outcome of deliberations of the MOWG over nearly two years, embodies that goal.

Implementation Plan for the 1990s

Space-based observations at visible and UV wavelengths will make possible major advances toward answering the fundamental questions of astrophysics.

The evolution and large-scale structure of the Universe, the energetics of active galactic nuclei, the details of stellar evolution, the composition of the interstellar medium, the study of planets in our own Solar System, and the search for planets in other solar systems are but a few of the many astrophysical questions that will be addressed by space-based observations at UV and visible wavelengths. The fine-scale structure of stars, galaxies, and active galactic nuclei can also be explored with instruments of high angular resolution, and the rapid motions of massive objects in binary systems can be probed with gravity astrophysics experiments now under study.

The plan presented in this report is ambitious, and fully consistent with recommendations of the National Academy of Sciences. Carried out over the next 10 years, it will produce major growth in our scientific knowledge of astrophysical sources and conditions. The plan maintains balance among large observatories, small and moderate missions, advanced technology research and development, and community support and participation. It also provides for the training of a new generation of scientists. The major components of the plan are as follows:

(1) Hubble Space Telescope,

(2) A commitment to the existing program,

(3) A vigorous program of Explorer missions,

(4) A strong research base to support future missions,

(5) Advances in General Relativity and gravity astrophysics, and

(6) A large space interferometer or telescope beyond HST.

The actions required to carry out the implementation plan are discussed below (see next page for summary). Data from both approved and future space missions are essential.

(1) Hubble Space Telescope (HST)

The Hubble Space Telescope, the first of four planned Great Observatories, will be the centerpiece of the NASA Ultraviolet, Visible, and Gravity Astrophysics program for the the 1990s (Figure 3). HST marks the beginning of an era of true observatory-class space telescopes.

In tandem with the other three Great Observatories—the Gamma Ray Observatory (GRO), the Advanced X-Ray Astrophysics Facility (AXAF), and the Space Infrared Telescope Facility (SIRTF)—HST will provide crucial coverage of key

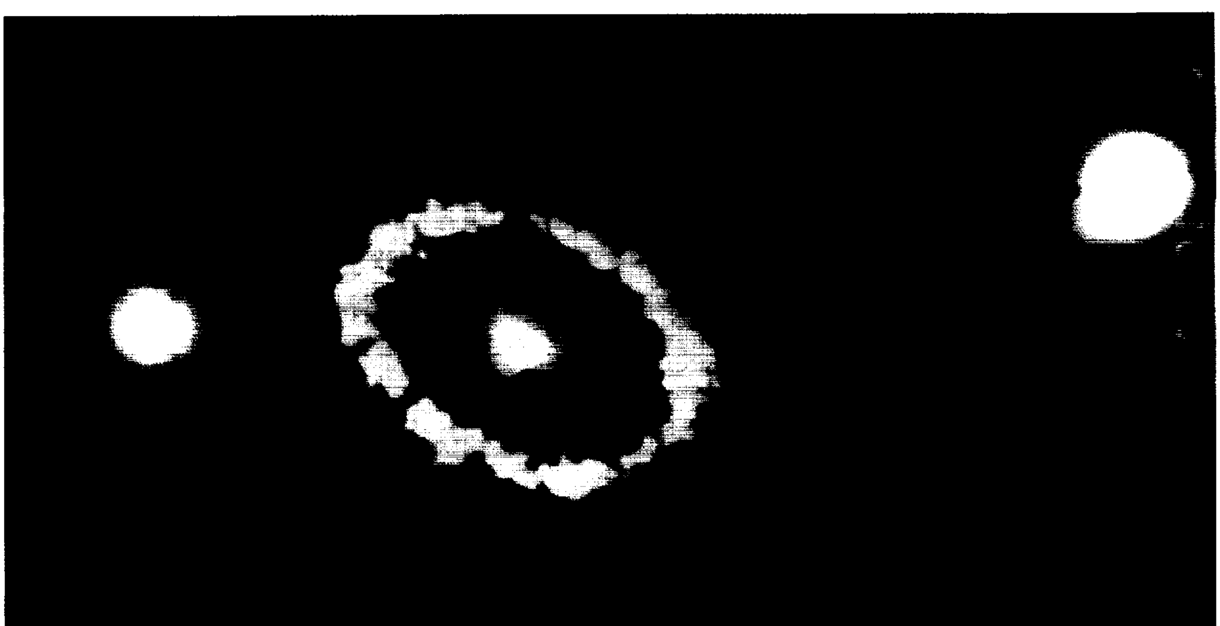

Figure 3. RING OF LIGHT AROUND THE REMNANT OF SUPERNOVA 1987A arises from illumination of previously ejected material by radiation from the supernova blast. This HST Faint Object Camera image, recorded in 1990, shows the ring structure in detail. Subsequent observations by HST and IUE have permitted measurement of the progression of the illuminated region and thus an estimate of the distance to the supernova.

Plan for the 1990s

(1) Hubble Space Telescope:

- Rapid correction of effects of spherical aberration
- Timely installation of second-generation instruments (within 5 years) and technology development leading to installation of third-generation instruments within 10 years

(2) Commitment to the existing program:

- Timely launch of EUVE, ORFEUS/IMAPS/AstroSPAS, and ASTRO-2
- Support of the operating missions

(3) Vigorous program of Explorer missions:

- Increased resources for Explorer missions
- Timely launch of FUSE
- A Small Explorer mission for a high-sensitivity, all-sky survey at UV wavelengths

(4) Strong research base to support future missions:

- An enhanced commitment to a research base that includes detector development, theory, data analysis, and laboratory astrophysics to keep pace with the explosive increase in observational capabilities
- An energetic program of astronomical research using sounding rockets
- Augmented resources for the training of new scientists

(5) Advances in General Relativity and gravity astrophysics:

- Continued program of advanced redshift and dynamical experiments aboard deep-space probes
- Timely launch of Gravity Probe-B and LAGEOS-3
- Support of current technical developments leading to future missions

(6) Large space interferometer or telescope beyond HST:

- A program leading to the construction of a powerful UV and visible-wavelength space interferometer or large-aperture telescope
- As an important step in this program, with its own strong scientific rationale, development of an Astrometric Interferometry Mission (AIM) in space for astrometric measurements to an accuracy of 3 to 30 micro-arcseconds

portions of the electromagnetic spectrum. Lesser spectral gaps will be filled by such smaller missions as the Extreme Ultraviolet Explorer (EUVE), the Far Ultraviolet Spectroscopic Explorer (FUSE), and HST second-generation instrumentation:

NASA is committed to ensuring that HST is restored to its full capabilities and then supported at the level required to attain its full scientific productivity.

Beyond efficient operation of the HST observatory, it is also of paramount importance to exploit the great potential of this telescope with the orders-of-magnitude improvements in performance available through approved second-generation and third-generation instrumentation:

Installation of the second-generation HST instruments within 5 years is of paramount importance.

In addition:

NASA release of an Announcement of Opportunity within the next 2 to 4 years for design and construction of one or more third- generation HST instruments will ensure the telescope's scientific pre-eminence.

As more sophisticated and powerful detectors are developed that exploit the currently unused potential of HST, we will witness a dramatic increase in the range and variety of new astronomical knowledge from this facility.

(2) Commitment to the Existing Program

During the past decade, NASA has created a research program in Ultraviolet, Visible, and Gravity Astrophysics founded on a powerful complement of flight missions:

It is crucial to the health of astronomy that NASA maintain its commitment to these missions.

The currently operating set of missions consists of HST, IUE, and the Ultraviolet Spectrometers (UVS) on the Voyager-1 and Voyager-2 deep-space probes. The Astronomy Observatory-1 (ASTRO-1) Space Shuttle payload was flown in December 1990; an ASTRO-2 mission is now in planning.

The Extreme Ultraviolet Explorer (EUVE) is scheduled for launch in 1992. Through a cooperative program with the Federal Republic of Germany, two additional instruments will be placed into orbit in 1993: the Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer (ORFEUS) and the Interstellar Medium Absorption Profile Spectrograph (IMAPS). The ORFEUS/IMAPS mission will use the AstroSPAS platform provided by Germany.

ULTRAVIOLET, VISIBLE, AND GRAVITY ASTROPHYSICS

Approved Missions

Hubble Space Telescope
(HST)—launched 1990

HST Second-Generation Instruments:

- **Wide Field/Planetary Camera II (WF/PC II)**
- **Space Telescope Imaging Spectrograph (STIS)**
- **Near Infrared Camera (NIC)**

HST Third-Generation Instruments

Voyager Ultraviolet Spectrometers
(UVS)—launched 1977

International Ultraviolet Explorer
(IUE)—launched 1978

Extreme Ultraviolet Explorer
(EUVE)—1992 launch

Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer
(ORFEUS)—1993 flight aboard the AstroSPAS platform

Interstellar Medium Absorption Profile Spectrograph
(IMAPS)—1993 flight aboard the AstroSPAS platform

Astronomy Observatory-2
(ASTRO-2)—1994 flight

Shuttle Test of Relativity Experiment
(STORE)—1994 flight

Far Ultraviolet Spectroscopic Explorer
(FUSE)—2000 launch

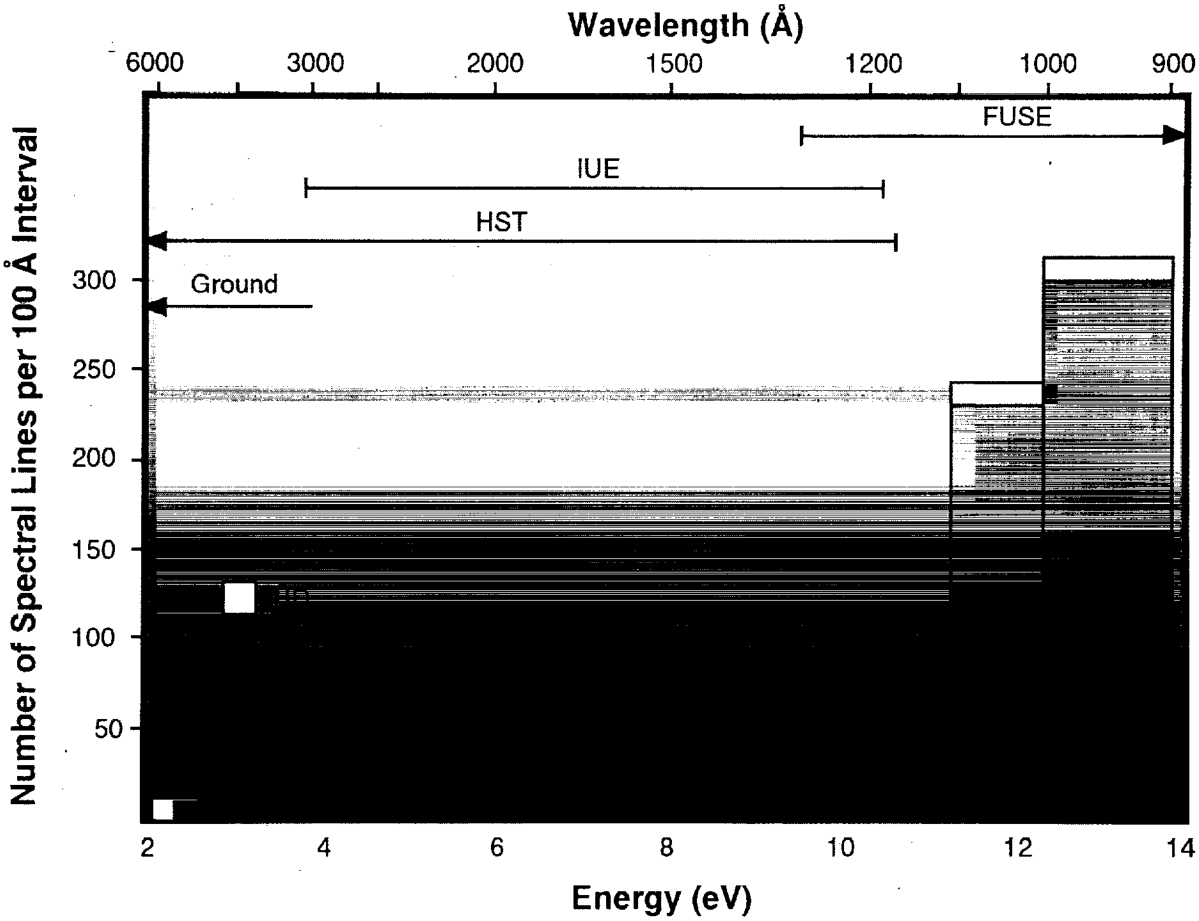

Figure 4. RICH CONCENTRATION OF RESONANCE ABSORPTION LINES in the far ultraviolet, inaccessible to IUE or HST, will be studied by NASA's Far Ultraviolet Spectroscopic Explorer (FUSE) mission. One half of the lines arise from molecular deuterium (HD) and molecular hydrogen (H_2).

(3) Vigorous Program of Explorer Missions

The Far Ultraviolet Spectroscopic Explorer (FUSE) is a far-ultraviolet astronomy mission that will give astronomers continuous access to a vital region of the spectrum that is currently observable only during 5-minute rocket flights.

The National Academy of Sciences' Astronomy Survey Committee for the 1980s, as well as numerous advisory and peer-review committees, have ranked FUSE as number one in its class of flight missions.

At least six times as many astrophysically important lines are present in the 300-Å wide far-ultraviolet (FUV) spectral region as in the 2,000-Å wide traditional UV region extending from 1,200 Å to 3,200 Å (Figure 4). Many important ionization states of astrophysically dominant atoms (e.g., hydrogen, oxygen, sulphur) radiate in the FUV. Knowledge gained from observations of these lines is essential to the analysis of non-thermal ionization processes in astrophysical plasmas and to determinations of the relevant atomic abundances.

Among larger Explorer-class missions, highest priority is placed on the timely launch of FUSE.

Historically, Explorer missions have been the backbone of our discipline's scientific program. Exciting new scientific investigations in astrometry, very high resolution UV and EUV astronomy, interferometry, multispectral observations, stellar seismology, and long-term studies of variability are all well-suited to larger Explorer-class missions:

We support the high priority NASA gives to augmentation of the Explorer Program.

The capabilities provided by the Small Explorer (SMEX) program are well matched to at least one category of experiment in our discipline. A deep UV survey with spectroscopic capability would provide rich scientific results and would represent an important resource for the future exploration of this region of the spectrum. Both point and extended sources need to be cataloged and characterized to the greatest sensitivity possible. From the survey, astronomers will be able to determine the classes of sources that emit at UV wavelengths, the morphology of the emission, and the range of luminosities in each class. Such measurements are critical to initiate an understanding of the emission processes that radiate at these wavelengths.

(4) Strong Research Base to Support Future Missions

Underpinning the scientific vitality of the discipline is the strength of our supporting programs, including research with new detectors, laboratory astrophysics techniques, sounding rockets, and pursuit of astrophysical theory. These programs, collectively grouped in the Research and Analysis (R&A) Program, provide support to develop new technologies and theories, and lend continuity and stability to NASA's astrophysical research program.

To the detriment of the nation's capabilities in science and technology, support for work in these areas has not kept pace with the need for fundamental data and instrument development generated by rapid advances in forefront scientific research from space. This component of the program continues to advance the resources of our nation in scientific and technical areas, and to train new generations of scientists.

The R&A program needs continued attention to augment its resources and to prevent erosion of its purchasing power.

We strongly endorse the planned augmentation of the Astrophysics Division Theory Program. We also support the Origins of Solar Systems Program and other Office of Space Science and Applications (OSSA) programs that serve to strengthen the nation's research base.

ULTRAVIOLET, VISIBLE, AND GRAVITY ASTROPHYSICS

Future Missions

Augmentation to Explorer Program:

- **Timely launch of FUSE**
- **Additional opportunities for Astrophysics missions**

Additional Small-Class Explorer:

- **Deep Ultraviolet Survey**

Laser Geodynamics Satellite-3 (LAGEOS-3)

New Flagship and Intermediate Space-Based Missions:

- **Astrometric Interferometry Mission (AIM)**
- **Imaging Optical Interferometer in Space**
- **16-Meter Telescope in Space**
- **Laser Gravitational Wave Antenna in Space**

Lunar Outpost Astrophysics Program:

- **Lunar Transit Telescope (LTT)**
- **Optical Interferometer**
- **Filled Aperture Segmented Optical Telescope**
- **Laser Interferometric Gravity Wave Observatory**

(5) Advances in General Relativity and Gravity Astrophysics

The technology needed for next-century missions and programs in General Relativity and gravity astrophysics has been reviewed in detail in the *Report of Ad Hoc Committee on Gravity Astrophysics Technology* to the Ultraviolet and Visible Astrophysics Branch of the OSSA Astrophysics Division. The report of the Ad Hoc Committee, now being prepared for publication by NASA, thus complements the present MOWG report, which highlights mission and programmatic opportunities for the 1990s (e.g., Gravity Probe-B and the Laser Geodynamics Satellite-3). NASA's growing commitment to gravitational-physics programs is demonstrated by the institution of a university Gravitational Physics component of the R&A program.

(6) Large Space Interferometer or Telescope beyond HST

The bold human vision that led to HST recognized the benefits to science from space observatories that took advantage of ongoing technological advances. Consistent with the view of exploiting new technologies for the benefit of science, education, and exploration, we support a plan for a powerful UV and visible-wavelength interferometer or large-aperture telescope that would use the full range of technologies developed in the 20 years since the inception of HST.

A National Academy of Sciences study, *Space Science in the Twenty-First Century*, published in 1988, concludes that imaging interferometry in space will ultimately play a central role in astrophysics and recommends the construction, through a well directed technology-development program, of a large, passively cooled space telescope operating at UV, visible, and infrared wavelengths as a successor to HST.

The design of the instrument to follow HST remains to be determined. It might be either a filled-aperture, segmented-mirror telescope in the 16-meter class (or larger), or a large, diluted-aperture interferometer consisting of widely separated telescopes phased to produce images in much the same manner as in radio astronomy.

It is crucial that we start now to develop the strategies and technologies required to implement this advanced instrument.

Even before imaging capabilities become feasible, however, optical interferometric technology can be applied to high-precision astrometry from space. In its March 1991 report, entitled *The Decade of Discovery in Astronomy and Astrophysics*, the Academy's Astronomy and Astrophysics Survey Committee for the 1990s notes that astrometry now lies on the verge of a technological revolution and recommends a space-based Astrometric Interferometry Mission (AIM) with an astrometric accuracy in the range of 3 to 30 micro-arcseconds. Such an instrument could vastly reduce the current uncertainty in the cosmic distance scale and could detect Jupiter-sized planets around hundreds of stars up to 500 light-years away.

An Astrometric Interferometry Mission, designed to carry out high-precision measurements at the forefront of science, is an important step in a long-range program of space interferometry and should be developed as the first dedicated optical interferometer in space.

The next steps will involve a serious evaluation of the scientific, technical, and cost questions and issues, with the goal of defining a successor to HST within the near future. The Lunar Outpost segment of the Bush Administration's Space Exploration Initiative (SEI), announced in 1989, provides an ideal site for very-long-baseline optical interferometers and for large telescopes that otherwise would have to be assembled in orbit.

Some Key Astrophysical Questions

The MOWG recommended plan and programs address many of the most exciting questions of modern astrophysics. A brief overview is presented below; further detail is provided in Part II of this report.

Structure of the Early Universe

It has become increasingly clear over the past decade that galaxies in the observable Universe are not distributed smoothly, but instead are "clumped" into structures of enormous extent. Studies of the nature and dynamics of these structures will give us a better understanding of the physical processes that shaped the early Universe, the period of initial condensation from the primordial fireball.

In order to see how these structures evolved, we must look further back into time. This is equivalent to looking at more distant and hence fainter objects. Such observations are best carried out in space. Until the advent of even larger and more sensitive telescopes, we will use the second-generation Near Infrared Camera (NIC) on HST to observe the most distant galaxies, permitting new insights into critical cosmological parameters, including the overall density of baryons in the Universe.

Energetics of Active Galactic Nuclei

To date, the internal conditions suggested by spectral analysis of these powerful sources of energy strongly indicate that they are powered by black holes with masses on the order of a million to a billion times the mass of the Sun. The increased spatial and spectral resolution of HST (especially when equipped with the second-generation Space Telescope Imaging Spectrograph, or STIS) and the Far Ultraviolet Spectroscopic Explorer (FUSE) will place more stringent limits on both the size and motions of the central sources. However, in order to view the actual details of these mysterious objects, we will require instruments with even higher spatial resolution.

Stellar Winds in Massive Stars

One of the first achievements of UV astronomy was the confirmation of the existence of winds from hot, massive stars and the discovery that such winds are ubiquitous. These winds carry away so much mass that they have a profound impact upon the star's subsequent evolution. This, in turn, affects the chemical composition of the material which they return to the interstellar medium to become available for the formation of subsequent generations of stars.

Stellar winds played a key role in the process by which the Galaxy evolved from a massive cloud of nearly pure hydrogen and helium to a composition containing the rich variety of elements we observe today. HST's increased resolution of spectral lines formed in the winds of hot stars will help determine the variability and clumpiness of the wind flows. The capability of STIS to observe many lines in the wind simultaneously will permit identification of the energetics of the flow. The additional spectral lines available to FUSE in the far ultraviolet will allow us to probe the high-temperature structure of these regions, providing further details about the dynamics of the instabilities.

Sources Powered by Accretion

Accretion processes pervade astrophysics. Study of close binary stars allows the physics of accretion to be probed in otherwise well-understood systems. The accretion-flow geometry, the structure and location of the boundary layer (where angular momentum is deposited), the composition and outflow geometry associated with outbursts, and mass transfer in close binary systems involving degenerate stars all represent current problems that can be explored directly with HST, EUVE, and FUSE.

Moreover, knowledge of the interaction between stellar magnetic fields and accretion flow obtained through space-based measurements is crucial to an understanding of the angular-momentum evolution of magnetic systems. Such knowledge is also needed to address problems as diverse as the origin of millisecond pulsars and quasi-periodic oscillations in accreting compact objects.

Composition and State of the Interstellar Medium

The composition of the interstellar medium (ISM) contains a record of Galactic evolution. Furthermore, the present state of the ISM and its response to such external influences as star formation and supernova explosions determine the dynamics of subsequent star formation and, therefore, the course of future Galactic evolution.

This complicated interplay among the ISM, the stars to which it gives birth, and its response to these stars must be understood in order to reveal the intricacies of Galactic evolution. The analysis of different interstellar spectral lines provides information about the motions of material at a variety of temperatures and allows us to uncover the kinematical and geometrical relationships between ISM phases at different temperatures.

Nature of the Galactic Halo

Another component of the ISM is the Galactic halo, a high- temperature plasma that surrounds the Galaxy. The existence of such a halo was predicted in the 1950s but remained unobservable until IUE was launched in 1978.

The plasma component of the halo is an interface between our Galaxy and the intergalactic environment, and may be driven by circulation (possibly in the form of gigantic convection cells) caused by explosive events occurring in the Galactic plane. The study of the Galactic halo can reveal conditions both within our own Galaxy and within the intergalactic medium that surrounds it. The highly ionized material of the halo can only be observed by space-based observatories, and only FUSE will be capable of sampling its highest-energy components.

Evolution of the Early Universe

The ratio of hydrogen to its stable isotope deuterium is a sensitive diagnostic of conditions in the Universe and the course of nucleosynthesis immediately after the Big Bang. Only far-ultraviolet measurements of the relevant spectral lines from space can provide a reliable empirical estimate of this ratio—an important future task for FUSE.

Chromospheric Activity in Cool Stars

By studying chromospheric activity in late-type stars, HST (equipped with second-generation instruments) and FUSE will work in tandem to place our Sun and its magnetic activity in the context of the total stellar population and general stellar properties. Signatures of high-temperature plasmas will define the evolution and decay of magnetic activity and identify the poorly understood processes that determine the mass loss and evolutionary state of cool stars.

Formation of Stars and Planetary Systems

The merging of observations obtained in the UV, visible, and infrared spectral regions will permit nearly direct observation of the collapse of the gas and dust involved in star formation. A comprehensive, multispectral approach is required to understand the complicated, sequential processes responsible for star formation.

Planetary systems will form around some of these newborn stars; visible and near-infrared observations will be used to investigate those systems that could be creating planets. Near-infrared observations, in particular, allow the greatest possible contrast between planets and the parent stars, yielding the best chance of successfully discovering and investigating such evolving systems. Visible-light astrometric measurements carried out by telescopes in the HST class could also provide important indirect evidence of the existence of other planets. However, truly giant instruments, such as an interferometer or a 16-meter class telescope in space, will be required to directly image planetary systems and search for signatures of life.

DEFINITIONS

Ångstrom: **(Å)** **A unit of length equal to 10^{-8} cm. Frequently used as the unit of measurement for visible and ultraviolet wavelengths of electromagnetic radiation.**

Micron: **(μm)** **A unit of length equal to 10^{-4} cm, or 10^{4} Å. Often used as the unit of measurement for infrared wavelengths.**

Near Infrared: **(Near IR)** **Electromagnetic radiation of wavelength longer than the long-wavelength (red) end of the visible spectrum, approximately in the range 7,000 Å (0.7 μm) to 30,000 Å (3 μm).**

Visible: **(VIS)** **Range of the electromagnetic spectrum visible to the human eye, approximately 4,000 to 7,000 Å.**

Ultraviolet: **(UV)** **Electromagnetic radiation of wavelength shorter than the short-wavelength (violet) end of the visible spectrum, roughly 1,200 to 4,000 Å. The lower limit marks the cutoff in the reflectivity of normal-incidence optics; shortward of 1,200 Å, grazing-incidence optics must be used.**

Far Ultraviolet: **(FUV)** **Electromagnetic radiation in the range from 912 Å (the hydrogen ionization limit) to 1,200 Å. This small region of the spectrum is rich in astrophysically important absorption lines.**

Extreme Ultraviolet: **(EUV)** **Electromagnetic radiation in the range from the low-energy end of the soft X-ray spectrum at about 100 Å to the beginning of the FUV spectrum at 912 Å.**

Part I. Introduction

The spectral range from the short-wavelength end of the extreme ultraviolet (about 100 Å) to the long-wavelength end of the near infrared (about 3 μm) can provide vital insights into all of the important questions that face astronomers today.

To achieve these insights, a number of complementary diagnostic tools must be employed to study this radiation, including imaging, spectroscopy, photometry, polarimetry, astrometry, interferometry, and gravitational-wave detection.

Advances in space astronomy have always gone hand in hand with advances in space technology. The NASA Ultraviolet, Visible, and Gravity Astrophysics Management Operations Working Group (MOWG) saw the need to systematically plan for the implementation of a space-astronomy program that builds on past discoveries, assimilates currently approved missions, and exploits emerging new technologies.

TOOLS OF MODERN SPACE ASTRONOMY

Imaging: Formation of an image to determine the location and structure of the emitting source.

Spectroscopy: Dispersal of light emitted by a source into its basic spectral elements (absorption and emission lines, and continuum). Used to determine composition, temperature, density, and dynamics of a source.

Photometry: Accurate measurement of the flux of light emitted by a source, often used in studies of source variability.

Polarimetry: Measurement of the extent, sense, and orientation of the polarization of the light emitted by a source, as clues to the source emission mechanisms and the nature of intervening matter.

Astrometry: Accurate measurement of the position of a source with respect to carefully established reference frames; used to determine the distance to, and motion of, the source.

Interferometry: Use of two or more telescopes or radiation collectors to sample different regions of the wavefront from a source, so that information on source direction and structure can be inferred from the interference patterns obtained; can be used to reconstruct an image of the source.

Gravitational-wave detection: Measurement of the motions of massive bodies in response to the extremely weak forces exerted by the gravitational waves predicted by Einstein's General Theory of Relativity and other theories of gravity. Detection systems have been proposed for placement on the Earth, on the Moon, and in space.

Approach

After surveying the most pressing questions in astrophysics today, the Working Group assessed the potential of new and emerging technologies for providing answers to these questions and for making further astrophysical discoveries. The group next examined the National Academy of Sciences' recommendations for Astronomy and Astrophysics, together with NASA's approved and proposed future missions in these areas.

Finally, the Working Group developed a plan for the implementation of the Academy recommendations that will address major scientific questions, capitalize on new technologies, build upon current program strength, and take into account other important concerns (e.g., program balance, the training of new scientists, and opportunities for international cooperation). The approved and future missions included in the plan are discussed in Part IV of this report.

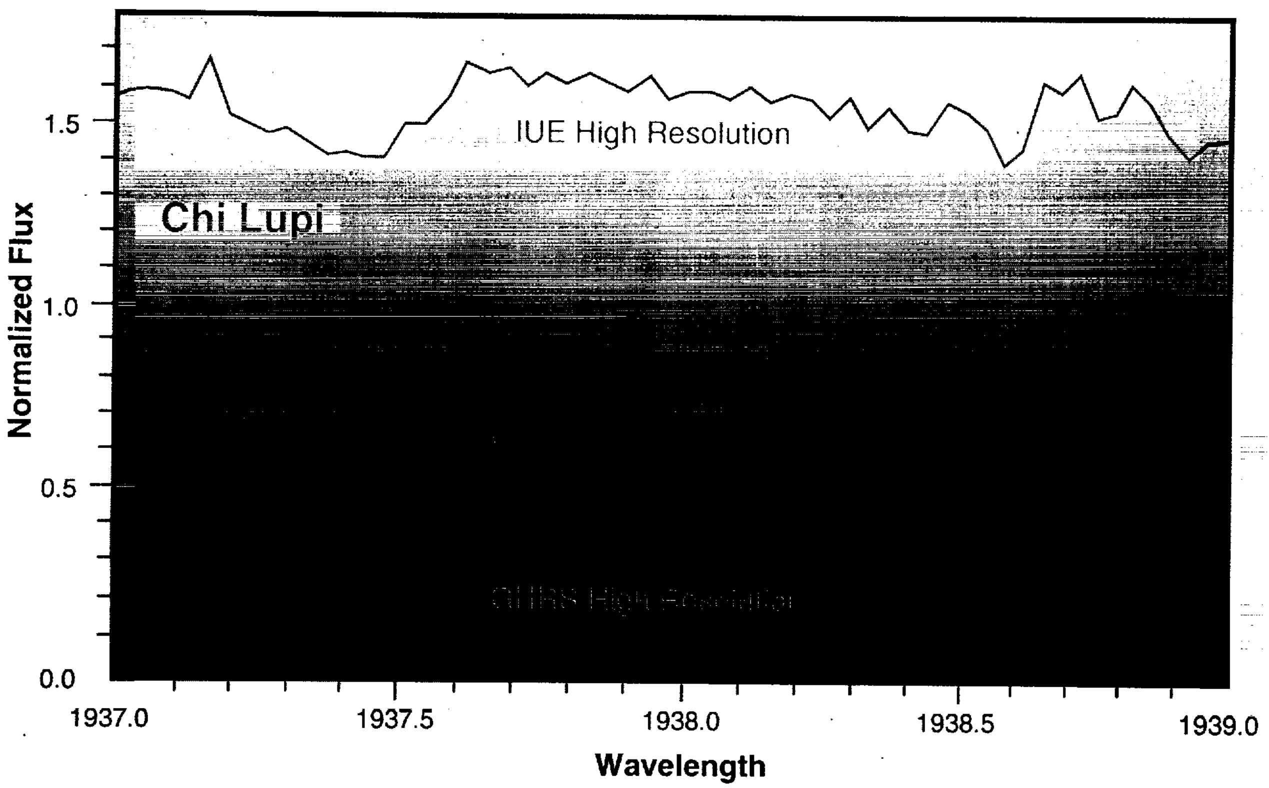

Figure 5. MAJOR ADVANCE IN ULTRAVIOLET SPECTRAL RESOLUTION FURNISHED BY HST is illustrated in this comparison of spectra of the chemically peculiar star Chi Lupi recorded by IUE (top) and the HST Goddard High Resolution Spectrograph (bottom). The atmosphere of Chi Lupi is rich in several unusual chemical elements, containing 100,000 time more mercury and 10,000 time more platinum per unit volume than that of the Sun. HST ultraviolet spectral observations are expected to help clarify the origin of such composition anomalies.

Perspective on the Plan

The International Ultraviolet Explorer (IUE), launched in 1978 and still operating in 1991, made use of new ultraviolet detector technologies to open a new window on the Universe. Some have argued that IUE is the single most productive astronomical instrument ever built.

Today we stand on the threshold of a new era in space astronomy. The launch of Hubble Space Telescope (HST) has placed into space an observatory whose size, pointing accuracy, and stability will eventually enable it to outperform all of its ground-based counterparts, as well as provide new and vastly improved observing capabilities in the ultraviolet and near-infrared spectral regions (Figure 5).

Smaller missions will also make major contributions. The ASTRO-1 Spacelab payload, flown in December 1990, returned important new ultraviolet observations that are now being analyzed; a reflight of the ASTRO ultraviolet telescopes is now being planned as the ASTRO-2 mission. The ORFEUS and IMAPS instruments are scheduled for 1993 Space Shuttle launch and operation aboard the AstroSPAS platform. Two Delta-class Explorer missions, the Extreme Ultraviolet Explorer (EUVE, scheduled for launch in 1991) and the Far Ultraviolet Spectroscopic Explorer (FUSE, in planning), will be dedicated to ultraviolet astronomy. These missions will employ new sensor technologies to extend observations into the extreme ultraviolet (EUV).

The past decade has brought a tremendous increase in the sophistication of space technology and instrumentation. When applied to space astronomy, these advances will lead to telescopes of unprecedented sensitivity and to significantly improved capabilities to probe and diagnose observed objects through studies of their temperature, density, dynamics, composition, and structure.

These technologies will, first of all, be used to enhance the capabilities of existing missions. In the case of HST, second- and third-generation focal-plane instruments will make full use of the substantial collecting area and imaging capability of the HST optical telescope. In addition, these advanced technologies will be applied to the development of new, special-purpose Explorer and Spacelab missions, such as the Deep Ultraviolet Survey.

Although we cannot know what important discoveries lie ahead, we can foresee how new generations of instrumentation will contribute to many fundamental and exciting areas of current research. The more advanced ("almost-state-of-the-art") technologies will form the basis for the preliminary designs for the next generation of major Ultraviolet, Visible, and Gravity Astrophysics facilities. Such facilities will provide orders-of-magnitude improvements in sensitivity and in spatial, spectral, and temporal resolution by comparison with the missions contained or planned in the current program.

Technologies that promise the most significant gains in capability will be developed under NASA sponsorship; these may be proven on sounding rockets prior to being deployed as the next generation of Explorers—or as even more advanced space-astronomy facilities that lie beyond the Great Observatories.

The implementation plan for Ultraviolet, Visible, and Gravity Astrophysics, while ambitious, nevertheless maintains a good balance among large observatories, small and moderate missions, advanced technology research and development, and community support and participation. The plan also provides for the training of a new generation of scientists and engineers. The program is designed to ensure that each element complements the others and, at the same time, produces growth at the forefront of astrophysical knowledge.

Part II. Astrophysical Questions

The primary goals of a plan for Ultraviolet, Visible, and Gravity Astrophysics must be the provision of answers to significant scientific questions and the potential for new scientific discoveries.

In this part of the report, we examine the most pressing scientific questions now under discussion in astrophysics—questions that have been raised in no small measure by the achievements of past and currently operating NASA space missions. These questions are grouped under five main headings:

A. Structure of the Universe;

B. Structure of galaxies and quasars;

C. Structure of the Milky Way;

D. Structure of stellar systems; and

E. Verification of relativistic theories of gravitation.

For each question, we provide examples of the major contributions to be made by the missions included in the recommended plan. Finally, recognizing the potential for serendipitous discovery that characterizes each of the missions that we have identified, we present a sixth category:

F. The unknown: serendipity.

A. Structure of the Universe

Current Program Contributors:

- Hubble Space Telescope (HST)
- HST Second- and Third-Generation Instruments
- Far Ultraviolet Spectroscopic Explorer (FUSE)
- Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer (ORFEUS)

Future Program Contributors:

- Optical Interferometers (space-based or lunar-based)
- 16-Meter Telescope (space-based or lunar-based)
- Lunar Transit Telescope

1. Scale of the Universe

Even six decades after Hubble's discovery of the expansion of the Universe and recognition of the cosmic distance scale, observational cosmology remains seriously data-deficient. Because of the faintness of objects at such immense distances, observations typically press the limits of current techniques.

The need for new, high-quality observations is underscored by the continuing controversy over the value of H_0, the Hubble constant, which specifies the velocity of recession of a galaxy through a proportionality with the distance. An overall uncertainty of about a factor of two in the value of H_0 results from the accumulation of contributing uncertainties at every step of the distance ladder.

A significant step towards improving this situation, based on Henrietta Leavitt's famous period-luminosity (P-L) relationship for Cepheid variable stars, will be taken by HST. A designated HST "key project" using current, first-generation instruments will carry out measurements of the periods and luminosities of Cepheid variables. A second-generation instrument, the Wide Field/Planetary Camera II, will be able to extend this work out to the distance of the Virgo cluster of galaxies.

Further improvements can also be expected from new initiatives in the next 10 years. The P-L relation of Cepheids at visible wavelengths has considerable scatter and is sensitive both to metallicity effects in the stars and to the effects of extinction in their neighborhoods. Near-infrared photometry provides a more accurate index of luminosity than measurements in the visible and yields a P-L relation with considerably less scatter. In the crowded fields of these relatively remote galaxies, however, such observations can be made only with the second-generation NIC instrument for HST.

2. Deuterium

The cosmic abundances of light elements place a powerful constraint on cosmological theories. Different explanations of the "Big Bang" and subsequent cosmic evolution, although developed within the common framework of Einstein's General Theory of Relativity, typically yield different abundance predictions. Observations of light-element abundances can therefore be used to discriminate among these competing theories. However, current observations are inadequate to do so.

The Far Ultraviolet Spectroscopic Explorer (FUSE) will observe and analyze the absorption of radiation by deuterium that was formed during the first 3 minutes after the Big Bang (Figure 6). Different cosmological models predict different ratios of the abundances of deuterium (D), helium (^3He and ^4He), and lithium (^7Li) to hydrogen (H) in the early Universe. These abundances can then be extrapolated to present-day values. However, since some of these elements are also products of stellar evolution, one must sort out the original component of the abundances produced by the Big Bang from the contributions subsequently made by stars.

Nuclear fusion within stellar cores converts deuterium to helium (^3He) and synthesizes other light elements. Since the interstellar abundances are modified by continuous injection of new material processed in stars, we need a means of extrapolating the modifications of abundances back to their values before stellar processing.

FUSE holds the key to this extrapolation. By studying differences in D/H ratios in many locations in the local interstellar medium (i.e., within 50 pc) and in many infalling gas clouds in our own Galaxy, astronomers will learn how the D/H ratio varies with degree of stellar development and mixing with the surrounding medium. These D/H ratios may then be compared with D/H ratios measured in distant (and apparently younger) external galaxies by HST to determine the primordial ratio.

3. Density of the Universe

We want to know the current density of the Universe so we can predict its future. To distinguish whether or not the Universe will continue to expand forever, or whether it will eventually collapse upon itself, we must know its density. The density at which there is just enough mass to allow gravity to stop the expansion and eventually initiate the collapse is called the critical density.

The simplest cosmologies are parametrized by the Hubble constant H_0 and the deceleration parameter q_0, or equivalently the mean density of the Universe at the current epoch. A reliable estimate of the critical density requires an accurate value for the Hubble constant.

Estimates of the density parameter fall into two categories. First are dynamical estimates, which are sensitive to the presence of both luminous and dark matter. Various estimates have been made from individual galaxy-rotation curves, studies of binary galaxies, cluster and supercluster dynamics, and so on. Most of these yield values for the

CEPHEID VARIABLES AS DISTANCE INDICATORS

Cepheid variable stars can be used to measure distances to stellar groups outside our Galaxy because there is an observed connection between the period (P) of a Cepheid's light variation and its luminosity (L): the longer the period, the higher the luminosity. This remarkable period-luminosity (P-L) relationship was discovered by Henrietta Leavitt in the course of studying Cepheids in the Small Magellanic Cloud, a nearby dwarf galaxy.

The P-L relationship has been refined since Leavitt's time, but its application to the extragalactic distance scale remains the same. By measuring the apparent magnitude and period of a Cepheid in a remote galaxy, we can determine the distance to the remote galaxy in terms of the distance to the calibrating galaxy (e.g., the Small Magellanic Cloud). Calibration of the P-L relation requires the measurement, by other means, of the actual distance to a Cepheid. The only direct way to do this is by triangulation—for example, from the Earth's orbital baseline (the method of trigonometric parallax). However, even the nearest Cepheids in our Galaxy are so distant that measurements from space are required.

New initiatives will provide other basic information necessary for a truly accurate value for H_0. The best current P-L calibration relies on data from Galactic clusters whose distances can be estimated from cluster main-sequence fitting and from stellar-pulsation theory. Future space-astrometry missions will provide direct parallax measurements to nearby Cepheids, while space interferometers will make possible direct measurements of their radii. A very large optical and infrared telescope in space can detect Cepheids more distant than those accessible to HST, thereby reducing the need for tertiary distance indicators, which are currently required to reach distances where velocity perturbations to the Hubble flow are negligible.

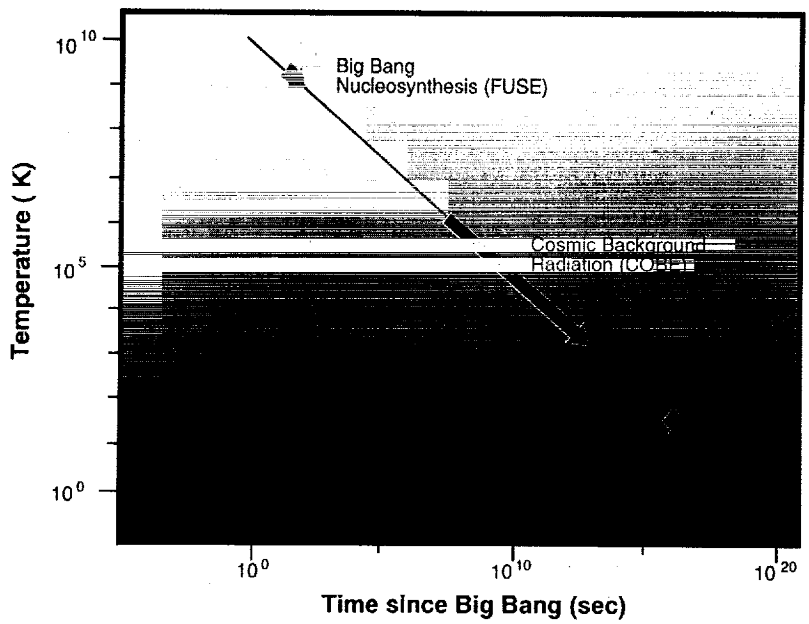

Figure 6. THERMAL HISTORY OF THE UNIVERSE can be reconstructed with the aid of data from NASA space missions. The Far Ultraviolet Spectroscopic Explorer (FUSE) will observe absorption lines arising from deuterium that was formed during the first 3 minutes after the Big Bang.

current mass density that lie in the range from 10% to 30% of the critical density, although some estimates up to 100% have been recently published.

A second sensitive estimate of the density parameter can be obtained from comparisons of the abundances of the light chemical elements with the predictions of hot Big Bang models, as discussed above. These estimates will constrain the fraction of the critical density which is present in the familiar "baryonic" form. It is important to recognize that other forms of matter (e.g., neutrinos) are known to exist, and that still other forms (e.g., postulated but undiscovered particles like axions) may also exist. The density of mass in these other forms could conceivably exceed the density of baryons and could even close the Universe.

A direct attack on the geometry of the Universe—H_0 and q_0—should prove feasible during this decade using supernova observations, since these objects currently serve as "standard candles" from the Local Group of galaxies to more distant galaxies (e.g., the Virgo Cluster). Surveys to detect supernovae from the ground have begun and will produce a reasonable number of candidates at low redshifts for spectroscopic observations using HST.

These measurements will be very difficult, and substantial effort will also be needed to advance our theoretical understanding of supernovae, but the potential reward is great. It may prove possible to measure directly the curvature of space. A project such as the Lunar Transit Telescope would play a key role in the detection of cosmologically distant supernovae. Comparisons of their light curves with those of the current epoch place direct constraints on the geometry of the Universe.

The standard Big Bang model agrees in a general way with available observations. However, difficulties emerge when observations of Big Bang remnants are attempted. For example, the recent Cosmic Background Explorer (COBE) microwave-background observations appear to be too isotropic on large angular scales by comparison with results now emerging from studies at visible wavelengths. Such discoveries have stimulated a new cross-fertilization between fundamental physics and observational cosmology. Since the early Universe is the only

HUBBLE SPACE TELESCOPE AND THE AGE OF THE UNIVERSE

The Hubble Space Telescope is named after Edwin Hubble, who discovered, in the 1920s, that the Universe is expanding. Hubble then initiated a program to estimate the age of the Universe through systematic observations of the distances and recessional velocities of external galaxies. It has not been possible to complete this program with telescopes on the ground.

However, a designated HST "key project" will finally finish Hubble's pioneering work after more than half a century, using one of the same distance indicators—Cepheid variable stars—that he used. When equipped with second-generation instruments that correct for spherical aberration, HST will be able to observe Cepheids seven times more distant than those studied so far with the largest ground-based telescopes.

DEUTERIUM

During the first 3 minutes after the Big Bang, conditions in the Universe were similar to those that now exist at the center of the Sun. The temperature and density were so high that protons and neutrons fused to yield chemical elements slightly more complicated than the initial hydrogen (H), deuterium (^{2}H), and the two forms of helium (^{3}He and ^{4}He). The deuterium is produced by an intermediate step in the fusion of hydrogen into helium.

Measurements of the ratios of the numbers of these atoms relative to hydrogen reveal the density of the Universe at this very early epoch. In general, the higher the density, the more hydrogen is ultimately converted to helium, and the less deuterium remains. Space observations, particularly those to be made by the Far Ultraviolet Spectroscopic Explorer (FUSE), offer the best means of obtaining this information. Present estimates suggest that the early Universe had a very low density, but the uncertainties in the data are still large.

environment energetic enough to allow observation of the most basic physical interactions, both cosmologists and physicists are now extremely interested in obtaining a more accurate observational understanding of the evolution of the Universe.

4. Distribution of Galaxies

The large-scale structure in the distribution of galaxies found from extensive redshift surveys (Figure 7) is difficult to reconcile with the standard Big Bang model of the Universe. No satisfactory picture of the formation of both galaxies and their large-scale distribution has emerged. Model universes whose density is dominated by cold dark matter are successful in producing galaxies with many of the observed properties, but are unable to produce the observed pattern of large voids. Hot universes dominated by dark matter are able to yield the large-scale pattern but have difficulty producing the individual galaxies.

Another test of models for the origin of structure in the Universe involves detection of gravitationally induced perturbations in the Hubble flow. Unambiguous detection of large peculiar velocities, such as those attributed to the "Great Attractor," have proved difficult with current extragalactic distance indicators. However, something must be responsible for the anisotropy in microwave radiation seen in the Local Group reference frame.

Redshift measurements are only sensitive to the radial dimension of galactic motion. To fully map the flow pattern of the luminous matter in the nearby parts of the Universe, proper motions are also necessary.

COSMIC DENSITY AND THE EXPANSION OF THE UNIVERSE

When we look out at the Universe through our telescopes, we see only luminous matter. However, we also observe indirectly the gravitational effects of matter that we cannot see—the so-called "dark matter." Measurements of dynamical interactions among galaxies suggest that there is approximately 10-100 times as much dark matter as luminous matter in the Universe.

The total density of matter of all kinds is a crucial number. Low density means that the Universe will expand forever. But if the density is sufficiently large, gravitational effects will not only slow the expansion, but eventually halt and reverse it—leading to a future collapse of the Universe. Although the density of luminous matter is now fairly well determined, the final answer on our cosmic fate awaits better information on the ratio of dark to luminous matter.

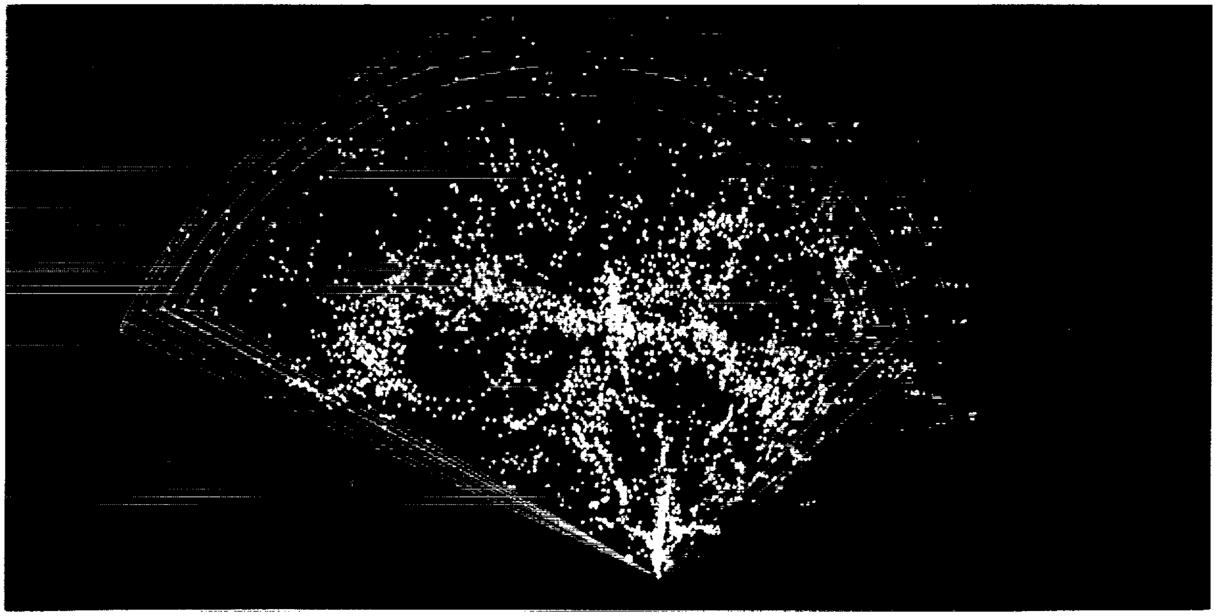

Figure 7. DISTRIBUTION OF GALAXIES in the Universe is shown in this Harvard-Smithsonian Center for Astrophysics map of 4,000 galaxies within 450 million light years of our own Milky Way (at origin of coordinate system, bottom center). The so-called "Great Wall" of galaxies, some 500 million light years long, stretches horizontally across the middle of the diagram.

An astrometric interferometer, located in space or on the Moon, would be capable, in principle, of measuring the proper motions of galaxies with compact nuclei out to a distance of approximately 100 megaparsecs.

Much work remains to be done if we are to connect the present observable Universe with the physics of the early Universe. "Lookback observations" of galaxies and their distributions are required out to the largest possible redshifts.

Imaging observations of galactic structure and morphology are possible out to moderate distances with HST. But even with second-generation visible and near-infrared spectrographs, HST is too small to provide the necessary dynamical data on these very faint sources. Even the largest ground-based telescopes lack the spatial resolution to carry out such observations; moreover, the spectral features of interest, associated with the peak of the galactic emitted-energy profile, are redshifted into a near-infrared region of relatively high sky background. A new, very large telescope in space, operating in the visible and near infrared and equipped for both imaging and spectroscopy over a broad range of these wavelengths, is required if we are to successfully attack the most basic questions remaining in cosmology.

LARGE-SCALE DISTRIBUTION OF GALAXIES

Distances to galaxies can be estimated by using the Hubble relationship, which establishes a proportionality between galaxy redshift and distance. Large-scale surveys of galaxy redshifts now in progress show that the three-dimensional distribution of matter in the Universe is not smooth, but filamentary. Large voids, sometimes as much as 200 million light-years across, appear to be surrounded by sheets and filaments containing most of the galaxies and galaxy clusters.

No satisfactory explanation has yet been given for this sponge-like geometry. If the measured sizes and velocities of the galaxies are correct, there has not been sufficient time for the normal motions of galaxies to have cleared out the voids. Perhaps they were swept out by colossal explosions—or perhaps, on the largest scales, the matter in the Universe was highly filamentary or clumped from the beginning.

B. Structure of Galaxies and Quasars

Current Program Contributors:

- Hubble Space Telescope (HST)
- HST Second- and Third-Generation Instruments
- International Ultraviolet Explorer (IUE)
- Far Ultraviolet Spectroscopic Explorer (FUSE)

Future Program Contributors:

- Deep Ultraviolet Survey
- Optical Interferometers (space-based or lunar-based)
- 16-Meter Telescope (space-based or lunar-based)
- Lunar Transit Telescope

1. Formation and Evolution of Galaxies

Particularly interesting questions in galactic formation concern the manner in which protogalactic gaseous clouds collapsed to form galaxies, the frequency of these collapses, and the frequency of interactions and mergers among galaxies or protogalactic condensations of stars and gas. The epoch at which galaxies formed in the early Universe also remains unclear, as does the total duration of the formation process.

The complex problem of galaxy formation has been attacked through sophisticated, systematic, and broadly ranging ground-based observational studies. Nevertheless, progress has been slow. While there remains much to be accomplished with ground-based telescopes, their inherent limitations are now clear.

The high spatial resolution, high spectral resolution, and wideband spectral coverage (X-ray to infrared) offered by substantial telescopes in space are critical for significant further progress. High spatial resolution will permit detailed observations within the crowded fields typical of remote galaxy clusters. High spectral resolution and wide spectral coverage will allow detailed study of key physical processes simultaneously throughout the electromagnetic spectrum.

One of the most exciting discoveries of the last decade was the recognition that galaxies undergo significant evolution on timescales much less than the age of the Universe, and that some evolution has occurred quite recently The resolving power of HST, potentially greater than that of ground-based telescopes for galactic studies, will have a major impact on our understanding of why some galaxies have undergone such recent evolution.

HOW DID GALAXIES FORM?

The question of galaxy formation is a wide-ranging one. It deals not only with the physical processes at work during the collapse of the protogalactic clouds, together with initial star formation and establishment of a stable dynamical structure for the galaxy, but also with the subsequent and less rapid stellar, chemical, and dynamical evolution that brought the galaxy to its present state. This question also leads astronomers to seek to determine the amount of dark matter associated with galaxies, the size of any dark-matter envelopes around galaxies, and the ratio of dark matter to luminous matter in different types of galaxies.

MILLI-ARCSECOND (mas) AND MICRO-ARCSECOND (μas)

The angular height of a 6-foot astronaut on the Moon, as seen from the Earth, is 1 milli-arcsecond (1 mas, or 0.001 arcsec). The angular thickness of a 5-cent piece (a nickel) held by such an astronaut is 1 micro-arcsecond (1 μas, or 0.001 mas). The accuracy expected from Hubble Space Telescope astrometric observations is a few milli-arcsec (mas). The accuracy of astrometric measurements from Earth orbit and from the Moon is expected eventually to approach the micro-arcsecond (μas) level.

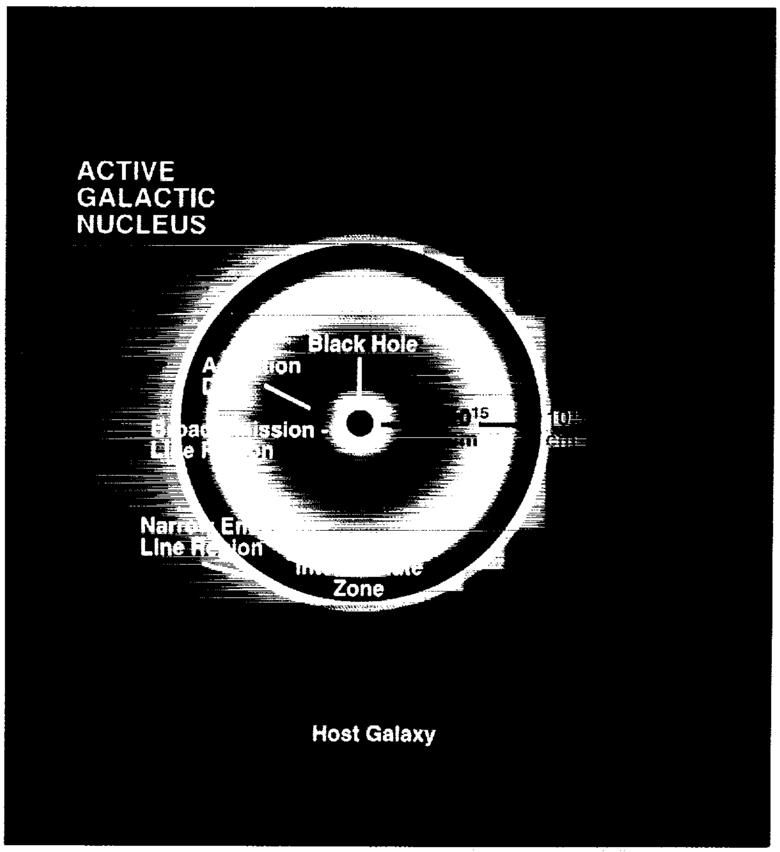

Figure 8. CENTRAL BLACK HOLE surrounded by accretion disk of high-temperature matter is believed to supply the power for radiation emitted by active galactic nuclei. The width of the spectral lines depends on the distance of the emitting region from the center; linewidth diminishes with distance.

For nearby objects, the high spatial and spectral resolution of HST will further our understanding of the contribution of evolutionary activity in galactic nuclei relative to that in galactic disks and envelopes. The role played by interactions and mergers will be greatly clarified by such studies. However, the sensitivity and resolving power of HST will still be a limitation at large distances, and even more powerful instruments will be required to study the most remote sources.

Observations of the absorption lines in quasar spectra, arising from intervening matter, have proved to be an invaluable tool for diagnosing conditions in the post-formation Universe. High-resolution ultraviolet spectroscopy is essential to extend this probe of the intergalactic medium and gaseous clumping from the nearest to the most distant quasars.

One of the primary objectives of the recommended plan is to probe the Universe at distances (and hence eras) associated with the primary episodes of galaxy formation. This objective places stringent demands upon the capabilities of even space-based telescopes.

A particular requirement is the resolution of low-surface-brightness structures with a spatial scale of 10^2-10^3 pc at redshifts greater than unity. These are the spatial scales typical of the structures that reveal what is happening in galaxies during their formation and evolution, e.g., star-forming complexes, spiral arms, and merger tails and structures. Their observation and measurement require angular resolutions on the order of 10-50 milli-arcseconds (mas) at wavelengths ranging from the ultraviolet well into the infrared.

While HST can meet the less demanding end of this requirement, a major advance in observational capability is actually needed. This could be provided by a large telescope that combines light-gathering power over a broad (UV to IR) spectral region with spatial resolution that matches the scales of the relevant structures in high-redshift galaxies. High throughput and wide-field spectroscopic instruments are also needed in such a telescope. Given these capabilities, astronomers will for the first time be able to unveil the early Universe and to witness directly the process of galaxy formation.

2. Active Galaxies

The central engines of active galactic nuclei are thought to be very massive black holes that produce power by accreting material into their deep gravitational wells (Figure 8). But even if this speculation is correct, many fundamental questions about active galactic nuclei remain to be answered. How do they manage to radiate photons with equal facility in so many wavebands? What is the source of their accretion fuel? Why do they occur in some galaxies and not others? What is it about young galaxies that amplifies their power? What determines their choices from the "menu" of activities? Why are some strong emitters in the radio region, while others are weak? Why are some highly variable on short timescales, while others are quiet? Why are some strongly polarized, and others hardly polarized at all?

Space astronomy has already played a major role in expanding our knowledge of active galaxies. Satellite observations were required to discover that such galaxies are substantial sources of power in the infrared, ultraviolet, X-ray, and gamma-ray regions of the electromagnetic spectrum, and not only in the optical and radio bands. The identification of possible thermal accretion-disk radiation was brought about largely through observations made by the International Ultraviolet Explorer (IUE). Future missions should bring further advances in our understanding of the nuclei of active galaxies.

Within the next few years, HST should be able to tell us a great deal about the characteristics of the galaxies that host active nuclei. This mission will provide the first close look at the interactions between relativistic jets and galactic material. It should also produce major strides in our understanding of gravitational lensing; the characteristic angular scale of the image formed by a galactic gravitational lens is 1 arcsec or less, well suited to HST's angular resolution but very difficult to measure from the ground.

When applied to studies of high-redshift quasars, the HST ultraviolet sensitivity (which extends down to 1,200 Å) will also provide a first look at the truly hard ultraviolet spectrum of active galactic nuclei. This portion of the spectrum should be particularly useful in revealing extreme relativistic phenomena at the very edge of the central energy engine.

The Far Ultraviolet Spectroscopic Explorer (FUSE) will also contribute significantly to studies of active galactic nuclei by measuring the hard-ultraviolet spectrum of

ACTIVE GALACTIC NUCLEI (AGNs)

At one time it was thought that galaxies were little more than self-gravitating collections of stars producing optical light by thermal radiation. Over the past several decades, however, we have learned that they are much more complicated and surprising objects. In addition to containing significant quantities of gas and dust unattached to stars, galaxies seem also to harbor large amounts of dark matter, and, in many cases, non-stellar nuclei of extraordinary luminosity. One or two percent of present-epoch galaxies produce as much power by means of non-stellar processes in their nuclei as is produced by all their stars combined.

In the early Universe, the same fraction of galaxies housed active nuclei, producing a hundred to a thousand times as much power as their surrounding stars. Moreover, this extraordinary power output is delivered in either of two remarkable ways. In most cases, the power is spread roughly equally over the entire electromagnetic spectrum, from the mid-infrared through the gamma-ray region. Sometimes, however, the power is emitted primarily in relativistic jets of matter, with comparatively little going into any kind of electromagnetic radiation.

Because the relative strengths of these different sorts of non-stellar processes vary from case to case, numerous subclasses of these active galaxies have been identified; among the most common are Seyfert galaxies, radio galaxies, "BL Lac Objects," and quasars. However, one of the achievements of the past decade is the recognition that all these different forms are at heart the same sort of system—hence the *portmanteau* name, "active galactic nuclei" (AGNs).

nearby active galaxies. This mission's EUV sensitivity will also permit the first observations of active-galaxy continuum emission in the neighborhood of 100 Å—the long-wavelength cutoff of the Advanced X-Ray Astrophysics Facility (AXAF), the third Great Observatory.

Other possible missions can contribute in major ways as well. An all-sky ultraviolet survey (e.g., the Deep Ultraviolet Survey) should be an ideal way to compile very large, homogeneous samples of active galactic nuclei because the contrast with ordinary stars and galaxies is greatest in the UV. In order to truly understand their dramatic cosmological evolution, such large well-defined samples are essential.

Space observations also hold unique promise for studies of variability. Such studies can be used both to infer the structure of the inner emission-line region of galaxies and to provide a new window for study of the central engine. Regularity of sampling is a prerequisite for variability studies. However, on timescales of days to years, regularity can best be achieved from space, where interruptions arising from weather, lunar phase, etc., do not occur.

Another reason to study AGN variability from space is the opportunity to bring absolute flux measurements to bear on the the extraordinarily wide spectral range characteristic of AGN emissions. Coordination of variability studies in many spectral regions is an important tool for the study of the central engine.

In the long term, further observational progress depends on the exploitation of new technology. The two technological frontiers in visible and ultraviolet astronomy are higher angular resolution and larger collecting area. A resolution of 0.1 arcsec (100 mas), available for the first time with the second-generation Wide Field Planetary Camera II (WF/PC II) on HST, will open up the possibility of spatially-resolved studies (in the nearer active galaxies) of the larger of the two principal emission-line regions, the so-called "narrow line region" (Figure 9).

However, it will take an angular resolution of 0.1 mas (100 μas) to resolve the stronger emission-line region, the so-called "broad line region," even in the nearest objects. The same resolution is required to resolve the inner core of active galaxies at cosmological distances to discern the boundary between those portions of the galaxy dominated by stellar processes and those truly controlled by the nucleus. Such high angular resolution can only be achieved by optical interferometry in space.

Collecting area is complementary to angular resolution. HST-level resolution is, in principle, high enough to allow imaging of even the most distant galaxies, but a practical limit is set by the rapid cosmological dimming of surface brightness. Considerably greater throughput will be necessary for efficient observations of host galaxies at high redshift. Because the efficiency of present detectors for much of the visible and ultraviolet approaches 100%, only greatly enlarged apertures will solve this problem. Thus, to achieve the full benefits of high angular resolution, a large collecting area is also necessary.

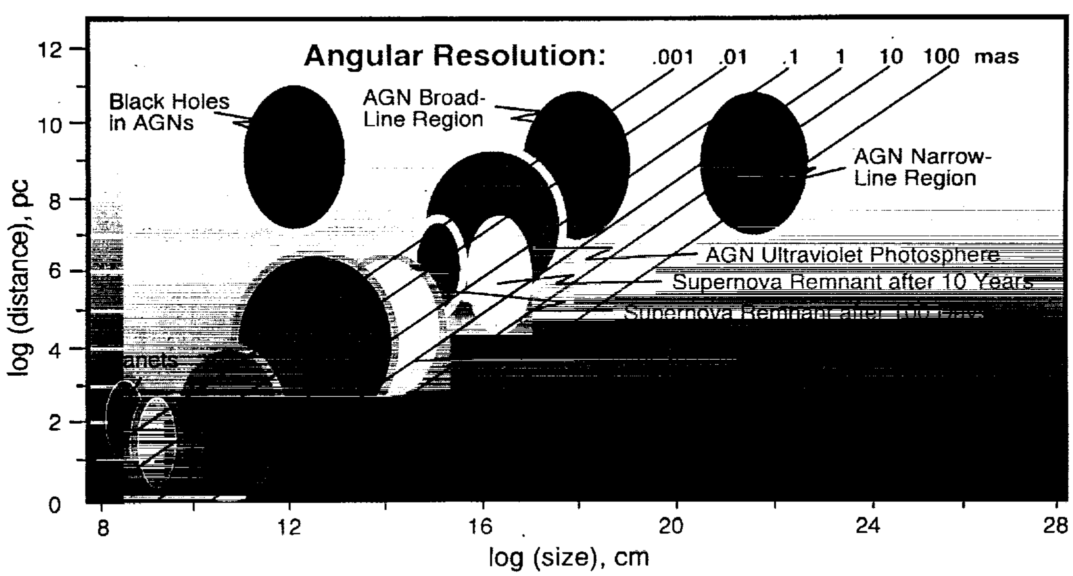

Figure 9. MAJOR ADVANCES IN ANGULAR RESOLUTION will be required for detailed studies of active galactic nuclei. The second-generation Wide Field/Planetary Camera II on HST will bring 100-milli-arcsecond resolution to bear on the AGN narrow-line region, but micro-arcsecond capability is needed to probe central AGN features and many other astronomical objects.

C. Structure of the Milky Way

Current Program Contributors:

- Hubble Space Telescope (HST)
- HST Second- and Third-Generation Instruments
- Extreme Ultraviolet Explorer (EUVE)
- International Ultraviolet Explorer (IUE)
- Far Ultraviolet Spectroscopic Explorer (FUSE)
- ORFEUS/IMAPS/AstroSPAS

Future Program Contributors:

- Deep Ultraviolet Survey
- Optical Interferometers (space-based or lunar-based)
- 16-Meter Telescope (space-based or lunar-based)
- Lunar Transit Telescope

1. Interstellar Dust

An interstellar dust grain absorbs light most strongly when the wavelength of the light approximates the size of the absorbing grain. In addition, there are "features" in the variation of absorption strength with wavelength that depend upon the composition of the dust. Analysis of the absorption spectrum of dust therefore provides clues to grain size and composition.

Shape effects can also be important, particularly at long wavelengths. It seems likely that dust grains with

INTERSTELLAR DUST

Although interstellar dust is a minor constituent of the interstellar medium (ISM), it has a profound impact on several fundamental astrophysical processes and issues (Figure 10). These include the formation and collapse of interstellar clouds into stars and planetary systems, the regulation of the rate at which galaxies evolve, and the determination of chemical composition of the ISM in our Galaxy and its evolution. To address these issues, a detailed understanding of the dimensions and composition of interstellar dust grains is required.

The ability of a gaseous plasma to radiate away heat, and thereby to contract and collapse, is strongly affected by the presence of metallic ions and molecules. Since dust is composed of metals that have "frozen out" of the interstellar gas, and since (under most interstellar conditions) the primary formation site for molecules is grain surfaces, the importance of interstellar dust in this fundamental process is clear.

Furthermore, the rate at which interstellar clouds collapse to form succeeding generations of stars regulates both the rate of new-star formation and the types of stars which can be formed. These two factors are instrumental in determining how a galaxy evolves. Dust plays critical roles at every stage of these processes. In addition, because dust has been detected in the earliest known galaxies and QSOs, dust must have played these roles since the first epochs of galaxy formation.

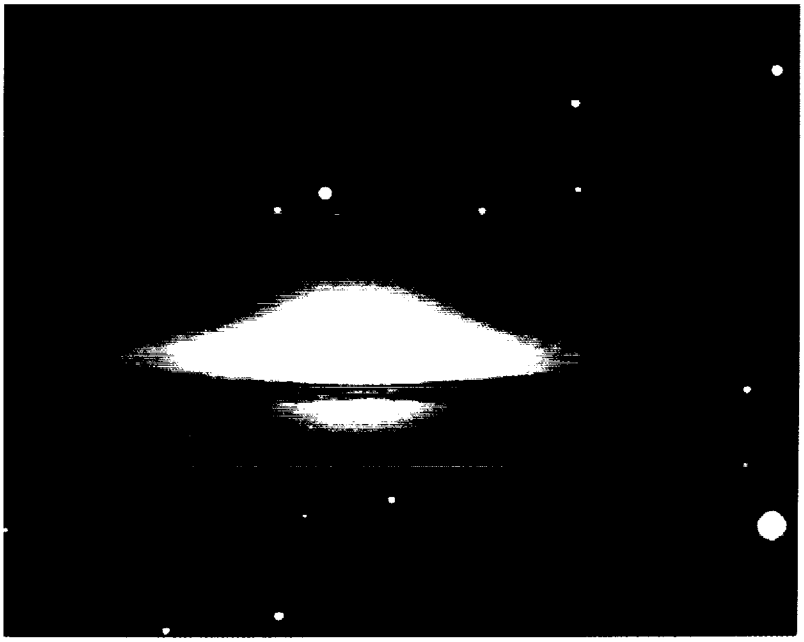

Figure 10. DARK LANES OF INTERSTELLAR DUST bisect the image of the "Sombrero Galaxy" (M 104) in the constellation Virgo. This flattened spiral system is inclined only 6 degrees to the line of sight; clouds of dust pervading the galactic plane are silhouetted against a background of millions of stars in the nuclear region.

elongated shapes or "fluffy" structures can account for the 100-μm cirrus emission observed by the Infrared Astronomy Satellite (IRAS). This dust may also be observed in the far-UV diffuse background emission.

Studies both from the ground and from space have shown that the mean size of an absorbing grain is small, on the scale of ultraviolet wavelengths. The ultraviolet is thus one of the most useful wavebands for the investigation of dust properties. Furthermore, because the absorption by dust effectively "shields" the inner regions of interstellar clouds from the ambient stellar ultraviolet radiation, which could disrupt the formation of molecules in the cloud core, understanding its absorption at ultraviolet wavelengths is particularly important.

The International Ultraviolet Explorer (IUE) has contributed greatly to our understanding of interstellar dust, and has even allowed us to sample the ultraviolet extinction by extragalactic dust for the first time. Because of IUE's limited sensitivity, however, we have not yet been able to probe grain properties in the densest regions of dust clouds, where much of the important cloud chemistry occurs. HST will enable us to probe these environments far more deeply than before.

Several important interstellar molecules are disrupted by radiation between the hydrogen ionization limit (912 Å) and the effective cutoff of the IUE and HST optics (about 1,200 Å). Only FUSE can provide studies of dust absorption at these wavelengths, permitting assessments of the role of dust in the chemistry that triggers the collapse of interstellar clouds.

2. Interstellar Gas

The appearance of interstellar ultraviolet absorption lines in stellar spectra recorded by the *Copernicus* satellite during the 1970s triggered a vigorous era of research on the chemical composition and physical state of atomic and molecular gases in space. For the first time, astronomers could investigate a variety of ionization states for different elements.

Determinations of the abundances of many elements (relative to those of atomic and molecular hydrogen) furnished broad new insights into the fundamental processes of depletion, caused by the condensation of free atoms onto dust grains. Comprehensive surveys of molecular hydrogen (H_2) were carried out for many lines of sight. The rotational excitation of this molecule provided estimates of local kinetic temperatures, densities, and ultraviolet starlight fluxes inside diffuse clouds of gas. The existence of pervasive, low-density, very hot gas in the disk of our Galaxy was revealed by the ubiquitous absorption features of five-times ionized oxygen (O VI).

In the decade that followed *Copernicus*, ultraviolet spectroscopy was carried out by the International Ultraviolet Explorer. Although this satellite provided several key ISM findings, IUE was not designed to provide the high spectral resolution and photometric precision necessary for forefront ISM research.

It will therefore be the task of the first-generation Goddard High Resolution Spectrograph (GHRS) currently on HST to build upon the earlier accomplishments of *Copernicus*. A vast increase in the capability to record a broad wavelength range in a single exposure will be provided by the Space Telescope Imaging Spectrograph (STIS), a second-generation instrument now being designed for installation on HST in the mid-1990s.

The Far Ultraviolet Spectroscopic Explorer (FUSE) will complement the HST observing program by extending spectroscopic observations to wavelengths below the HST sensitivity cutoff near 1,200 Å. This region contains all but a few of the Lyman bands of H_2 and HD; the entire Werner

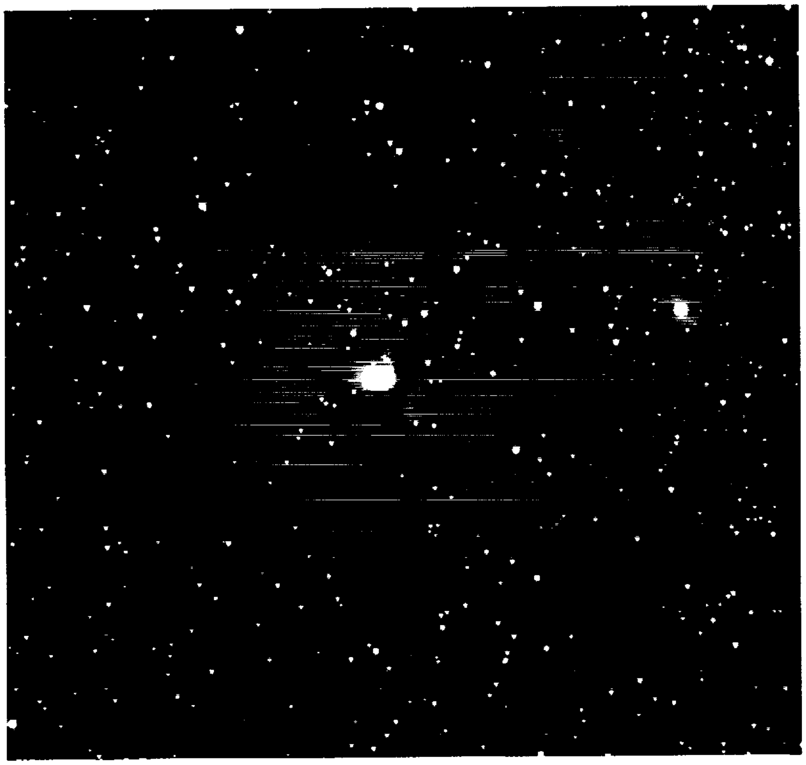

Figure 11. TRIFID NEBULA (M 20) in the constellation Sagittarius glows from the radiation of hot, internal stars. Dense lanes of interstellar dust obscure light from surrounding clouds of hydrogen and helium, driven outward by radiation pressure and stellar winds from stars in the center.

system of H_2; weaker members of the Lyman series of hydrogen, which are crucial for measurements of the atomic D/H ratio; and all the resonance lines of certain key atoms and ions. The spectra of O VI and S VI are of particular importance, since these ions are produced only in high-temperature, collisionally ionized plasmas.

These ultraviolet observations will sample a wider range of physical conditions than is possible at visible or radio wavelengths. Of particular importance is the ability of FUSE to detect molecular hydrogen, the most abundant molecule in the Universe.

The cold component of the ISM has an appreciable amount of H_2. However, *Copernicus* observed this component only along sightlines toward brighter stars in the solar neighborhood; such lightly obscured regions cannot be typical of star-forming environments generally (Figure 11). The much more sensitive FUSE instruments will record spectra of stars that are more heavily obscured by interstellar dust, allowing us to sample the major constituent of molecular clouds to greater depths.

Many additional questions can be addressed only by space ultraviolet spectroscopy. For example, young hot stars, old giant stars, and supernovae inject enriched gas into the ISM, heating the surrounding matter and accelerating it to supersonic speeds (Figure 12). Ultraviolet absorption lines yield important insights into the effects of these processes and into the subsequent dynamical disturbances. In many circumstances, shock-heated gas can rise high above the galactic plane, forming a highly ionized, dynamic halo that can be studied in the ultraviolet; this material could circulate in a "fountain

THE INTERSTELLAR MEDIUM (ISM)

In our Milky Way Galaxy, the average density of gas between the stars is only about one atom per cubic centimeter—about ten billion times less dense than the "empty space" produced by a good laboratory vacuum pump. This interstellar gas consists almost entirely of hydrogen (about 90%) and helium (about 10%), with small traces of heavier elements. If we were to look through a tube from a platform above the Earth's atmosphere toward the most distant star visible to the naked eye, we would view this star through approximately the same amount of gas as that in a similar tube only 1 meter long containing air at sea-level pressure.

The ISM is continually recycled as it coalesces under the influence of gravity to form new stars, only to be replenished as the stars evolve and die. Explosions from supernovae violently disturb and heat some of the gas, raising temperatures from about 50 K to 10^6 K or more. The contrast in density between the cold and hot interstellar matter is about the same as the ratio of the densities of water and air—about 1,000 to 1.

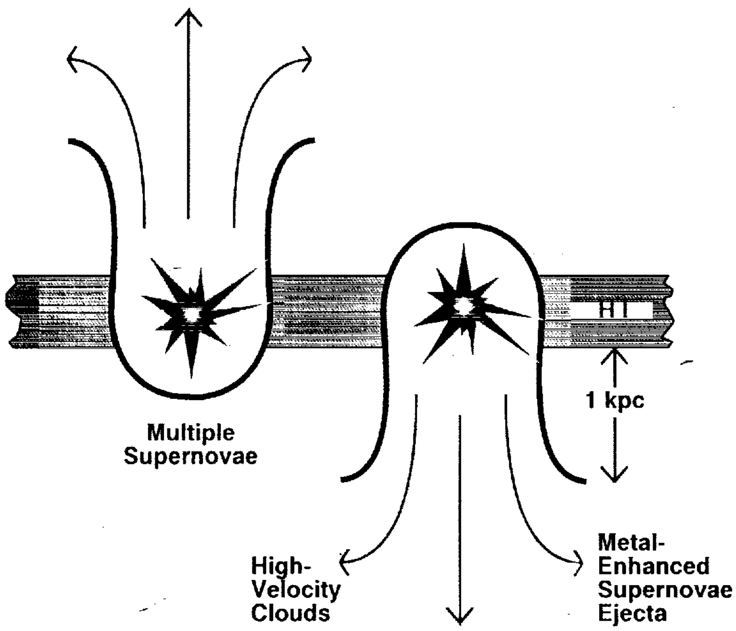

Figure 12. SUPERNOVA DETONATIONS IN THE GALACTIC PLANE shock-heat surrounding hydrogen gas to million-degree temperatures and eject high-velocity clouds of material enriched in heavy elements. Ultraviolet observations from space are essential for the study of these dynamic processes.

flow" as it cools or, alternatively, escape from the galaxy in a wind. Both HST and FUSE can provide significant insights into these processes.

3. Complex ISM Structure

The complex, filamentary character of the ISM is conspicuous in photographs of absorption and emission nebulae. With very few exceptions, observations of interstellar absorption lines merge the contributions from individual gas parcels as they sample a complex, heterogeneous environment. Even HST and FUSE will have insufficient velocity resolution to always differentiate contributions from regions with widely disparate physical conditions or modest differences in location. (The velocity channel separations of radio receivers are often fine enough to resolve the separate domains, but we are then defeated by the finite beam widths of the telescopes!)

With the power to isolate and study small parcels of gas, we could address still further questions about how different phases of the ISM interact—specifically, how the gas within individual clouds responds to external dynamical disturbances. What happens internally when a cloud is overtaken by a shock wave in the surrounding medium? How does a cloud respond to the ram pressure from a smooth, external flow of intercloud gas? Do magnetic fields modify this reaction? Atoms with excited fine-structure levels allow us to correlate kinematics with local pressures.

It is important to investigate interstellar shock waves at high spectral resolution to determine their chemical and ionization structures, both for structures that are softened by coupling to magnetic pressures and those that are not. The stratifica-

Figure 13. SHOCK-HEATED INTERSTELLAR GAS CLOUDS in the constellation Cygnus glow with the ultraviolet radiation emitted by triply ionized carbon atoms. This image, recorded by the ASTRO-1 Ultraviolet Imaging Telescope aboard the Space Shuttle in December 1990, shows a portion of the "Cygnus Loop," shaped by shock waves from a supernova explosion some 20,000 years ago.

tion of cooling and recombining material in post-shock regions can be resolved only if we measure components separated by about 1 km/sec. (Some chemical species are predicted to exhibit displacements of less than 1 km/sec from others, even if they are viewed perpendicular to the shock front.) The GHRS and STIS instruments for HST will provide the first steps, supplemented by observations with the Interstellar Medium Absorption Profile Spectrograph (IMAPS) in the far ultraviolet.

Theories of the ISM predict the existence of other interesting processes, such as conductive and evaporative interfaces between cool, dense clouds and the much hotter, low-density medium. We need to explore the interface structure, the exchange of material between the two media, and the effects of magnetic fields on the stucture. We also need to know the spectrum of hydromagnetic disturbances in the ISM. At very high resolutions, we may examine the clumping in velocity and carry out an inventory of subsonic motions that pervade individual domains.

Finally, we can determine the temperatures of regions that predominantly contain atomic gas. Comparisons of line widths for species having different masses but similar ionization properties would allow us to differentiate turbulence from thermal Doppler broadening.

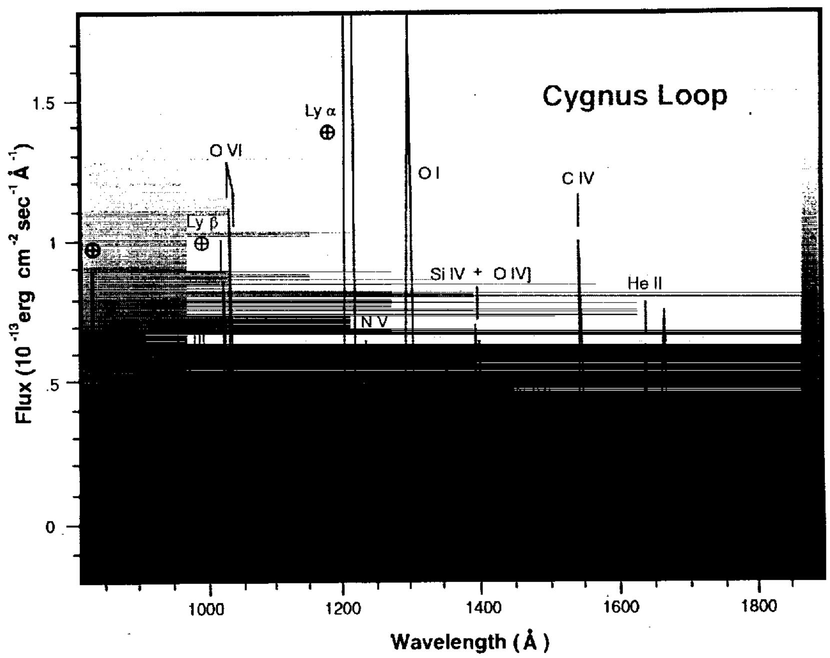

Figure 14. ULTRAVIOLET SPECTRUM OF GLOWING GAS IN THE CYGNUS LOOP, recorded by the ASTRO-1 Hopkins Ultraviolet Telescope during a 9-minute exposure from the Space Shuttle, displays more extensive wavelength coverage and higher spectral resolution than can be provided by IUE. The nebular spectrum is dominated by emission lines from such highly ionized species as C IV and O VI; features marked with an Earth symbol are airglow lines originating in the Earth's atmosphere.

4. Diffuse Ultraviolet Emission

Investigations of ultraviolet emissions from the ISM remain primitive. IUE has recorded good spectra of planetary nebulae and the shocked clouds within supernova remnants, but only the brightest wisps of emitting material can be detected. Tantalizing glimpses of diffuse emission from highly ionized atoms in the hot gas of the Galactic plane and halo have been obtained with simple instruments on sounding rockets and Space Shuttle missions (figures 13, 14).

Measurements of other emission features have also been made, but low signal-to-noise ratios and spectral resolutions have prevented us from identifying plausible origins (e.g., H_2 fluorescence, collisionally excited or recombining gases, or starlight scattered from dust grains). We do not know if any of the background emission detected at high Galactic latitudes is extragalactic.

The most controversial but theoretically important parameter characterizing the very hot ISM is its relative filling factor in the plane of the Galaxy. Our understanding of this key topic would be significantly advanced by comparisons of emissions from certain highly ionized ions (e.g., O VI, S VI, N V) with their corresponding absorption features in the same directions. Within certain temperature regimes, the absorption lines reveal the integrated electron density along a line of sight, whereas the emission lines measure the mean square of the electron density. Previous attempts to compare ultraviolet absorptions and emission fluxes in soft X-ray bands have been muddled by the difference in temperature responses for the two sampling methods.

5. Stellar Populations

The observable structures and substructures of galaxies in general, and of our own Galaxy in particular, have intrigued astronomers since galaxies were first recognized as massive stellar systems similar to (but external to) our Milky Way.

Evidence suggests that the Galaxy collapsed from an initial agglom-

OUR MILKY WAY GALAXY

The Milky Way is flat, in a state of differential rotation, and composed of a variety of stellar and gaseous subsystems. It is the birthplace of the Sun and our Solar System. One of the biggest challenges to modern astrophysics is understanding how the Galaxy fragmented out of the primordial matter of the Big Bang and evolved into its current state. Ultraviolet and visible-wavelength instruments in space will make major contributions to our understanding of the Milky Way and its evolution in two areas: studies of stellar populations, and studies of the properties of the interstellar medium.

eration of primordial gas. During this collapse, the protogalaxy began forming stars with a wide range of masses, and the most massive of these stars enriched the primordial cloud in the chemical elements found today in the Solar System. The earliest generations of stars were formed in a large, spherical halo; most stars, however, were formed after the Galaxy had partially collapsed to a disk.

The evolution of the Galaxy through these different stages has been accompanied by the formation of a variety of objects whose physical and dynamical properties derive from the material out of which they were formed, as well as from their initial locations and motions. These characteristics are the clues to the mysteries of the structure and evolution of the objects themselves and of our Galaxy as a whole. Here we give a few examples of the questions that may be addressed by the ultraviolet and visible space missions of the future in this important area.

Several populations of stars within the Galaxy have been identified. First formed was a spheroidal component of old-population stars and clusters which developed in the early stages of the collapse of the Galaxy. More recently, young stars were (and are still being) formed in the collapsed disk. Accurate three-dimensional stellar locations and space motions for large samples of often distant stars will require space astrometry. The measurement of chemical abundances in the atmo-

THE COLOR-MAGNITUDE DIAGRAM

Two easily derived characteristics of stars of known distances are their absolute magnitudes (or luminosities) and their surface temperatures. The absolute magnitudes can be found from the known distances and the observed apparent magnitudes. The surface temperature of a star is indicated either by its color or its spectral type. Before the development of yellow- and red-sensitive photographic emulsions—and, of course, photoelectric techniques—the spectral types of stars were usually used to indicate their temperatures. Now that stellar colors can be measured with precision, the color index is more often employed, even though the use of spectral types is still of great value.

A plot of absolute photographic magnitudes versus color indices for a given group of stars yields a color-magnitude diagram; if spectral types are used instead of color indices, one obtains an essentially similar Hertzsprung-Russell (H-R) diagram (Figure 15).

The most significant feature of the color-magnitude (or H-R) diagram is that the stars are not distributed over the diagram at random, but rather are clustered into certain regions. Most of the stars are aligned along a narrow sequence running from the upper left (hot, highly luminous) part of the diagram to the lower right (cool, less luminous) part. This band of points is called the main sequence. Three other populations are also obvious. These are the giants and supergiants, which lie along the top and right of the diagram, and the white dwarfs, which lie to the bottom and left.

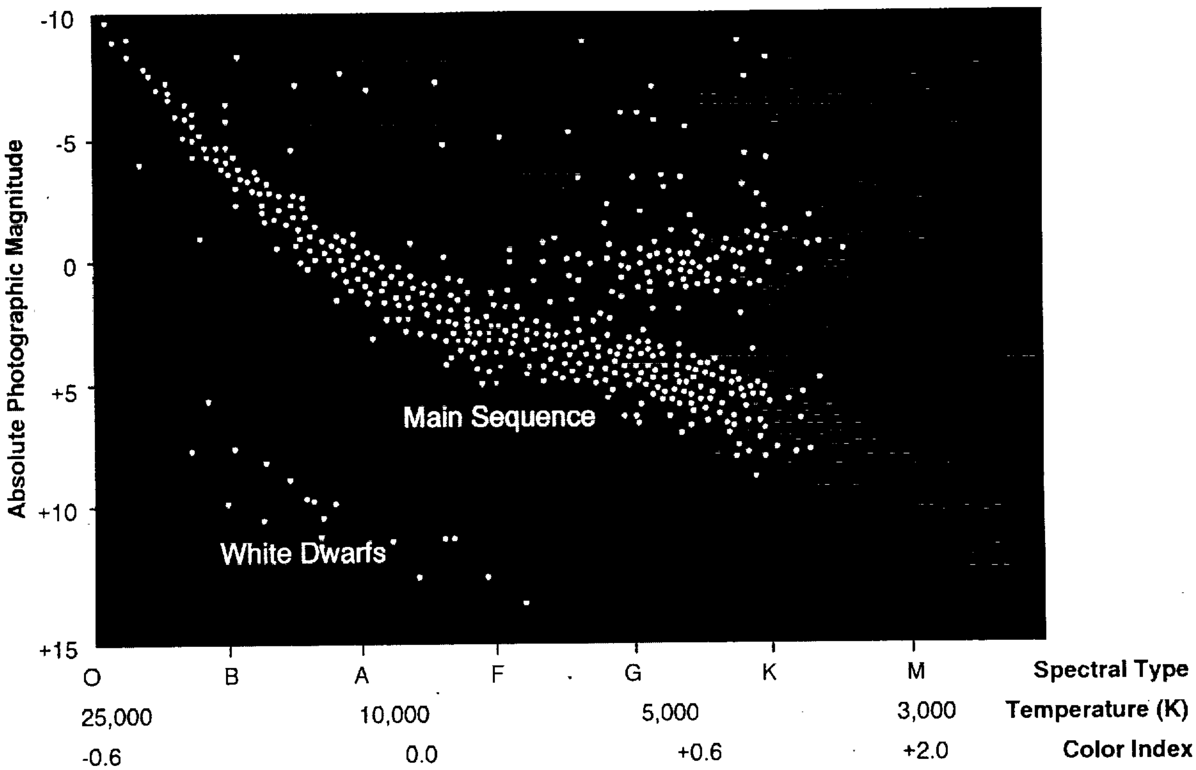

Figure 15. HERTZSPRUNG-RUSSELL DIAGRAM, or color-magnitude diagram, displays the correlation between stellar absolute magnitudes (a measure of luminosity) and spectral types or colors (a measure of temperature). Stars on the "main sequence" are in the prolonged, hydrogen-burning phase of evolution.

spheres of globular-cluster stars, or the members of close binaries, for which the masses can be determined empirically, will require both the collecting area and the resolving power of large space-based telescopes.

In the cases of the globular clusters in the Galactic halo, and the open clusters and associations in the Galactic disk, ages can be derived from studies of color-magnitude diagrams. These require high-resolution imaging to permit accurate photometry in crowded stellar fields, and completeness in star counts down to faint magnitudes. Such color-magnitude studies are among the highest-priority observations scheduled for HST, and they are likely to form a significant part of the research to be attempted with future imaging space telescopes.

Nearby and Local Group galaxies will be resolvable into individual stars by HST and subsequent large imaging space telescopes. Members of different populations within these galaxies will be studied to determine the similarities and differences between the main population groups in these galaxies and our own. For example, photometry of individual stars in the M31 and M33 globular clusters will provide color-magnitude diagrams that will determine the reasons for the differences in the populations of the cluster systems already detected from the ground. The observations will provide insight into the differences between the evolutions of these different populations.

The establishment of reliable population models for the Milky Way and neighboring galaxies is a prerequisite for interpreting the properties of more remote galaxies; for these, resolution into individual stars is not possible, and only integrated starlight can be studied. The ultraviolet spectrum below 3,000 Å is quite sensitive to the presence of young stars within an otherwise ancient population. Space telescopes will provide spectroscopy of distant galaxies in this spectral region. Such studies will reveal the duration and nature of star formation within galaxies at different lookback times.

D. Structure of Stellar Systems

Current Program Contributors:

- Hubble Space Telescope (HST)
- HST Second- and Third-Generation Instruments
- International Ultraviolet Explorer (IUE)
- Extreme Ultraviolet Explorer (EUVE)
- Far Ultraviolet Spectroscopic Explorer (FUSE)
- Voyager Ultraviolet Spectrometers (UVS)
- Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer (ORFEUS)

Future Program Contributors:

- Deep Ultraviolet Survey
- Advanced Explorer Missions
- Optical Interferometers (space-based or lunar-based)
- 16-Meter Telescope (space-based or lunar-based)

Knowledge of our Solar System has undergone a revolution over the last two decades as a result of fly-by missions to every planet except Pluto (Figures 16, 17). This scientific program has been greatly augmented by remote observations from the ground and Earth orbit.

These combined measurements have enjoyed a productive relationship, with each data set identifying new phenomena for the other to study. Planetary atmospheres and plasmas with temperatures ranging from less than 100 K up to some 10^6 K or more have been observed remotely and sampled directly during these fly-bys (Figure 18). Such knowledge, gained from a comparison of the remotely sensed and planetary-probe data, is applicable to other astrophysical problems for which direct measurements are not possible.

A complementary relationship also exists between remote planetary observations and astrophysics observations because of the large number of atomic and molecular emissions common to planets and other astrophysical sources. One example is the fluorescence of H_2 that occurs in both outer planetary atmospheres and circumstellar molecular clouds. In addition, the growing emphasis on studies of the origin and evolution of planetary systems around other stars is blurring the distinction between "solar system" and "astrophysics" investigations. Some of the specific areas of interest in the structure of stellar systems, including the Solar System, are addressed below.

1. Formation of Stars, Planets, and Protoplanetary Disks: Origin of Solar Systems

A fundamental goal of astronomy is to understand the formation of our Solar System, and to determine whether such systems are commonplace. Protoplanetary disks around stars other than the Sun have already been observed (Figure 19), and these observations can be greatly improved and expanded with HST's high angular resolution, low scattered light, and high sensitivity. There is a good chance for the detection of planets around other stars within the next decade. These observations will help to decipher the origin and evolution of our own Solar System and will provide information for estimating the frequency of planetary-system formation around other stars.

Both HST and FUSE will provide unique insights into these questions. HST, in particular, will help define the mechanisms governing the development of stars and protoplanetary systems at the earliest phases of their formation (Figure 20). HST observations of star-forming regions at high spatial and spectral resolution can help to determine the detailed chemical composition of young stellar neighborhoods. This is of great importance, since the evolution of a star is determined by its mass and its chemical composition. By

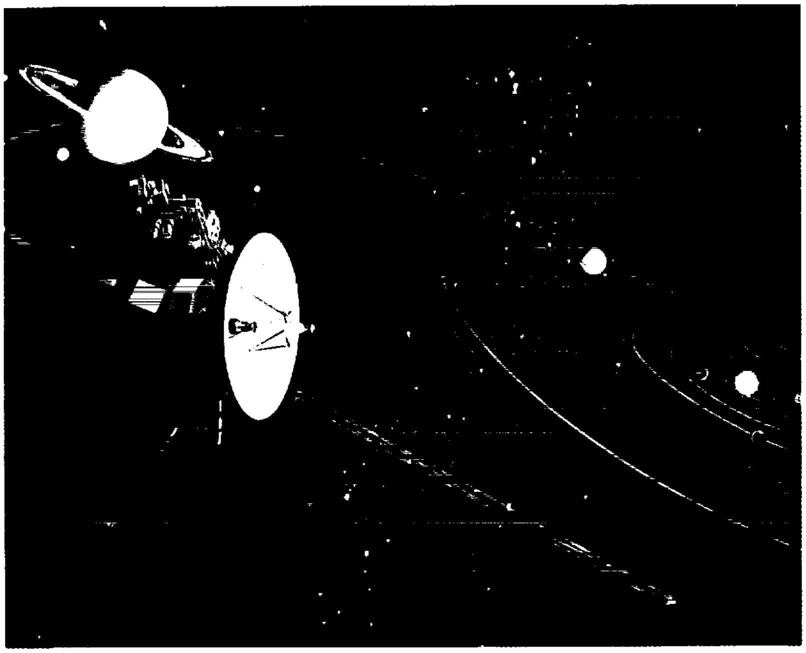

Figure 16. VOYAGER II DEEP-SPACE PROBE, shown leaving Saturn (1981) after flying by Jupiter (1979), heads toward Uranus (1986) and Neptune (1989). With the completion of the Voyager I and II missions to the outer Solar System, NASA had sent probes to all the planets except Pluto.

planetesimal accumulation, the radial variation of temperature within the disk, and the timescale for disappearance of the accretion disk. HST and FUSE will provide valuable observational data to better understand these processes. Moreover, spectroscopic observations at visible wavelengths will detect small variations in stellar radial velocities caused by the presence of planets in orbit around a normal star. Interferometric observations, either from space or from the surface of the Moon, may lead to the first direct detection of planetary systems around nearby stars.

The detection of other solar systems would provide evidence that our own solar system is not an anomaly, but rather, came into existence as part of a normal set of processes by which all stars form. This, in turn, would mean that observations of the dynamics and compositional variations in our own solar

examining the high-temperature plasmas surrounding young stars, FUSE will help determine the nature of the dissipative forces that cause the equatorial disks observed around very young stars to break up and collapse into planetary systems.

Important features of stellar collapse can be investigated through observations in the visible and ultraviolet during the later stages of the process. Interactions of the newly formed star and the accretion disk, mediated by the stellar magnetic field, lead to bipolar outflows of matter and energy and to a copious amount of ultraviolet radiation (Figure 21). Understanding the energetics, extent, and timescale of these phenomena will help astronomers understand how material can be captured by the star through the dissipation of angular momentum by the accretion disk.

The differences between terrestrial planets and giant gaseous planets may well hinge on a delicate balance between particle coagulation,

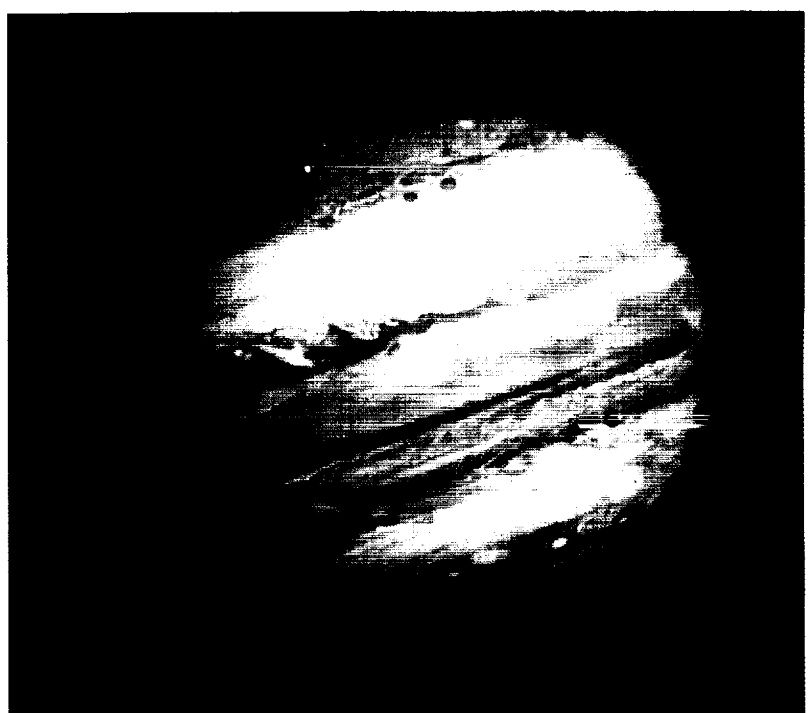

Figure 17. THE SPLENDOR OF JUPITER is revealed by Voyager I cameras. Visible here are complex cloud-band structure and the famous Great Red Spot (lower left), a long-lived feature of the stormy Jovian atmosphere. Images from HST will permit continuation of high-resolution planetary studies from space.

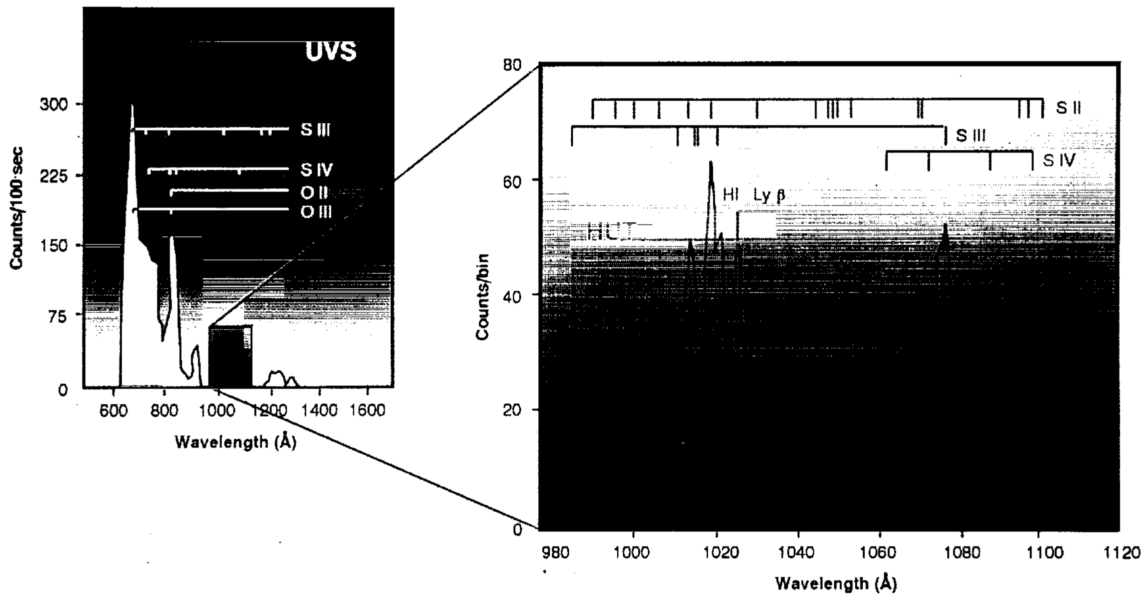

Figure 18. ULTRAVIOLET SPECTRUM OF PLASMA TORUS associated with Jupiter's moon Io was recorded in 1979 by Voyager ultraviolet spectrometers (upper left) and in 1990 by the ASTRO-1 Hopkins Ultraviolet Telescope aboard the Space Shuttle (lower right). The ASTRO-1 observations probed an unresolved feature of the Voyager spectrum to reveal a rich concentration of emission lines.

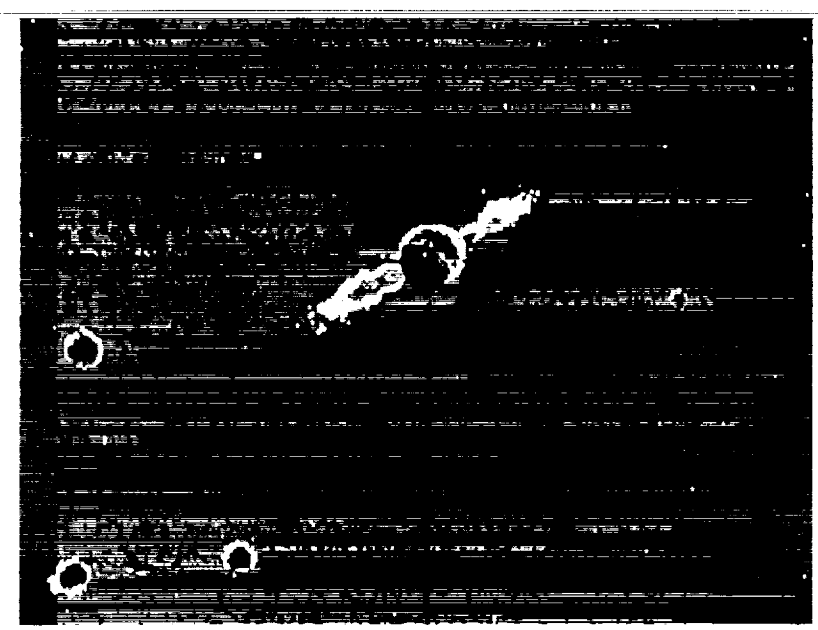

Figure 19. IMAGE OF BETA PICTORIS IN VISIBLE LIGHT shows circumstellar disk of material (seen edge-on) detected earlier at infrared wavelengths by NASA's Infrared Astronomical Satellite (IRAS). This Southern Hemisphere star is one of several stars that appear to show evidence of current planetary formation.

system can be used to refine and test models for the formation of stars with masses similar to that of the Sun.

2. Stars and Stellar Atmospheres

Stars and stellar systems, in our own Galaxy and others, challenge us to understand their never-ending cycle of formation and evolution. Stars form from the stuff of the interstellar medium, then live their lives replenishing the interstellar medium with reprocessed stellar material, which, in turn, is used to form new stars.

How these processes work is still a puzzle. Space observations can uniquely investigate the outer atmospheres of stars and the structure of their atmospheres. Such observations can determine whether strong magnetic fields capture the hot plasma in the star's atmosphere and bind it to the surface or whether this material flows smoothly and gently, or in erratic puffs, into the interstellar medium. With space observations we may determine how quickly stars lose mass and investigate the underlying energy source driving the hot atmospheres and the mass loss.

The diversity in mass-loss rates from different stars appears to be enormous, ranging over ten orders of magnitude. The rate of mass loss can profoundly effect the evolutionary history of a star. For example, some hot, massive stars can lose an entire solar mass in a million years, a significant time frame with respect to the lifetime of these stars and the time required for star formation.

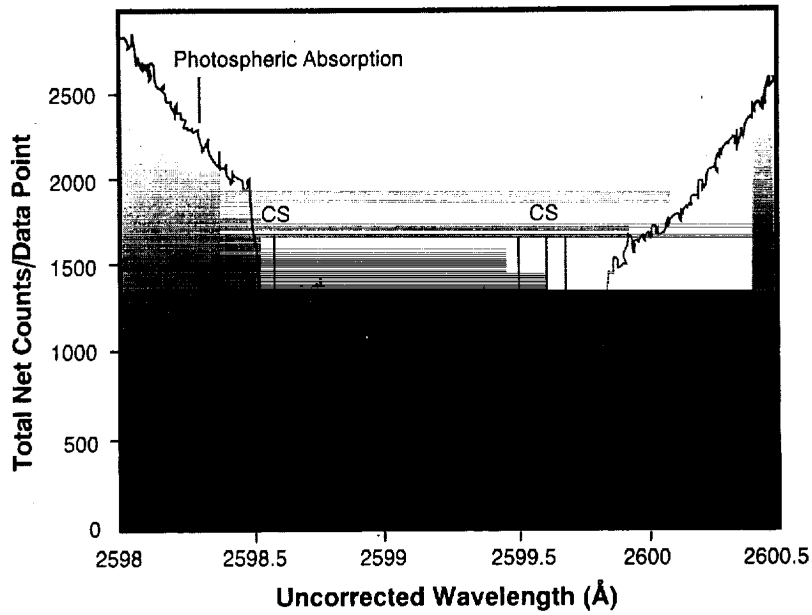

Figure 20. ULTRAVIOLET SPECTRUM OF BETA PICTORIS recorded by the HST Goddard High Resolution Spectrograph in 1990 shows strong circumstellar (CS) absorption features and variable spectral asymmetries that arise from infalling gas. Such spectra strengthen the evidence for protoplanetary collapse.

Space observations in the ultraviolet spectral region are sensitive to the outermost layers of a star's atmosphere (see again Figure 21). In these layers the acceleration and eventual escape of matter from a star can be detected. Spectra taken with HST and FUSE will reveal the important sequence of resonance lines of highly ionized carbon, nitrogen, and oxygen (C IV, N V, and O VI) that will allow us to derive meaningful rates for mass

THE ORIGIN OF SOLAR SYSTEMS

It is believed that our Solar System was formed about 4.5 billion years ago through a process that gave rise to a protostar surrounded by a rotating disk of material. Accretion within this disk produced the planets and moons that we know today, while the central star, our Sun, evolved rapidly toward the main sequence.

Although we have only the geologic record on comets, the major and minor planets, and planetary satellites from which to deduce how our Solar System formed, we can learn much more about the process by studying other, nearby stellar systems in the early stages of collapse, star formation, and accretion. Circumstellar material is very difficult to detect amid the glare of the light of the parent star, since the star would typically be 10,000 to 100,000 times brighter than any orbiting planet, and since an Earth-like planet would typically be separated from the star by an angle of 0.1 arcsec or less at the distances in question.

However, advances in astronomical instrumentation have now permitted detection of protoplanetary material in the stellar systems Beta Pictoris and Vega, and we may expect to detect the first planet orbiting about another star during this decade. We anticipate that observations with HST will reveal the next level of material and giant planets around nearby stars, and that the next generation of large space-based telescopes and interferometers beyond the Great Observatories will continue the quest for Earth-like planets about other stars.

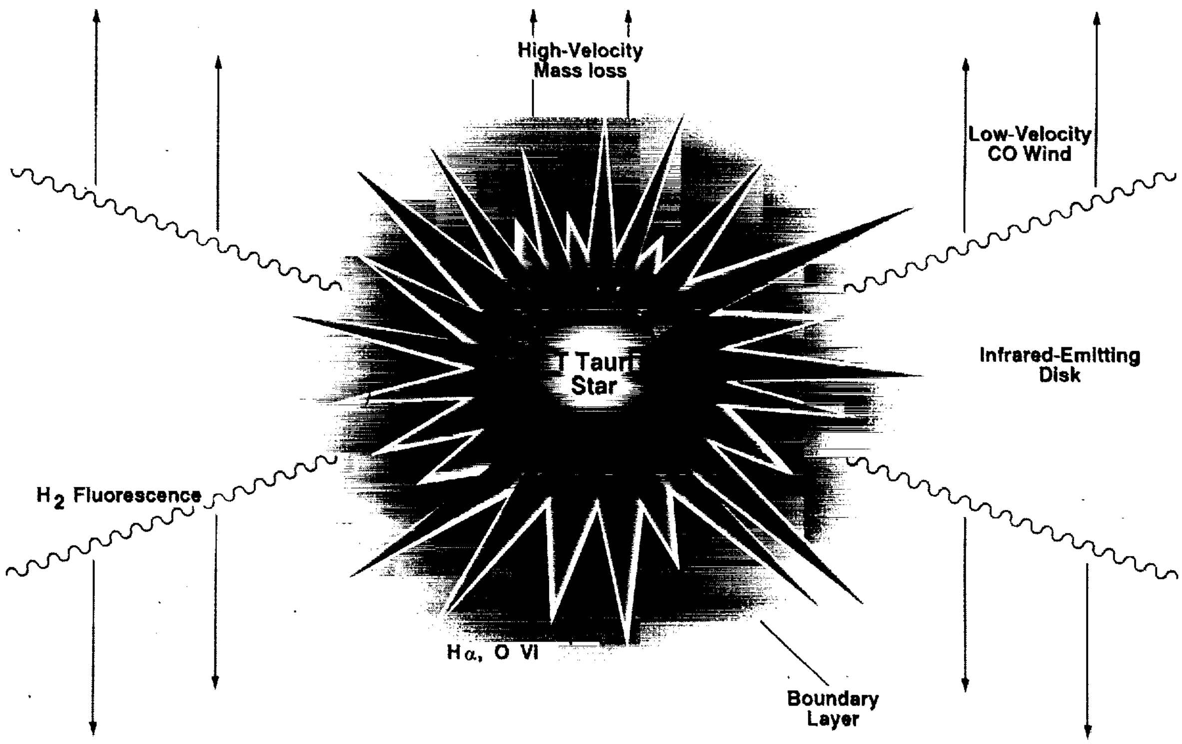

Figure 21. EARLY "T TAURI" PHASE OF STELLAR EVOLUTION marks emergence of newborn stars from dusty, infrared-emitting disks into optical visibility. Details of subsequent mass loss are revealed by far-ultraviolet emissions from neutral and molecular hydrogen and from highly ionized heavier species (e.g., O VI).

loss. Because metal abundances can vary from star to star, the atmospheric energy balance of stars in other galaxies can differ from that of stars of our own Galaxy. HST will let us study stars in different galactic environments.

To determine accurate rates of mass loss, particularly for massive, early-type stars, as well as the energy mechanism responsible, it is important to determine the degree to which the stellar wind is ionized. HST will provide only partial information, because it can only observe saturated ultraviolet lines; however, with the addition of FUSE, the degree of the ionization of the wind can be addressed directly.

The high sensitivity of both HST and FUSE will allow us to study various steady-state and time-dependent behaviors that relate to mass loss and the radiative energy budget of the star. These studies would include magnetic activity in late-type stars (and possibly also early-type stars), radiative instabilities and nonradial pulsations in early-type stars, and the determination of densities and energy balance of the wind in both types of stars.

It will be possible to construct a detailed picture of the stellar-wind structure and its relationship to the atmospheric emitting region through the use of simultaneous measurements of hot and cool ions at many stages of ionization. The question that remains open is whether mass loss comes from a fairly steady process occurring over the entire surface of a star, or instead, from material ejected from smaller regions, as in the case of solar coronal holes. The rate and character of mass loss is needed to build a physical theory of the evolution of stars.

Development of a very-long-baseline optical interferometer capable of resolving stellar disks and imaging accretion disks and circumstellar shells would profoundly advance our knowledge of the distribution of activity on stellar surfaces and characteristics of the stellar environment. By resolving stellar disks, it would also be possible to locate magnetic activity or "starspots" and test the predictions of magnetic-dynamo theories.

3. End Products of Stellar Evolution

Although considerable progress has been made toward defining the final stages of stellar evolution, the details of the transition from post-red-giant stars to white dwarfs remains poorly understood.

Observations with IUE have revealed a few very hot white dwarfs (temperatures in the range 60,000 K to 80,000 K) that exhibit a wide range of surface-layer compositions. The high temperatures of white dwarfs, and the fact that many are nearby, make them ideal candidates for study in the ultraviolet, far ultraviolet, and extreme ultraviolet with HST, FUSE, and EUVE, respectively. The increased sensitivity and spectral resolution of these missions will allow temperature and composition measurements to be obtained for a large sample of white dwarfs, subdwarfs, and nuclei of planetismal accumulations. Such measurements will establish accurate temperature limits and permit the detection of trace elements, which will, in turn, allow a more exact evolutionary history to be developed.

Some white dwarfs exhibit other peculiarities that appear to result from the properties of matter in a high-gravity environment. Soft X rays have been observed from several rather low-temperature (less than 25,000 K) white dwarfs. Still others display high-temperature lines indicative of mass outflow. Observations with FUSE and EUVE will clarify whether the high-energy emission is powered by purely thermal, photospheric radiation or by some other mechanism (e.g., accretion). Sensitive spectroscopic measurements covering a broad range of lines will permit detailed study of such objects and a better understanding of the apparent outflow of material.

4. Sources Powered by Accretion

Emission from interacting binary systems arises from the conversion of gravitational potential energy into radiative energy, either through dissipative forces associated with viscous accretion disks or through shock waves generated by the impact of material on the stellar surface. Accretion is important in X-ray binaries containing neutron stars (pulsars), in cataclysmic variables containing white dwarfs (dominated by disk accretion or magnetic accretion), and in symbiotic stars and Algol-type systems with high-temperature components.

The temperatures of the inner portions of the accretion disks are estimated to lie in the range 10^5-10^6K. These temperatures produce radiation at wavelengths that lie predominantly in the unexplored far-ultraviolet and extreme-ultraviolet spectral regions (Figure 22).

The Far Ultraviolet Spectroscopic Explorer (FUSE) and the Extreme Ultraviolet Explorer (EUVE) are ideally suited to carry out spectroscopy in these regions. These missions can provide the accurate flux distributions and spectral-line measurements needed to discriminate among increasingly complex models for the disk emission. Such models must include surface and atmospheric effects as well as hydrodynamic and magnetic processes.

The Hubble Space Telescope (HST), offering high signal-to-noise ratio and good temporal resolution in the ultraviolet, will be able to observe moderate-temperature plasmas throughout an orbit. These observations can be used to construct detailed maps of disk structure, including locations of the "hot spots" and obscuration zones suggested by previous studies of the brightest, low-mass X-ray binaries and cataclysmic

THE NORMAL LIFE OF A STAR

Birth: **A star begins its life as a contracting mass of gas and dust within a giant molecular cloud. Compression and subsequent heating of the interior continue until the core reaches a temperature sufficient (greater than 10^7 K) to ignite the fusion of hydrogen into helium.**

Middle Age: **During the longest period of its life—the "main sequence" stage—the stability of the star is maintained by a balance between the inward pull of gravity and the outward pressure of radiation. This stage persists until all the hydrogen in the hot core is consumed—about ten billion years for a star with mass comparable to that of our Sun. After hydrogen fusion ends, the outer layers of the star expand enormously, marking the beginning of the red-giant phase; the density and temperature of the core continue to increase, leading to the fusion of elements heavier than hydrogen.**

Death: **When this final episode of fusion ends, the outer layers of the star are ejected into space through formation of a planetary nebula or in a supernova explosion. The fate of the remaining core region depends on its mass. Stellar remnants of less than 1.4 solar masses collapse into white dwarfs, whereas more massive remnants collapse into neutron stars or black holes.**

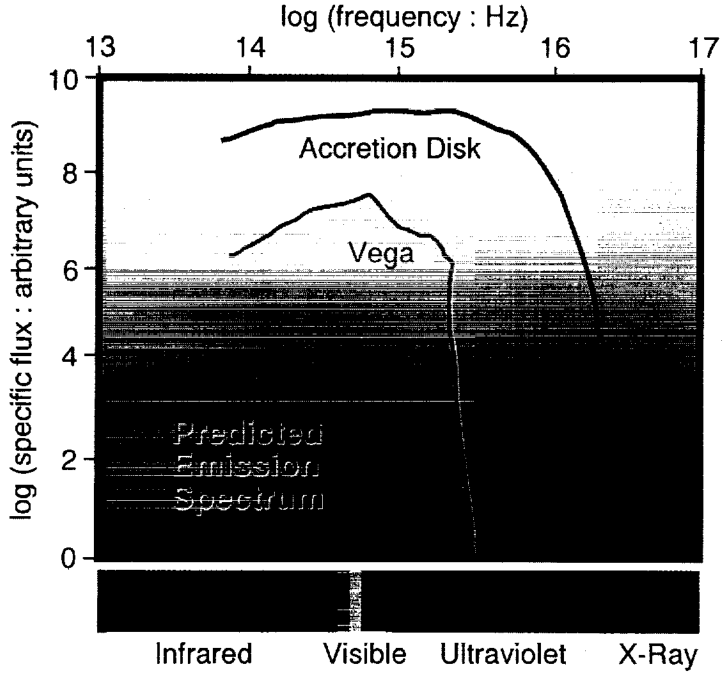

Figure 22. PREDICTED ACCRETION-DISK EMISSION SPECTRUM (top curve) extends over many decades of frequency into the extreme ultraviolet, whereas emission from an ordinary hot star (e.g., Vega, bottom curve) is normally restricted to a decade or two. These are predictions of theoretical models; only ultraviolet observations from space can confirm them.

variables carried out by IUE and the European Space Agency's X-Ray Observatory Satellite (EXOSAT).

Studies with HST can also help determine the properties of two kinds of observed disk variations: rapid, random variability ("flickering"), believed to be associated with accretion at hot spots or at the inner disk boundary layer; and quasi-periodic oscillations (QPOs), thought to arise from thermal or magnetic instabilities.

In the cases of cataclysmic binaries displaying outbursts (i.e., novae and dwarf novae), studies with HST, FUSE, and EUVE will investigate how the outburst modifies the temperature of the underlying white dwarf, as well as determine the composition of the ejected material (Figure 23). In addition to providing constraints on outburst models, these results will also help explain the differences between (or possible con-

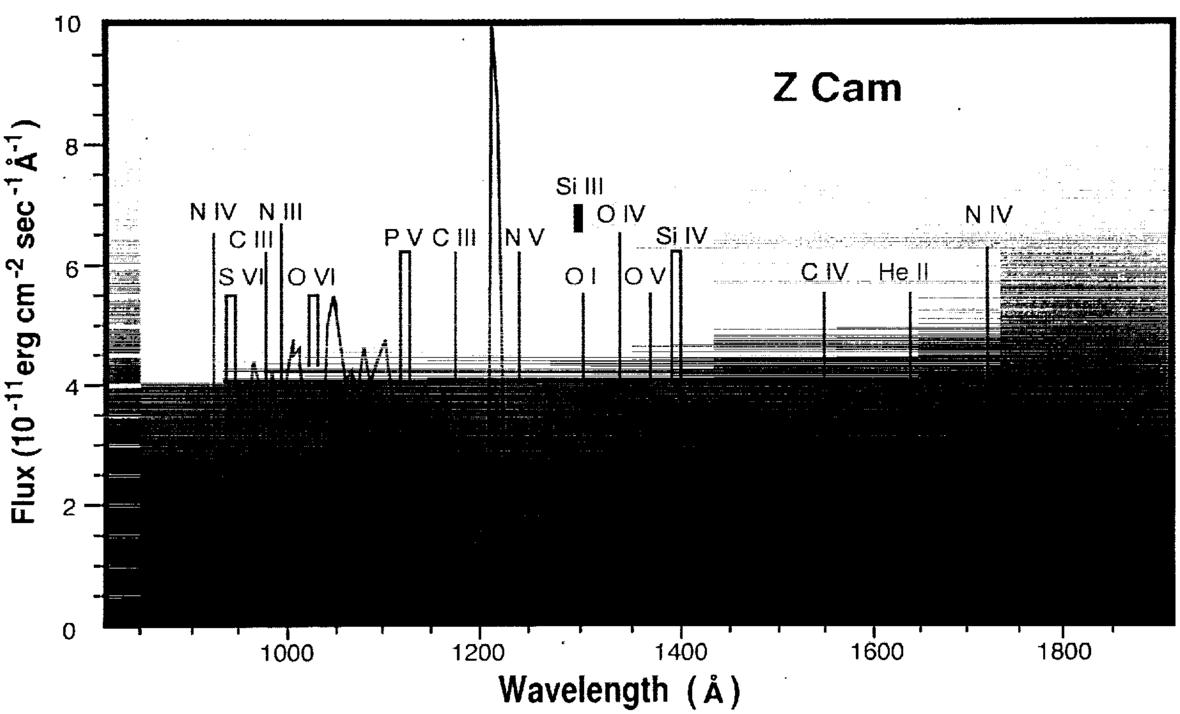

Figure 23. ULTRAVIOLET SPECTRUM OF THE CATACLYSMIC VARIABLE STAR Z CAMELOPARDALIS, recorded by the ASTRO-1 Hopkins Ultraviolet Telescope in December 1990, shows numerous broad absorption lines against a complex continuum. This star is the prototype of a class of dwarf novae that exhibit irregular outbursts of light.

nections between) novae and dwarf novae.

Studies of accretion flows in cataclysmic binaries with magnetic white dwarfs (AM Her and DQ Her systems) will particularly benefit from extreme-ultraviolet observations. The deposition of accreted material in a small area at the magnetic pole, rather than over a disk boundary layer, produces an increased X-ray flux that heats the white dwarf. This flux has a component in the extreme ultraviolet. Concurrent, time-resolved observations of this component over many wavelength regions will provide direct knowledge of the processes occurring at the white-dwarf surface. The temperature, flux level, and geometry are important constraints on the total accretion scenario. Extreme-ultraviolet observations will permit the resolution of current discrepancies between the observed ratios of soft and hard X-ray fluxes and those predicted by accretion models.

Several symbiotic binaries, as well as Algol-type and W UMa-type systems, also have high-temperature emission components. In many cases, the high-temperature lines observed cannot be produced by the stars alone. To understand the nature of the hot component will require detailed study of density and temperature parameters. These parameters will be determined from HST, FUSE, and EUVE observations of ultraviolet, far-ultraviolet, and extreme-ultraviolet emission-line fluxes. Some of the accreting binaries also show evidence of highly ionized outflowing winds. Time-resolved studies of the changing shapes of the spectral lines are crucial diagnostics of the ionization and velocity properties of these winds.

5. Positions and Motions of Astronomical Objects

High-accuracy measurements of the positions and motions of astronomical objects—the province of astrometry—lie at the foundations of astronomy and astrophysics. Astrometric knowledge is needed particularly for Solar System and stellar-mass studies, and for calibration of the extragalactic distance scale.

Kinematic and dynamical studies must be referred to a non-rotating reference frame, classically defined by the rotation axis of the Earth and the orbital motion of the Earth around the Sun. The best current optical reference frame is known with an overall accuracy of about 0.1 arcsec, but the accuracy is less than this in several regions, especially in the Southern Hemisphere. The European astrometry satellite HIPPARCOS may produce an optical reference frame with milli-arcsecond (mas) accuracy. At this level of accuracy, however, the HIPPARCOS reference frame must still be tied to extragalactic objects—a job ideally suited to HST.

Until milli-arcsecond (mas) astrometric accuracies are achieved, we may assume that extragalactic objects are moving so slowly that their transverse angular motions will not be detected with respect to a truly inertial frame—i.e., one defined by local dynamics and the "true" laws of gravitation. This assumption can be tested by observation. On the other hand, radio observations of quasars at the mas-accuracy level have re-

ASTROMETRY

Astrometry, the measurement of the positions and motions of celestial bodies, is one of the oldest and most fundamental branches of astronomy. It has made momentous contributions to science at least since the time of Hipparchus of Rhodes, who compiled the first comprehensive catalog of stellar positions more than 2,000 years ago.

Systematic measurements of planetary positions made by Tycho Brahe in the late 16th century permitted Johann Kepler to deduce his famous three laws of planetary motion; together with Galileo's telescopic observations of 1609, Kepler's work set the stage for Newton's synthesis of calculus, dynamics, and gravitation. In our own century, astrometry has played a key role in confirming the predictions of Einstein's General Theory of Relativity. Astrometric data remain essential for direct determinations of stellar and planetary masses and for calibration of the extragalactic distance scale.

Astrometry now lies on the verge of a technical revolution. Within the next decade or two, optical interferometers in space will be able to achieve positional accuracies of 3 to 30 micro-arcseconds, sufficient to reduce dramatically the uncertainty in the cosmic distance scale. Such instruments will also vastly expand the numbers of stars that can be searched for Jupiter-sized planetary companions.

vealed apparent motions on the timescale of a year that have been interpreted as actual, internal motions. We must therefore begin to consider the effects of possible temporal changes within the extragalactic objects (e.g., quasars) used to define the reference frame.

Every order-of-magnitude increase in astrometric accuracy reveals many new effects that had not earlier been known or did not previously need to be considered. (At the μas level, for example, we may ask intriguing questions about the nature of gravity itself.) At present, it appears that only optical interferometers in space could provide a dramatic improvement in the optical coordinate reference frame. Such instruments would yield dynamical measurements that are uncontaminated by reference-frame motions, permit a reconciliation at the mas-to-μas level of reference frames defined at various wavelengths, and help to determine whether the Universe is rotating.

Astrometry can also provide values of astrophysical quantities that cannot be measured directly in any other way. For example:

Distances to the nearest "standard candles." A few RR Lyrae stars, some Cepheid variables, and the Hyades cluster already lie within the trigonometric-parallax range of HST. However, astrometric missions with near-μas accuracy would also yield precise distances to globular clusters in our Galaxy and could detect the parallaxes of the nearest extragalactic objects, the Magellanic Clouds. Such measurements would greatly reduce the uncertainty in the cosmic distance scale.

Masses in the Solar System. Astrometry, combined with the laws of dynamics, could provide more accurate measurements of the masses of the planets and the mass distributions of the minor bodies, thus improving our knowledge of perturbed motions. These advances would yield a better understanding of the gravitational field structure in the Solar System and permit more sensitive tests of the General Theory of Relativity.

Detection of planets around other stars. Astrometric detection of the "wobble" of a star's path across the sky would provide the best evidence for a planetary companion. In combination with radial-velocity measurements, astrometric observations would also permit a thorough investigation of the dynamics of such a planetary system.

Major advances in all of these research areas will be made possible by NASA's Astrometric Interferometry Mission (AIM), designed to provide astrometric accuracy in the range 3 to 30 micro-arcseconds. It will provide this accuracy for sources separated by 30 or more degrees of arc.

The HIPPARCOS astrometric satellite, currently in operation, is capable of milli-arcsecond accuracy; it will extend direct parallax measurements to many thousands of stars beyond the reach of ground-based parallax techniques. However, AIM will provide a hundredfold improvement in angular resolution over HIPPARCOS, permitting distance determinations for many Cepheids in our Galaxy and hence a dramatic reduction in the uncertainty of the cosmic distance scale—an achievement made possible both by higher accuracy and by the skipping of several rungs on the distance ladder. AIM will also permit major strides in our knowledge of Solar-System masses and of possible extrasolar planetary systems.

Two candidate AIM design concepts are already under study; both make use of Michelson interferometers, and both can achieve the AIM mission objectives. In addition to providing the promise of outstanding scientific return, the Astrometric Interferometry Mission represents an important first step in a long-range plan for UV and visible-light interferometry from space.

E. Verification of Relativistic Theories of Gravitation

Current Program Contributors:

- Shuttle Test of Relativity Experiment (STORE)
- High-precision dynamical tests using advanced transponders aboard deep-space probes
- Lunar laser ranging

Future Program Contributors:

- Gravity Probe-B (GP-B)
- Laser Geodynamics Satellite-3 (LAGEOS-3)
- Precision clock experiments
- Laser Gravitational Wave Antenna in Space

Gravitation, one of the four fundamental forces of Nature, is long-range and couples universally to all matter. On the cosmic scale, gravity dominates the other three fundamental forces (electromagnetism, the weak nuclear interaction, and the strong nuclear interaction). Gravitation controlled the way in which the initial density perturbations following the Big Bang evolved into galaxies and stars, and it has controlled the dynamics of these objects ever since.

In the form of massive rotating black holes, gravitation is also thought to provide the "central engine" that powers radio galaxies and collimated radio jets. Relativistic theories of gravitation are essential to an understanding of supernovae, quasars, X-ray binaries, and the expansion and large-scale structure of the Universe itself.

As the oldest mathematically rigorous and experimentally testable physical theory, Isaac Newton's classical theory of gravitation, in combination with his laws of motion, provided the first application of physics to objects beyond the Earth. Newton's predictions of planetary motion, published in 1687, have been verified by increasingly precise Solar System observations over several centuries. Buoyed by this achievement, physicists extended Newton's theory to the binding and interactions of stars and galaxies. Astronomy had become astrophysics.

By the beginning of this century, however, precise measurements had revealed a discrepancy between the observed rate of advance of Mercury's perihelion and the rate predicted by Newtonian physics. The discrepancy was slight: only 43 arcsec per century. Nevertheless, attempts to explain it within the Newtonian framework—for example, by postulating the existence of one or more additional, perturbing planets—were unsuccessful.

In 1915, Albert Einstein announced the General Theory of Relativity, the first comprehensive new theory of gravitation since that of Newton. The name was chosen to mark the contrast with the Special Theory of Relativity, announced in 1905, which included electrodynamic interactions but excluded gravitational effects.

In the General Theory, Einstein treated gravity as a distortion of the otherwise "flat" four-dimensional geometry of space-time. In this distorted geometry, particles move along geodesics—paths of shortest four-dimensional distance. In the limit of small velocities and weak gravitational fields, the relativistic laws governing the motions of such particles reduce to Newton's laws.

Einstein's new theory ("General Relativity") immediately explained the observed discrepancy in the motion of Mercury's perihelion. It also predicted that light passing through a gravitational field would be bent and delayed; wavelengths of light escaping from a gravitating mass would be shifted toward the red; gravitational interactions propagate at finite speed (the speed of light); there exist "gravitomagnetic" forces between moving bodies; and gravitational energy may, under certain conditions, be radiated from a system in the form of gravitational waves.

The deflection of light by a gravitational field was first observed during a solar eclipse in 1919; the displacements of apparent stellar positions away from the Sun agreed with those predicted by General Relativity within about 20%. More precise ray-bending experiments and tests of the gravitational redshift have come with space-age improvements in measurement technology. However, gravitational waves have yet to be detected directly.

Einstein's General Theory of Relativity has also provided the theoretical basis for modern cosmology. Plausible evolutionary models of the entire observable Universe became available for the first time, and the theory soon became essential for an understanding of the cosmic expansion. This revolution in our world view is perhaps the most significant single contribution of General Relativity. All of our concepts about the age and development of the Universe, and of its constituents, have been affected by it. Stars, galaxies, clusters of galaxies, and even the origin of the chemical elements are now placed in this context.

Two space missions currently under study are specifically intended to provide more precise tests of the General Theory of Relativity than have previously been carried out: Gravity Probe-B (GP-B) and a Laser Gravitational Wave Antenna in Space. It may also be possible to use the proposed Laser Geodynamics Satellite-3 (LAGEOS-3) for a relativity test. Further tests of the General Theory can be carried out through the use of highly accurate satellite clocks and the incorporation of transponders on deep-space probes.

Gravity Probe-B will measure the orientations of the axes of four superconducting gyroscopes relative to the direction to a guide star (Rigel) of known proper motion. This measurement will determine both the geodetic and the "frame-dragging" precessions of the gyroscopes. Geodetic precession is the gyroscope spin change caused by motion along a path in curved space-time. Frame dragging, by contrast, is caused by the "gravitomagnetic" effect of matter in motion—in this case, the rotating Earth. Its effect is to rotate the inertial frame in which the GP-B gyroscopes spin.

For the proposed orbit of GP-B, General Relativity predicts a geodetic precession of about 6 arcsec/year and a frame-dragging precession of about .045 arcsec/year. For one year of tracking, the anticipated accuracy of the experiment is about 1% of the frame-dragging effect, a precision limited mainly by uncer-

WHAT ARE GRAVITATIONAL WAVES?

Gravitational waves are propagating, polarized gravitational fields, "ripples" in the curvature of spacetime. Like electromagnetic waves, they are transverse to the direction of propagation, have two independent polarizations, travel at the speed of light, and carry energy and momentum. The absorption of gravitational waves will slightly change the separations of test masses or the rates at which separated clocks keep time—effects that can be used to design detectors for these waves.

Unlike electromagnetic waves, however, gravitational waves couple universally to all matter, not just to charged matter. They are also much weaker: the ratio of gravitational forces to electrical forces is about 10^{-39} (1/1,000,000,000,000,000,000,000,000,000,000,000,000,000).

This extraordinary weakness has two consequences: (1) Gravitational waves are generated at detectable levels only by very massive sources undergoing very violent dynamics (i.e., astrophysical phenomena), and (2) These waves propagate unchanged from their sources, unaffected by scattering or absorption by intervening matter. Gravitational waves thus offer observational astronomy a new window on the Universe, one that contains information fundamentally different from that contained in the electromagnetic window.

All theoretical models of violent activity in supernovae, galactic nuclei, and quasars presuppose bulk motions of matter at relativistic speeds within strong gravitational fields. Detection of gravitational waves from these objects would therefore provide our first observations directly into the high-gravity, relativistic-velocity interiors of such systems. Moreover, since these waves would be unaffected by intervening matter, important information about source structure and time variation would not be compromised by subsequent absorption or scattering.

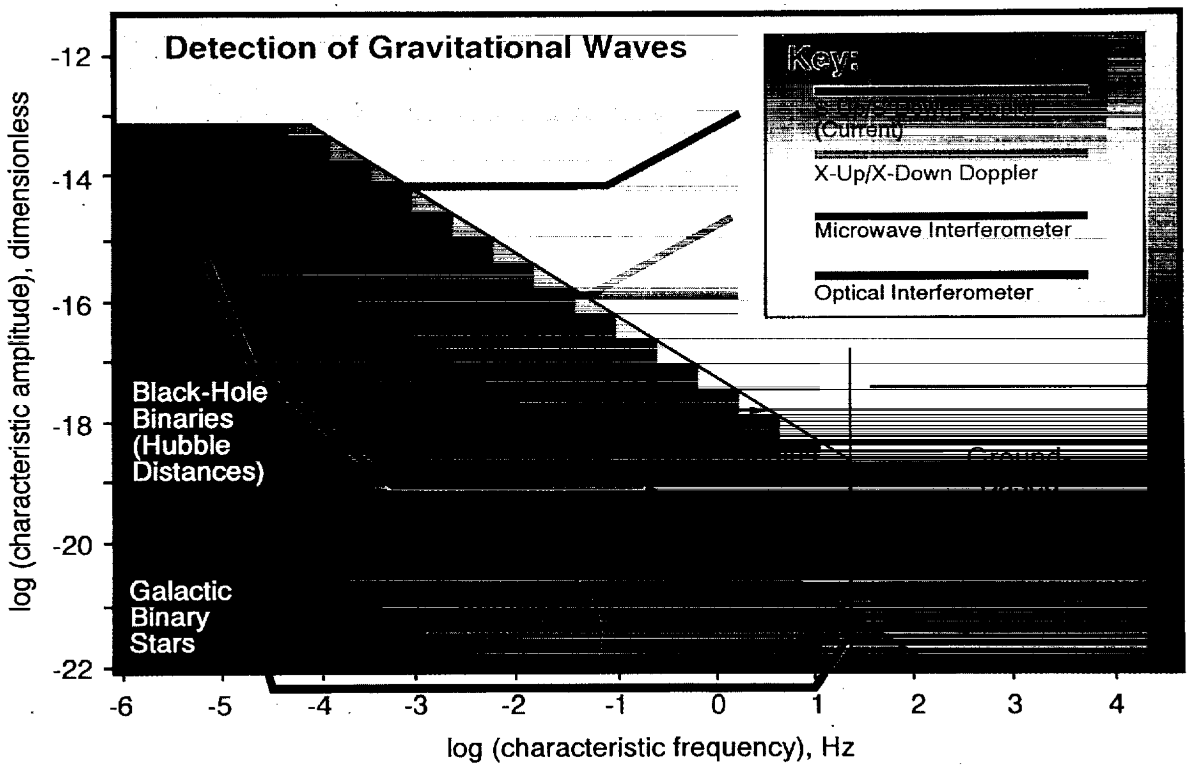

Figure 24. PROSPECTS FOR DETECTION OF GRAVITATIONAL WAVES are limited by current techniques to the cases of large amplitude or high frequency. Microwave and optical interferometers in space will extend the search to small amplitudes and low frequencies, vastly expanding the numbers of radiating systems that can be studied.

tainty in the proper motion of Rigel. With improvements in proper-motion measurements, the anticipated accuracy will improve to about 0.2%.

A Laser Gravitational Wave Antenna in Space, incorporating test masses separated by distances of about 10^7 km, would be capable of observing bursts, periodic sources, and stochastic backgrounds of gravitational waves with unprecedented sensitivity (Figure 24). Time-resolved periodic signals would be expected from roughly 10^4 binary stars of different types in our Galaxy. Other possible sources of gravitational waves include bursts from white dwarfs and from neutron stars coalescing into black holes within active galactic nuclei, and stochastic waves arising from amplified relic gravitons from the Big Bang.

The LAGEOS-3 mission is proposed as the third in a series of geodynamics satellites that began with the launch of LAGEOS-1 in 1976; LAGEOS-2 is scheduled for launch in 1992. These satellites are intended for measurements of the geoid through accurate laser ranging. However, a suitable orientation of the LAGEOS-3 orbit relative to that of LAGEOS-1 makes it feasible to measure the slight non-Newtonian contribution to the orbital precession rates of the satellites.

In addition, it is important to continue to test one of the most fundamental predictions of General Relativity: the variation in the rate of flow of time with position in a gravitational field. In a radial field, for example, a clock nearer the field source should run more slowly than an identical clock farther from the source. In the case of the Earth's field, this prediction was confirmed to high accuracy in 1976 by NASA's rocket-borne Gravity Probe-A (GP-A).

It is now technically feasible to conduct an advanced gravitational redshift experiment that will measure this effect to much greater accuracy. One possibility is to place a hydrogen-maser "clock" in an eccentric orbit around the Earth and compare its readings with those of ground-based clocks as the maser clock traverses regions of higher and lower field strength. By placing such a clock on a spacecraft that will pass within four solar radii of the center of the Sun, such as NASA's proposed Solar Probe mission, the redshift prediction could be tested with a precision nearly five orders of magnitude greater than that achieved by GP-A.

Finally, it is important to continue the tests of General Relativity made possible by the incorporation of transponders on deep-space probes, which permit radio ranging over Solar System spatial scales. The most accurate confirmation of the geodetic bending and time-delay of light to date was obtained by radio ranging to the two Viking spacecraft that landed on Mars in 1976. It is essential that transponders be incorporated on future NASA deep-space missions for such purposes.

F. The Unknown: Serendipity

Current Program Contributors:

- All Missions and Programs

Future Program Contributors:

- All Missions and Programs

Every time a completely new means of looking at the heavens is found, exciting new and unexpected astrophysical phenomena are discovered. These discoveries can arise when a previously unexplored region of the electromagnetic spectrum is investigated, or when celestial objects are viewed with vastly increased sensitivity in spatial, spectral, or temporal resolution (Figure 25).

The implementation plan recommended by the Working Group encompasses both types of opportunity for discovery. The Extreme Ultraviolet Explorer (EUVE) and the Far Ultraviolet Spectroscopic Explorer (FUSE) will open up new windows in the electromagnetic spectrum. An all-sky survey at ultraviolet wavelengths will yield hundreds of thousands of objects to study.

On the other hand, the Hubble Space Telescope (HST) will provide the high sensitivity and spectral resolution needed to study objects already known, as well as those that will be discovered by HST itself and other missions. An optical interferometer in space will provide spatial resolutions long thought to be unattainable. Finally, a Laser Gravitational Wave Antenna in space will offer us new opportunities to study the rapid motion of massive objects in binary systems.

The program we have detailed systematically in this document extends our study of the sky as we currently understand it. A lively and vigorous program must, however, also be able to respond to new discoveries as they are made.

We can fully expect, for instance, that HST will make discoveries that will require new kinds of investigations. We can also project that the HST observing program will have the flexibility to respond to new ideas and innovative theories. Other examples of such "externally induced" serendipity include rare celestial events. In the last decade the Supernova (SN) 1987A offered an unprecedented opportunity to study the death throes of a star in its final stages of evolution. Further serendipitous opportunities can be expected when new technologies arise and permit new kinds of more powerful instruments to be developed.

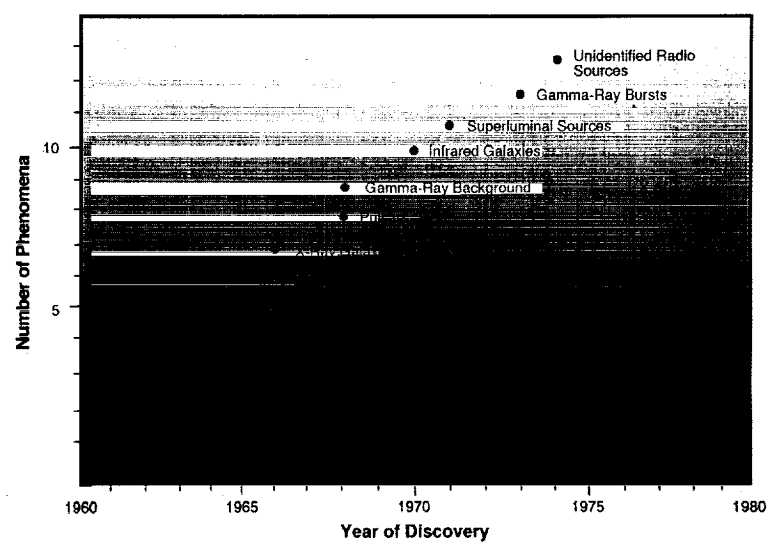

Figure 25. SERENDIPITOUS COSMIC DISCOVERIES made between 1960 and 1979 illustrate the rewards of opening up new channels of cosmic information—in particular, previously unexplored regions of the electromagnetic spectrum. Major advances in angular, spectral, and temporal resolution can also produce new discoveries.

Part III. Program Concerns

The preceding part of this report has discussed the major scientific questions in Ultraviolet, Visible, and Gravity Astrophysics identified by the Management Operations Working Group. Part III treats four concerns that were additionally considered by the Working Group in developing the implementation plan for the 1990s. They are:

A. Program balance and the realities of the budget process,

B. The need for continuing support of the scientific community and for opportunities to train new scientists,

C. The availability of near-term critical technologies and the promise of emerging technologies, and

D. The implications and desirability of continued international cooperation.

A. Program Balance

In a discipline such as space astrophysics, where projects have inherently long lead times, directions set for the next decade will determine the nature and vitality of the science into the next century. With this in mind, it is necessary to address the balance and mix of projects and programs within the NASA Astrophysics program.

The Working Group has, for convenience, grouped future projects into categories on the basis of anticipated cost. It must be understood, however, that it is the priority assigned to a project within a category, and not the category itself, that determines its importance to a vital Astrophysics program for the next decade.

There are now greater opportunities than ever before. These include a decade of use of HST, including the upgrade of its instruments to the cutting edge of technology. We shall also have available FUSE and other spacecraft complementary to HST, permitting unprecedented observations ranging from the far-ultraviolet through the visible and into the near-infrared regions of the spectrum.

A balanced, evolutionary astrophysics program is needed to turn these dreams into realities. The many aspects of our program—small experiments, sounding rockets, moderate missions, theoretical studies, gravity physics, laboratory astrophysics, and analysis of observations—must receive balanced support in the overall program to encourage students and scientists to continue in our exploration of the Universe.

We must take care that our program remains in balance among these varied activities. Four important themes illustrate the balance we seek: access to space, commitment to infrastructure and continuity, access to the electromagnetic spectrum, and project support to completion.

1. Access to Space

This report presents a vigorous scientific program that can be achieved with a variety of instruments using a number of paths to space. For success, scientific researchers need frequent access to space. Missions in the Flagship or "Great Observatory" class may occur only once per quarter century in any one field. But forefront science can also be done with moderate-class missions and small programs that can be initiated more frequently and implemented more rapidly than missions in that class.

Modest efforts are, however, frequently overlooked and underfunded when the focus is on large programs and big new initiatives. A focus on big missions can be counterproductive in the long term because the moderate and small missions, with their multiple opportunities for flight, provide the way to challenge scholars and to train each generation of students and instrumentalists.

In addition, the ability to put an experiment quickly into space is a requirement for a vital astrophysics program. NASA's rapid response to Supernova 1987A is an excellent example. The opportunity to respond quickly to a new scientific discovery or a theoretical insight can most easily be accommodated with small and moderate-sized experiments.

2. Commitment to Infrastructure and Continuity

Our community needs both infrastructure and continuity to capitalize on these opportunities and others that derive from new initiatives. People for these activities will be trained in the universities. There must be a strong component of university support within the NASA Astrophysics Program during the coming decade. The new NASA Fellowship Program, which we applaud, is one element to address these issues. Further initiatives are needed to encourage and sustain the work at universities needed for programs in the next century.

3. Access to the Electromagnetic Spectrum

This report describes a program that is a stable and vital scientific endeavor. Our plan calls for a number of projects to be initiated within the next decade. A strength of this program lies in its ability to explore the Universe in wavebands that span two decades of the electromagnetic spectrum containing unusually large numbers of astrophysically important absorption and emission lines. Through the recommended mix of current and future projects, we seek to ensure our scientific goals with balanced access to the spectrum.

4. Project Support to Completion

Projects must be supported to completion to ensure that the scientific objectives are met. The nature of the funding process makes it attractive to argue for funding for new initiatives rather than for completing existing ones. Throughout this report we have sought to achieve a balance between new initiatives and obtaining the scientific benefits from current projects. There are three specific examples of this balancing of needs that illustrate the importance of supporting projects to completion:

Hubble Space Telescope. HST was designed to be a national facility with a 15-year observing lifetime. The timely refurbishment and replacement of HST focal-plane instrumentation is critical to achieving the scientific goals originally envisioned for this facility, particularly in view of the limitations now imposed by spherical aberration in the HST primary mirror. Second- and third-generation instruments fitted with corrective optics will permit most or nearly all of the scientific potential of HST to be realized over the projected 15-year mission lifetime.

Data reduction and analysis. Data from existing space projects must be fully reduced and analyzed in order to yield definitive scientific results. The Astrophysics Data Program and the NASA Fellowship Program recognize this need. The impact of these programs must not be diluted or diverted.

Productivity of current missions. HST, IUE, and UVS are the only missions currently active in gathering data for this discipline. There is a strong rationale to continue operation of IUE until it can no longer provide unique and highly significant scientific results.

B. Community Support and the Training of New Scientists

A stable community of space astrophysicists, with appropriate numbers of members ranging from interested undergraduates through leaders of major research groups, is crucial. These people must represent and maintain expertise in the techniques needed to allow exploration of all accessible wavelength regions of the electromagnetic spectrum. As in the past, it will fall to the universities to recruit and train these people.

There must therefore be a strong component of university support within the NASA Astrophysics Program during the coming decade. The NASA Fellowship Program is one element that addresses these issues, but further initiatives to encourage and sustain the work at universities are needed to provide the scientists to implement and productively use the Astrophysics missions planned for the next century.

NASA's interactions with our universities must remain broad and diverse. The universities must be in a position to train the next generations of theorists, space-data analysts, and hardware Principal Investigators (PIs). No single program will accomplish this. A balanced program of small, medium, and large missions, combined with the suborbital and grants programs, are all necessary components.

Data from existing space projects must be fully analyzed and reduced to yield scientific results. The Astrophysics Data Program and the NASA Fellowship program are steps in the right direction to provide support for scientific research. The needs-based budget for analysis of HST data is also central to the health of the discipline. The resources for these programs must not be diluted or diverted.

C. Technology

As has been stressed earlier, a vigorous program in Ultraviolet, Visible, and Gravity Astrophysics depends upon the use of advanced technology. Here we discuss the importance of detectors, optics, structures, pointing, and command, control, and data management. Additional technical challenges, such as the provision of radiation shielding, will have to be met in the course of establishing an astronomical observatory on the Moon.

1. Detectors

Several instruments for missions already in progress (e.g., HST, EUVE, FUSE) will provide detectors considerably more advanced than their predecessors in terms of number of pixels, quantum efficiency, out-of-band rejection, and noise.

To ensure full performance capabilities for these missions and instruments, continued effort is required in several technological areas, including photocathodes, windows, quality microchannel plates (MCPs), readout systems for photon counters, and ultraviolet sensitization and particle damage protection for charge coupled devices (CCDs). Critical technologies require systematic long-term development to insure their use in future astronomical instruments.

Desirable improvements for missions in their early stages or under consideration include the extension of pixel formats (particularly for FUSE spectroscopy), the reduction of pixel size to control the overall instrument size, the reduction of cost of detectors, and accommodation of curved focal planes.

There is a particular need for a large-format, high-count-rate UV and visible-light detector for camera use to obtain simultaneous measurements of faint and bright sources. Current approaches to the development of this type of detector include optimization of MCP resistivity and stacking of multiple MCPs, the development of discrete-dynode MCPs, and the development of intensified-analog CCDs.

The use of CCDs may be a solution for visible and extreme-ultraviolet bands in orbital environments of low particle radiation, but caution is required in high-radiation environments. Currently, direct-illuminated CCDs are less suitable for astronomical detectors in orbits above the Earth's geomagnetic shield because the cosmic-ray impact rate increases dramatically. CCDs with low read-out noise could use the combination of many frames or coincidence techniques to eliminate cosmic-ray hits. In the case of lunar observatories, shielding below the lunar surface is possible.

The development of 8- to 16-meter telescopes and large interferometers in space will place further demands on detectors. Larger pixel formats, including mosaics of detectors (about 10,000 x 10,000 pixels), will allow imaging of large sections of the sky to extremely faint limiting magnitudes, when combined with the angular resolving power of the telescopes. This is especially true in the ultraviolet, where the zodiacal-light background is much fainter than at visible-light and infrared wavelengths.

The decade of the 1990s may also see the development of rudimentary "3-D" detectors for ultraviolet and visible-light photons. Gamma-ray and X-ray detectors have long been able to record simultaneously both the two-dimensional incident location and the energy of each photon (the "third dimension") to reasonable accuracy. With this capability at visible wavelengths we could, for example, map the large- scale structure of galaxies by obtaining their redshifts while taking images. To detect a visible photon and resolve its energy to a significant degree requires a detector with a band-gap of roughly one milli-eV. Such band-gaps are achievable in superconducting materials.

2. Optics

The development of the primary mirror for the HST represented a major milestone in ultraviolet optics, spherical aberration notwithstanding. Optics for future missions will need to meet even more stringent requirements. Among the goals to be achieved are larger and much smoother mirror surfaces, lighter-weight mirrors, lower thermal coefficient mirror and mirror structure materials, higher-efficiency ultraviolet reflective coatings, and the maintenance of extreme cleanliness during manufacture, system integration, and deployment in space. Good materials and optical designs are hard to find in the UV and, especially, the EUV spectral regions.

It will also be important to apply the emerging technologies of adaptive optics to space missions. Adaptive optics has been most vigorously pursued in connection with ground-based observations, since these techniques can help to overcome the blurring effects of the Earth's atmosphere on timescales of a few hundredths of a second and thus increase spatial resolution. However, through similar approaches to wavefront sensing and restoration, the performance of large, segmented radiation collectors in space can also be optimized through active control of the shape of the reflecting surface.

3. Structures

Large 8- to 16-m telescopes in space, and particularly space interferometers, present a number of major technological challenges in the area of structures. For all interferometer configurations, understanding of the behavior of the underlying structure is essential to designing a sound optical configuration and control system. Because variations in the

TECHNOLOGY DEVELOPMENT

Detectors: **In order to increase the field of view and improve spatial resolution and spectral coverage, detectors must have a large format, high dynamic range, geometric stability, particle-radiation insensitivity, high quantum efficiency, and low noise. For isolation of the ultraviolet portion of the spectrum, rejection of visible-wavelength radiation is also required. Furthermore, it is possible in principle to measure the energy as well as the time of arrival of every photon detected; array detectors with this capability would revolutionize the fields of ultraviolet and visible-light astronomy.**

Optics: **Optical systems with large collecting area, high spectral transmission, extreme smoothness, low thermal-expansion coefficient, and low weight are required for use with increasingly sensitive future instrumentation.**

Structures: **In order to support these optical systems, particularly for interferometry, structures must be very stable, with low thermal-expansion coefficients. They must not contaminate the optics and detectors. Although fitting into a launch vehicle smaller than the structure, they must also be deployable in space to provide long baselines.**

Pointing: **For interferometry, pointing-control systems must be further improved beyond HST.**

Command, Control, and Data Management: **Data storage capacity and transmission rates must be enlarged to read images sent down from detectors of larger format.**

baselines of only 50 Å are important, materials and structural properties will have to be well understood to that level.

To generate a database of information, a combination of ground and flight experiments is needed. Neither test methodology nor analytical modeling are currently designed to address these submicron-level questions. Structural-motion damping mechanisms are poorly understood when the deflections are in the tens of Ångstroms (nanometer) range. Major efforts to define laboratory tests and modeling programs to this level will be required.

Another area requiring development for large future missions is deployment. These instruments are too large to launch with any foreseen capability, so that partial assembly in space will be required. Concepts and mechanisms that allow a spacecraft to be packaged in a small launch volume, but which could achieve 10- to 100-m dimensions on orbit, must be developed. The deployment methods and mechanisms must result in small setup errors, must exhibit linear dynamic behavior, and must not be a source of disturbance once deployed.

A third area where new developments are necessary is in low thermal expansion, low-contamination structures and materials. This is of particular importance for ultraviolet optical performance, since many materials currently in use can cause catastrophic degradation in ultraviolet reflectivity if they are deposited on the mirror surface.

4. Pointing

The HST pointing-control system is a major advance in precision over previous spacecraft. The combination of careful structural design, low mechanical noise gyroscopes and reaction wheels, and an advanced guidance sensor and control system are responsible for this gain.

Large space telescopes and, especially, large interferometers require pointing stabilization one or two orders of magnitude better than the HST design goals. Much further work is therefore necessary in these areas. A major goal of the technology-development effort for the control systems is achieving simplicity, or at least avoiding debilitating complexity and extreme expense. An understanding of mutual dependencies among structural, optical, detector, and control subsystems is critical for optimization.

5. Command, Control, and Data Management

Current spacecraft, particularly HST, seriously tax the capabilities of available spacecraft computer and general bus systems. A program to develop a stable of low-cost, standard spacecraft at various different levels of weight, power, and onboard control capability would greatly benefit science, by enabling more future missions to be implemented within a given budget.

A large increase in the amount of onboard processing capability is also necessary for the major new missions discussed in this report. Artificial intelligence applied to flight systems could greatly increase the efficiency of science observations. Ground systems will also need to become more powerful and sophisticated to manage the operations and accept the data flow from these new initiatives.

D. International Cooperation

Astronomy and astrophysics are inherently international activities. Scientists from all countries can observe the Universe without regard to national boundaries. Many scientific problems require continuous, multi-site observations, or access to specialized instruments or specific sites. Thus, there exists a long history of international collaboration in astronomy that predates access to space for scientific purposes.

NASA and many other nations and agencies have substantial accomplishments in space science. These nations can be attractive partners for space science efforts. For some experiments, the synergy of international cooperation could produce a better NASA mission. In other cases, cooperation might make the mission possible by reducing the cost to each participant.

Additional opportunities may arise for NASA investigators to participate in the programs of other nations. Either way, more scientific results may accrue, and each partner will benefit when a better mission is achieved. Cooperation must be a bargain in which each partner perceives a benefit. At the minimum level, conversations and correspondence must take place with other spacefaring nations to be aware of planned programs, to avoid repetition of experiments, and to encourage coordination of missions and sharing of results.

To ensure that the total program is optimized for science, opportunities for participation in international missions must fall within the general strategy of the Ultraviolet, Visible, and Gravity Astrophysics disciplines, and must be evaluated in the context of the NASA Astrophysics Division's science plan for these disciplines. NASA also needs to be a responsible partner in these arrangements. Some Congressional action may be required to maintain the continuity of funding that is required for international missions to proceed smoothly.

Part IV. The Recommended Program

This part of the report describes the elements of the plan developed by the Management Operations Working Group in accordance with the scientific strategy and priorities furnished by the National Academy of Sciences. The missions included in the plan have been divided into two categories:

A. Approved missions, and

B. Future missions.

We conclude by discussing the vital underpinnings of these missions:

C. The Research and Analysis (R&A) program, including the sounding-rocket program.

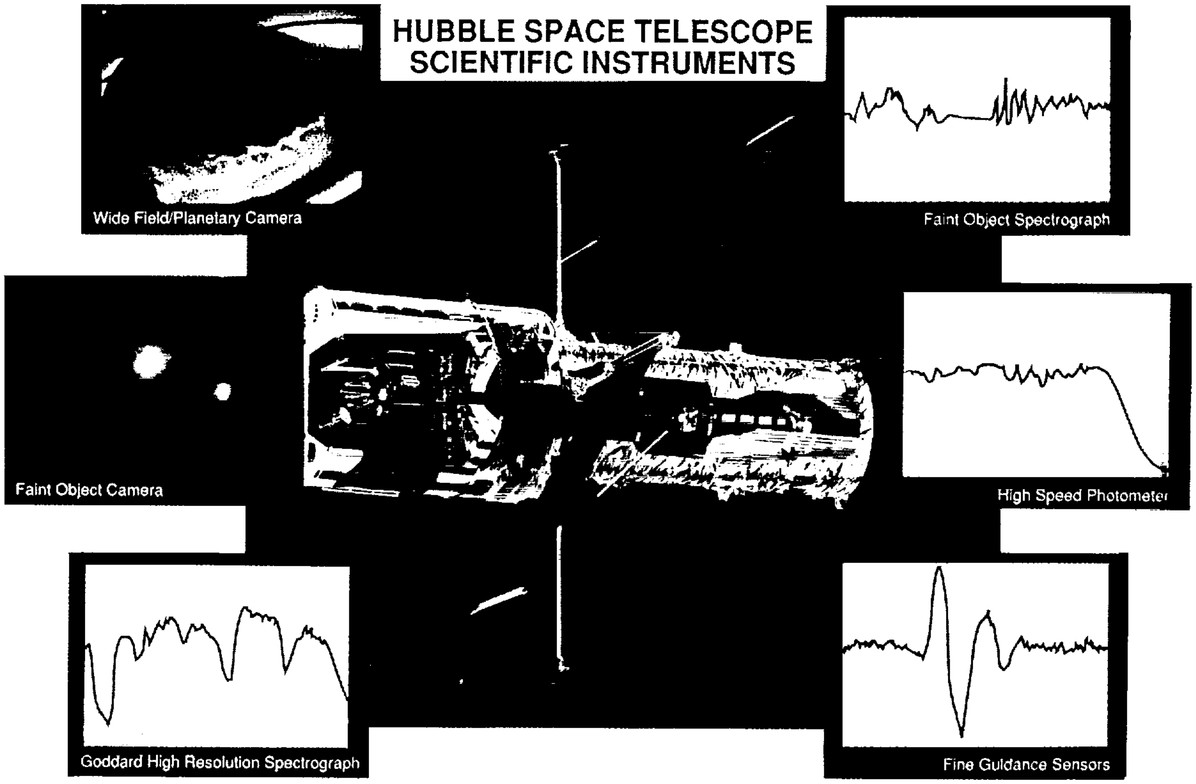

Figure 26. HUBBLE SPACE TELESCOPE SCIENTIFIC INSTRUMENTS have been designed to carry out an enormous variety of investigations. Illustrated here are actual data from WF/PC I (Saturn), FOC (Pluto and Charon), GHRS (Chi Lupi spectrum), FOS (quasar spectrum), HSP (calibration test), and FGS (study of visual binary star).

as modules to be repaired or replaced in orbit as required.

In addition, all of the original HST scientific instruments were designed for eventual replacement by second- and third-generation instruments, so that new advances in technology (e.g., larger and more sensitive detectors) could be brought to bear on the HST observing program. Over the past 15 to 20 years, while HST was being designed and developed, these advances have been particularly important for ultraviolet and infrared astronomy.

With the discovery of spherical aberration in the HST primary mirror, the need for such second- and third-generation instruments becomes even more critical, since the effects of the aberration can be removed through use of suitably designed correcting optics on each of the new instruments.

(a) *Wide Field/Planetary Camera II*

The Wide Field/Planetary Camera II (WF/PC II) will be the first instrument to be installed aboard HST in orbit. In an engineering sense, it is a copy of the first-generation WF/PC. However, in addition to providing corrective optics to bring the HST image into sharp focus, WF/PC II will incorporate a number of important scientific improvements.

The detectors in the new camera will be much more stable in their performance, thereby increasing the overall efficiency of the HST observatory. In addition, a Woods-type filter will be included to provide an ultraviolet imaging capability below 2,000 Å (while rejecting undesirable visible light) at the high spatial resolution afforded by HST. A set of linear variable filters will also be added to provide narrow-band imaging over a 13-arcsec field of view with a 1% passband from 4,000 Å to 10,000 Å. Finally, the addition of on-board calibration lamps will produce flat fields of higher fidelity and will reduce the amount of observatory time and resources needed to calibrate the camera.

(b) *Space Telescope Imaging Spectrograph*

The Space Telescope Imaging Spectrograph (STIS) is a multi-resolution, high-sensitivity spectrograph that will incorporate several advances over first-generation HST spectrographs and allow HST to be much more productive. The use of large-format detectors (2,048 x 2,048 pixels) allows improvement by a factor of 40 to 130 to be obtained for echelle-spectrograph formats with resolving powers in the range 15,000-140,000, and up to 1,000 elements to be imaged simultaneously along the slit with resolving powers in the range 1,000-20,000.

Both photon-counting and CCD technologies will be used in the spectrometer, so that the instrument will be sensitive in the ultraviolet, visible, and near-infrared wavelength regions, covering the range 1,050 Å to 11,000 Å in four bands. Two multi-anode microchannel arrays (MAMAs) will be the ultraviolet photon-counting devices in STIS because of their quantum efficiency, low noise, geometric and photometric stability, resolution, and insensitivity to visible wavelengths. Two CCD detectors will be used for the visible and near-infrared because of their high quantum efficiency.

The two-dimensional ultraviolet spectra obtained by STIS will be particularly useful for studies of interstellar ultraviolet absorption lines and for investigations of such extended objects as galaxies, supernovae, and accretion-powered sources.

(c) *Near Infrared Camera*

The Near Infrared Camera (NIC) will open up a whole new vista to HST. Operating at near-infrared wavelengths (1.0-3.0 μm), and using extremely sensitive detectors developed specifically for this project, NIC will more than triple the wavelength range of the electromagnetic spectrum observable by HST.

NIC uses dispersive spectroscopy in four resolution modes—100, 1,000, 6,000 and 10,000—to achieve the highest possible sensitivity. It is scheduled for insertion into HST in the late 1990s. NIC will then use its infrared array sensors to see deeply into the dust-obscured regions in our Galaxy that are the birthplaces of newly forming stars. It also will penetrate the centers of external galaxies that are so obscured that virtually no visible light escapes, but which house prodigious energy sources and prolific stellar nurseries, among other exotic phenomena. No other instrument is capable of giving images of these regions with the clarity afforded by NIC to HST. In addition, NIC will study the organic compounds of Solar System objects, such as water, which are blocked from ground-based view by the same compounds in the Earth's atmosphere.

3. HST Third-Generation Instruments

Examples of the kinds of instrumentation that are being considered for future HST generations are as follows:

Advanced camera. A camera more sensitive in both ultraviolet and visible wavelengths would be a major improvement over current capability. Higher performance in the ultraviolet requires a visible-blind large array detector with good dynamic range. Higher performance in visible wavelengths requires CCDs with efficient coatings over broad wavelength ranges and lower readout and dark noise.

Ultra-high-resolution spectroscopy. There is evidence that much information about the structure of interstellar clouds is available at velocity separations under 1 km/sec. A spectrograph that could perform spectroscopy with a resolution in excess of 1,000,000 would therefore be invaluable.

Narrow-band imaging. A device that could use the high-resolution imaging of HST across a wide field in a very narrow spectral band could provide new insights into complicated fields. This might be accomplished with a Fabry-Perot setup or an acousto-optical filter.

Improved imaging. It is possible that imaging could be pushed below the 0.1 arcsec level by a properly designed instrument. This is particularly true at the short-wavelength end of the spectrum, where the HST telescope is not diffraction-limited.

High-sensitivity spectroscopy. The current generation of spectroscopic instruments leaves significant room for improvements in throughput, particularly for high resolution. Similarly, low internal background instruments might allow significant gains in limiting magnitude through longer observations.

Programmable-slit imaging/spectroscopy. One current limitation that might be overcome is the restriction to observation of one target at a time. A device with a remotely openable, arbitrarily shaped entrance slit for multi-object or long-slit spectroscopy could greatly enhance the productivity of the HST mission.

Wide-band spectroscopy. It is possible to design spectrographs that cover the entire four decades of the HST spectral band simultaneously without lowering sensitivity. Such an instrument could enhance productivity and provide new science through simultaneous monitoring of the target over a broader band.

Spectropolarimetry. It is possible to build a general spectrograph with linear and circular polarimetric capability, together with far-ultraviolet capability, that would use the high angular resolution of HST in the ultraviolet and visible regions of the spectrum.

These are just a few of the promising ideas now under discussion. The astronomical community is full of new and powerful observing techniques waiting to be harnessed by HST. NASA should continue to support research into the best use of HST through study of these opportunities.

4. International Ultraviolet Explorer (IUE)

The International Ultraviolet Explorer (IUE) has been observing astronomical spectra almost continuously since its launch into a geosynchronous orbit in January 1978. For more than 13 years, IUE has been the only orbiting instrument capable of obtaining ultraviolet spectra in the region from 1,200 Å to 3,000 Å.

The prodigious scientific output of IUE is attributable to the uniqueness of this research opportunity and to IUE's capability for measuring a very wide region of the spectrum in a single exposure. Its two spectrographs cover the ranges 1,150-1,950 Å and 1,900-3,200 Å. With SEC Vidicons as detectors, quantitative measures of the full spectrum within either of these regions are obtained either at high resolution (0.1- 0.3 Å) or at low resolution (6-7 Å). The high observing efficiency possible in geosynchronous orbit also contributes to IUE's exceptional scientific productivity.

HST will be vastly superior for many kinds of science formerly restricted to IUE, and will open up whole new areas impossible for IUE to approach. However, there are special categories of observations for which IUE will remain unique. These include many-object surveys, variability monitoring, extensive wavelength coverage, and other projects requiring large numbers of observations or large blocks of time—all of which are worthy science but do not require the greater sensitivity of HST.

For example, continuous observation of planets in our Solar System, detection and characterization of stellar variability, and regular monitoring of active galactic nuclei are but a few of the projects ideally suited to IUE. By capitalizing on IUE's continued "good health," its operational flexibility, and its unique capabilities in ultraviolet spectroscopy, this mission will continue to provide significant science throughout the next decade—and at extremely low cost.

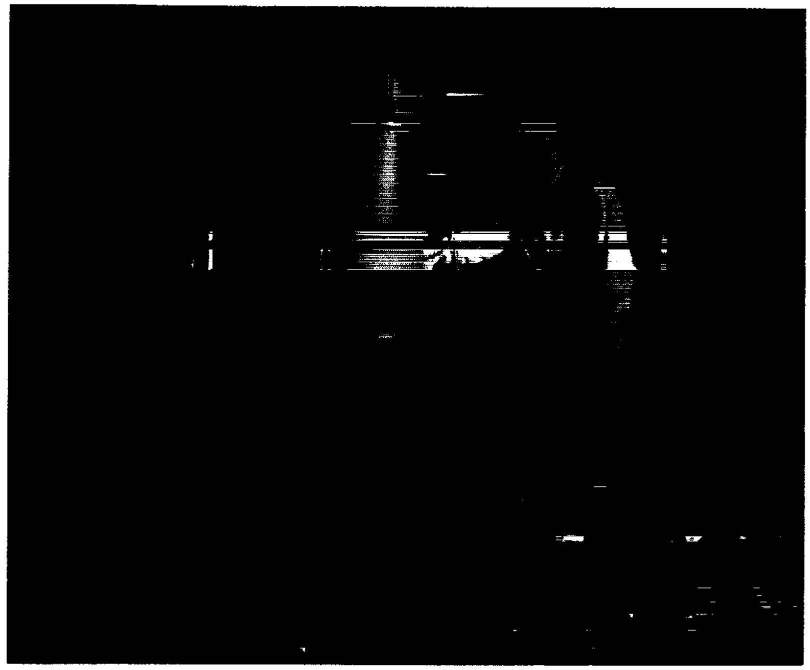

Figure 27. THE EUVE DEEP SURVEY SPECTROMETER, shown here undergoing final laboratory testing, will obtain spectra of extreme-ultraviolet sources detected during the initial, all-sky survey phase of the EUVE mission.

5. Extreme Ultraviolet Explorer (EUVE)

The Extreme Ultraviolet Explorer (EUVE) consists of four grazing-incidence, EUV-sensitive telescopes housed on an Explorer platform. During the early months of its 30-month design lifetime, EUVE will make the first map of the sky throughout the 80-800 Å EUV portion of the spectrum. Approximately 95% of the sky will be mapped in 0.1-degree increments. From this map, a catalogue of EUV sources will be obtained, providing motivation for future missions in the EUV band. EUVE is currently scheduled for a Delta rocket launch in 1992.

Limited exploration of the EUV region has been carried out by instruments on the Apollo-Soyuz, EXOSAT, and Voyager missions. These missions gave hints of the wealth of new scientific insights that will be obtained on classes of objects such as white dwarfs, cataclysmic variables, cool stars and their coronae, and planetary emissions. Additional EUV data on about a thousand sources have now been obtained by instruments on the Federal Republic of Germany's Roentgensatellit (ROSAT) mission, in which the United States is participating. As with all exploratory missions like EUVE, the discovery of as yet unknown sources of extreme ultraviolet emission may prove to be the most significant scientific return.

Once new EUV stars are discovered by EUVE, the next scientific task undertaken by the mission will be to obtain spectra of these stars to understand the processes and conditions leading to the observed emissions. The EUVE science payload includes a spectrometer that will be able to obtain spectra with a resolution of 0.1-3 Å (Figure 27).

Scientific studies to be carried out on nearby stars by EUVE Guest Investigators will extend our understanding of stellar chromospheres and coronae. Combined with similar studies carried out using IUE, astronomers will be able to study stellar chromospheres and coronae over a very wide range of conditions and stellar types.

6. Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer (ORFEUS)

ORFEUS is a joint project of NASA and the German government designed to obtain medium ($3x10^3$) to high (about 10^4) resolution spectra of a wide range of sources at FUV and EUV wavelengths (Figure 28).

The science payload is a 1-m class normal-incidence telescope with two spectrographs that alternately share the beam. An echelle spectrograph, operating at high dispersion in the range 900-1,200 Å, is to be provided by Germany; a system of four Rowland spectrometers covering the range 400-1,200 Å will be provided by the United States. The echelle spectrograph will have a resolution of 0.14 Å, and the Rowland spectrographs will have a resolution of 0.40 Å. The pointing accuracy will be 5 arcsec. The telescope will be carried on the German AstroSPAS platform, which will be deployed by the Space Shuttle for several days of science data gathering. The flight is scheduled for early 1993.

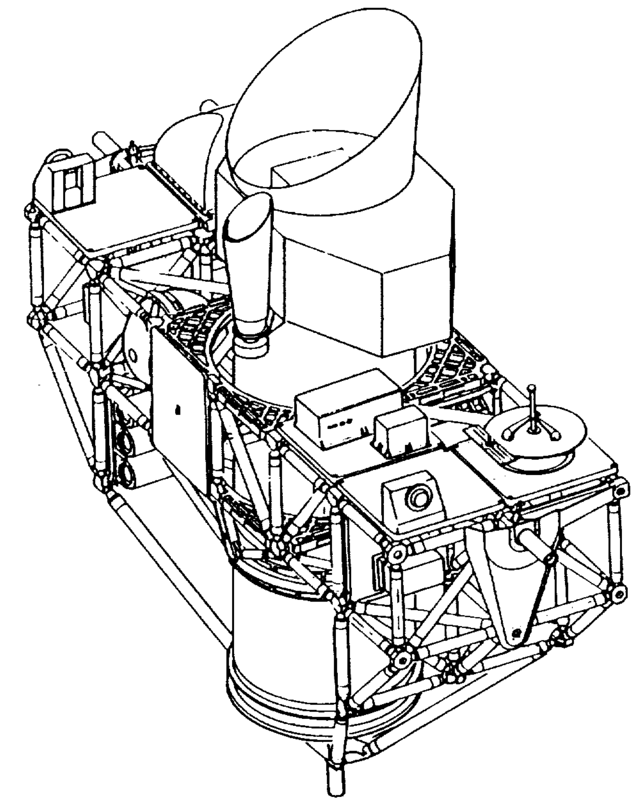

Figure 28. ULTRAVIOLET SPECTROSCOPY AT MEDIUM AND HIGH RESOLUTION will be carried out by the Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer (ORFEUS) mission, a joint U.S.-German project scheduled for Shuttle launch in 1993. Instruments on the German-built AstroSPAS platform will probe properties of the interstellar medium.

ORFEUS is capable of observing up to 150 sources with a spectral resolution comparable to the very high resolution of the earlier *Copernicus* satellite but with a 100-fold increase in sensitivity. The high resolution and signal-to-noise ratio provided by ORFEUS will permit the study of narrow interstellar lines to determine the ionization state of the interstellar medium. Of equal importance is the reliable determination of the ratio of isotopes of the cosmologically important light elements deuterium and hydrogen in the interstellar medium. The absorption lines of these elements lie in the FUV and cannot be observed with IUE or HST.

7. Interstellar Medium Absorption Profile Spectrograph (IMAPS)

IMAPS is an objective-grating, ultraviolet echelle spectrograph (Figure 29) that can record stellar spectra over a 200-Å wavelength interval between the Lyman limit of hydrogen at 912 Å and the wavelength at which HST loses sensitivity (about 1,100 Å).

The principal mission of IMAPS is to study absorption lines produced by many different atoms, ions, and molecules in space. IMAPS provides exceptionally spectral resolution—it can distinguish wavelength differences of 1 part in 200,000, permitting a very fine differentiation of Doppler velocities for different parcels of gas and the study of special phenomena. IMAPS was developed for use on sounding rockets and is now being converted to operate in orbit on the German AstroSPAS platform in early 1993.

8. Astronomy Observatory-2 (ASTRO-2)

The ASTRO-2 mission is a Space Shuttle reflight of the ASTRO Spacelab payload flown aboard the ASTRO-1 mission in December 1990. The ASTRO payload consists of three separate but complementary UV telescopes, aligned with each other on a single pointing system so that all three may observe the same object simultaneously:

(a) *Hopkins Ultraviolet Telescope*

The Hopkins Ultraviolet Telescope (HUT) is a 0.9-m telescope with a low-dispersion spectrograph (3-Å resolution) optimized for observations in the range 900-1,200 Å but able to observe between 425 Å and 1,850 Å. It is intended primarily for studies of the behavior of quasars, galaxies, and active galactic nuclei in the far ultraviolet.

(b) *Ultraviolet Imaging Telescope*

The Ultraviolet Imaging Telescope (UIT) is a 0.38-m telescope that images over a 40-arcmin field of view (2-arcsec resolution) with various filters over the range 1,200-3,200 Å. Its principal application is to investigations of hot stars and galaxies in broad ultraviolet passbands with a wide field of view.

(c) *Wisconsin Ultraviolet Photo-Polarimeter Experiment*

The Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE) is a 0.5-m telescope with a spectropolarimeter (6-Å resolution) sensitive between 1,400 Å and 3,200 Å. It is used to explore the polarization characteristics of hot stars, galactic nuclei, and quasars.

(A fourth telescope designed for X-ray spectroscopic observations--the Broad Band X-Ray Telescope, or BBXRT--was also flown on the ASTRO-1 mission; however, BBXRT will not be included in ASTRO-2.)

Flight of ASTRO-2 is tentatively scheduled for 1994.

9. Far Ultraviolet Spectroscopic Explorer (FUSE)

The newest addition to NASA's approved observatories is the Far Ultraviolet Spectroscopic Explorer (FUSE; see Figure 30). This mission will conduct high-resolution spectroscopy of faint sources at wavelengths from 912 Å to 1,200 Å and moderate-resolution spectroscopy down to 100 Å. It will consist of a 0.7-m aperture telescope, grazing-incidence spectrographs, and associated detectors that will achieve an angular resolution of about 1 arcsec, a spectral resolving power of approximately 30,000, and a sensitivity of about 100 cm^2 for wavelengths in the previously unobservable FUV band from 900 Å to 1,200 Å .

The FUV region of the spectrum contains unique diagnostics that will allow us to measure the physical state and evolution of some of the most

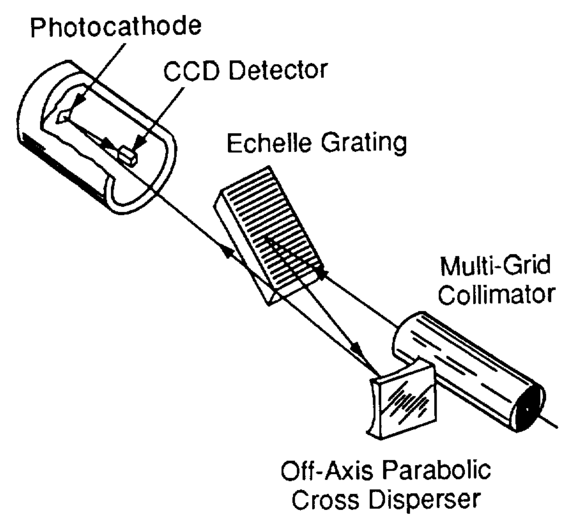

Figure 29. ECHELLE-GRATING SPECTROMETER will be used by the Interstellar Medium Absorption Profile Spectrograph (IMAPS) mission to study absorption lines in the interstellar medium between 912 Å and about 1,100 Å. The exceptionally high spectral resolution of IMAPS will permit detailed dynamical investigations.

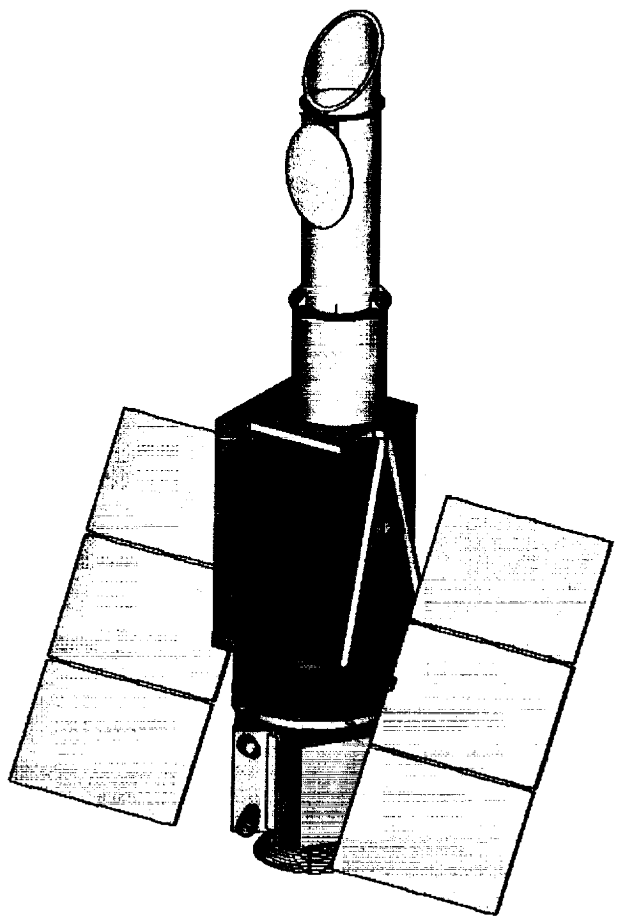

Figure 30. FAR ULTRAVIOLET SPECTROSCOPIC EXPLORER (FUSE) mission will carry out UV spectroscopy at high resolution from 912 Å to 1,200 Å and at moderate resolution down to 100 Å. The widely ranging research program of this satellite is central to the MOWG plan for the 1990s, and a timely FUSE launch commands high priority.

basic material of the Universe. Hydrogen, and its related forms of deuterium and molecular hydrogen, can be studied effectively only in the far ultraviolet. With its ability to study high-temperature, ionized states of atoms, FUSE will also allow us to constrain models for the production of light elements in the early Universe. Using FUSE, we can also measure the ionization and heating source of stellar winds and flares and can study the accretion processes that power the high-energy sources in collapsed stars and active galactic nuclei.

10. Shuttle Test of Relativity Experiment (STORE)

The Gravity Probe-B (GP-B) mission (discussed in Section B to follow) is intended to provide novel, high-precision tests of Einstein's General Theory of Relativity as well as geodesy and other co-experiments. The GP-B science payload represents over 25 years of research and embodies state-of-the-art technologies in many fields, including gyroscope fabrication, suspension, and readout; cryogenics (superfluid helium cooling to 1.8 K); magnetic shielding; superconductivity; precision optics and alignment methods; and satellite drag compensation far more accurate than any yet flown.

An engineering test of portions of this advanced technology, assembled into a Shuttle Test Unit (STU), will be carried out on a Space Shuttle flight through the Shuttle Test of Relativity Experiment (STORE). The STU will incorporate a quartz telescope block assembly, test gyroscopes, computer control and suspension electronics, a flight suspension system, and other components operating at ambient temperatures.

B. Future Missions

The missions that were identified by the Working Group as elements of the Ultraviolet, Visible, and Gravity Astrophysics plan, but which have not yet been approved, are discussed below. Each has been selected to make major and unique contributions to the scientific questions raised in Part II of this report.

1. Augmentation to Explorer Program

The Explorer program has been vital to the development of space astronomy and astrophysics. Explorers of the past, such as the Small Astronomy Satellite (SAS) series that included the *Uhuru* X-ray mission, as well as the International Ultraviolet Explorer (IUE), the Infrared Astronomical Satellite (IRAS), and the recent Cosmic Background Explorer (COBE) have left indelible imprints upon contemporary astrophysics. IUE, IRAS, and COBE were all larger Explorer missions.

The scientific goals that can be accomplished with Explorers are rich and varied. However, serious problems exist in the Explorer budget line. Funding for this level-of-effort program has not kept pace with inflation, and extraordinarily long times now pass between mission selection and flight. Fresh ideas and scientific goals are abundant, but the rate of new scientific results from Explorers is diminishing as flight programs are stretched out.

In 1986, the National Academy of Sciences' Committee on Space Astronomy and Astrophysics (CSAA) examined the deplorable situation in the Explorer program. Even 5 years ago, Explorer opportunities were scarce, and the time from Phase A studies to launch of an Explorer exceeded 15 years. Moreover, the Explorer budget had to accommodate substantial additional charges, most of which were a direct result of the delay in Shuttle launch opportunities during the late 1980s.

The Office of Space Science and Applications subsequently sought and received an Explorer funding augmentation for a new Small Explorer (SMEX) mission class designed to provide a "fast track" to space. In 1991, in response to the recommendations of the Bahcall Committee, OSSA furthermore created two new mission classes--Middle and University--as successors to the "Delta-class" missions, such as FUSE, currently in the Explorer queue. However, no funding augmentation has yet been provided for these larger Explorer-class missions.

Consider, in particular, one of the most recently selected Delta-class Explorers—FUSE, the mission of highest priority in its category in the 1982 report of the National Academy of Sciences' Astronomy Survey Committee (the "Field Report"). FUSE has been studied since 1982 and is now scheduled for launch in 2000. However, three other Explorers in this class—EUVE, XTE, and the Advanced Composition Explorer (ACE)—are in line ahead of FUSE, and experience shows that initial launch dates are optimistic. Thus the situation that galvanized the CSAA into action in 1986 has, in fact, worsened considerably during the 5 years since their report.

Much outstanding science that needs to be done is well matched to the Explorers. The three-axis stabilization and fine pointing needed for astronomy Explorers generally demand the capabilities of larger spacecraft buses. Some examples of science in this class include multispectral observations, astrometry, high-resolution UV and EUV spectroscopy, stellar seismology, and long-term studies of variability. Peer review will decide the next selection for all Explorer categories.

Explorers permit a flexible response to scientific problems and complement the capabilities of both small payloads and the Great Observatories. We believe an augmentation of the Explorer budget line is necessary now to recapture scientific leadership in space astronomy and astrophysics.

2. Additional Small-Class Explorer: Deep Ultraviolet Survey

A high-sensitivity, all-sky survey in the 1,200-2,000 Å spectral region is important to the development of ultraviolet astronomy. This is an extremely "dark" region of the electromagnetic spectrum—a hundred times fainter than the visible-light background—and the potential for unexpected discoveries is great.

Moreover, the fact that a survey so potentially rich in scientific content can be undertaken by a Small Explorer (SMEX-class) instrument lends it a special attractiveness. Both diffuse and point-source surveys are desirable and, while the optimal instrument design for the two survey types may differ, it is possible that both surveys can be accommodated adequately by the same mission.

A diffuse-source survey in this region of the spectrum will benefit from the coincidence that a number of different emission mechanisms contribute to the background. These emission mechanisms convey information on media characterized by a wide range of physical conditions. They include probable back-scattering of Galactic-plane starlight by dust, including interstellar cirrus clouds, H_2 fluorescence arising in the cold, neutral phase of the interstellar medium (ISM), and radiation from collisionally-ionized gas at high temperatures. With some spectral information, the various ISM components will be separable and the spatial distributions of several different components will become evident.

A point-source survey can increase by two or three orders of magnitude the number of known active galactic nuclei (AGNs), quasars, white dwarfs, cataclysmic variables, and evolved stars. The richness of the resulting data set will substantially increase our insight into such issues as the luminosity function and evolution of AGNs and quasars; the correlation of AGNs with galaxies, clusters, and large-scale structures; the nature, history, and global behavior of star formation in normal galaxies; and the evolutionary paths to cataclysmic variables, Type I supernovae, and X-ray binaries of low mass. With the number of newly detected sources approaching one million, there is potential for such a mission to become the ultraviolet equivalent of the Palomar Sky Survey.

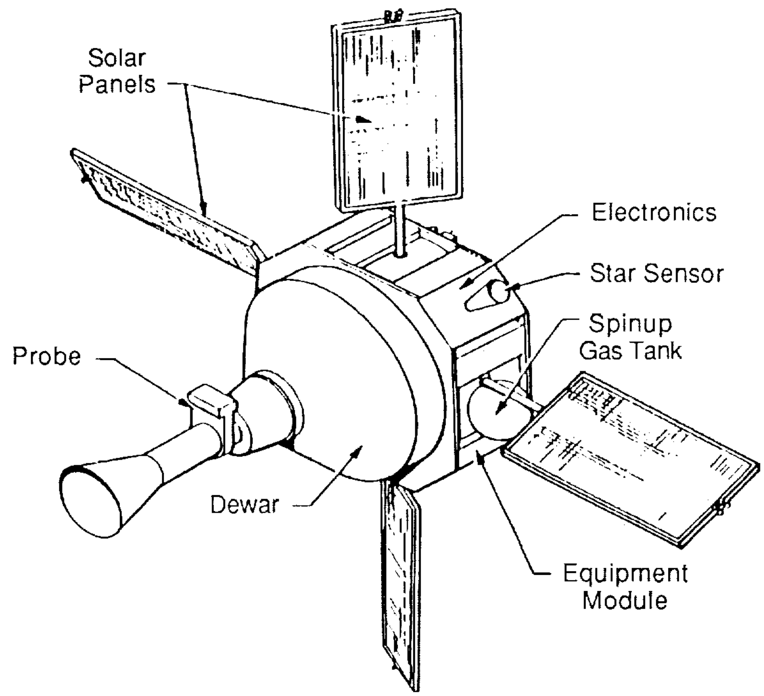

Figure 31. GRAVITY PROBE-B will test predictions of Einstein's General Theory of Relativity by measuring the precession of cryogenically cooled superconducting gyroscopes in the gravitational field of the rotating Earth. The experiment is designed to assess both the curvature of space-time and the gravitomagnetic or "frame-dragging" effect of matter in motion.

3. Gravity Probe-B (GP-B)

Gravity Probe-B (Figure 31) is proposed for launch into a polar Earth orbit for a one-year mission following the Shuttle Test of Relativity Experiment (STORE).

GP-B will measure the orientation of four cryogenically cooled superconducting gyroscopes relative to a guide star (Rigel) of known proper motion. This measurement will determine both the geodetic and frame-dragging precessions of the gyroscopes. For the orbit chosen for GP-B, General Relativity predicts a geodetic precession of about 6 arcsec/year and a frame-dragging precession of about .045 arcsec/year. For one year of tracking, the anticipated accuracy of the experiment is about 1% of the frame-dragging precession, limited primarily by uncertainties in the proper motion of the guide star. Improvements in proper-motion measurements will improve the anticipated accuracy to about 0.2%.

4. Laser Geodynamics Satellite-3 (LAGEOS-3)

The Laser Geodynamics Satellite (LAGEOS) series was initiated with the launch of LAGEOS-1 in 1976. The launch of LAGEOS-2 is projected for 1992, and a third member of the series, LAGEOS-3, is now under study. LAGEOS is a joint project of NASA and the Italian government.

The LAGEOS satellites are dense, inert spheres covered with retroreflectors for laser ranging. Because of their high ratio of mass to frontal area, these passive, long-lived satellites are relatively insensitive to atmospheric perturbations and thus permit highly accurate determinations of the Earth's gravitational field (the geoid). The success of LAGEOS-1 for such measurements has prompted successors in other orbits chosen to permit the sampling of different combinations of the Earth's multipole moments.

The orbit of LAGEOS-2 has already been fixed by geodynamical research requirements; however, the orbit of the proposed LAGEOS-3 satellite remains to be chosen. By giving LAGEOS-3 an orbital inclination supplementary to that of LAGEOS-1, the large Newtonian contributions to the precession rates of the two satellite orbits can be made to cancel. It then becomes feasible in principle to measure the General Relativity contribution to the precession rates with an accuracy of perhaps 20% over the course of a few years. Since the supplementary LAGEOS-3 orbit would also be acceptable for geodynamic research, this choice would appear to be an attractive one.

5. New Flagship and Intermediate Space-Based Missions

Future, Flagship and intermediate-class missions in space offer prospects for dramatic advances in angular resolution and in the imaging of faint objects. We discuss below the missions that have been proposed as free-flying satellites; in several cases, however, these instruments or their analogues could also be placed on the Moon (see No. 6: "Lunar Outpost Astrophysics Program").

(a) *Astrometric Interferometry Mission (AIM)*

NASA's Astrometric Interferometry Mission (AIM), planned for launch early in the 21st century, will be the first dedicated optical interferometer in space. It will be capable of astrometric measurements having an accuracy of 3 to 30 microarcseconds.

AIM will make highly accurate measurements of the positions and motions of distant stars, star clusters, quasars, and other faint astronomical objects. These fundamental new data will furnish precise distances to objects throughout our Galaxy, vastly improving the calibration of the cosmic distance scale and permitting definitive estimates of the size of the Universe. Using quasars as common points of reference, AIM will forge a vital link between the radio and optical reference frames. Observations of the dynamics of globular star clusters in our Galaxy will shed new light on galactic formation and evolution. AIM will also be capable of detecting planets around remote stars by measuring perturbations in stellar motions caused by orbiting companions.

Two promising candidate design concepts for AIM are already under study: an Orbiting Space Interferometer (OSI) and a Precision Optical Interferometer in Space (POINTS). Both make use of Michelson interferometers, and both can achieve the mission objectives. Mission development will be accompanied by an advanced technology program designed not only to support an AIM new start, but also to further a more general, long-range plan for UV and visible-light interferometry from space. In particular, AIM will represent an important step toward the development of an Imaging Optical Interferometer in Space.

(b) *Imaging Optical Interferometer in Space.*

The primary goal of the first Imaging Optical Interferometer in Space will be to achieve an order-of-magnitude improvement in angular resolution in the ultraviolet and visible spectral regions by comparison with HST. The imaging interferometer should also have significant light-collecting area, since many of the objects to be studied will be quite faint. A location either in Earth orbit or at a lunar base would be acceptable.

For an orbiting interferometer, two approaches are feasible. One employs a rather stiff structure, about 30 meters in size, with sources of mechanical and thermal disturbances minimized. The other is based on a more flexible structure and makes extensive use of developments from the field of control-structure interactions. A lunar-based interferometer, by contrast, would be more like a ground-based instrument. It would have the advantage that additional telescopes could be added after the initial configuration is established.

The development of an Imaging Optical Interferometer in Space will benefit strongly from work on ground-based interferometry. This work will test different instrument designs and will provide complementary observations at longer wavelengths.

(c) *16-Meter Telescope*

The 16-Meter Telescope, or Next Generation Space Telescope, has been conceived as a vastly more powerful successor to HST that will build upon the HST scientific base. It will fully exploit the potential of space observatories by having precision optics that will perform at the optical diffraction limit allowed by physics. It will be cooled to temperatures only 100 degrees above absolute zero so that it can work in the infrared with a background less than one-millionth of the background that limits ground-based infrared telescopes.

The 16-Meter Telescope will also have wide-field, state-of-the-art cameras and spectrographs that will work over the entire ultraviolet, visible, and mid-infrared spectral range. Its clarity, wide bandwidth, and dramatically lower background radiation will allow us to go to the heart of some of the most fundamental questions of astrophysics—for example, how stars like our Sun formed, and how galaxies like our Milky Way formed and changed as the Universe evolved. It will even allow us to address the question of whether planets like our own, with atmospheres like our own, exist around nearby stars.

(d) *Laser Gravitational Wave Antenna in Space.*

A laser gravitational wave antenna in space, with test masses separated by distances of about 10^7 kilometers, has been proposed. One possible configuration, called the Laser Gravitational Wave Observatory in Space (LAGOS), consists of an L-shaped array of three spacecraft located 60 degrees behind the Earth in solar orbit.

The orbits of the two outer spacecraft are somewhat eccentric and inclined in order to keep their distances to the central spacecraft

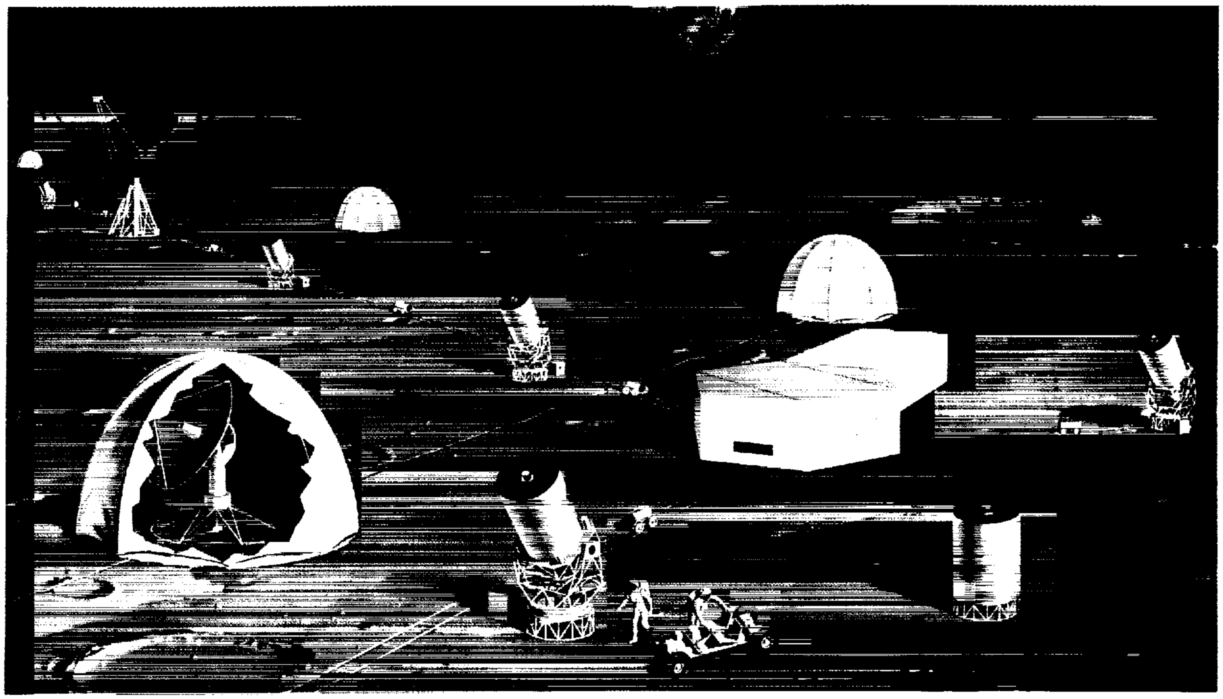

Figure 32. ASTRONOMICAL INSTRUMENTS ON THE MOON could provide powerful imaging and spectroscopic capabilities together with extremely high angular resolution at ultraviolet, visible, and infrared wavelengths, opening up new research areas at the frontiers of astrophysics. Shown in this artist's concept are the proposed Lunar Transit Telescope, the Optical Interferometer, and the Filled Aperture Segmented Optical Telescope, together with an interferometer for submillimeter and far-infrared observations.

constant within 1% over 10 years. Each spacecraft is held centered on test masses within 10^{-4} cm to reduce gravitational-force changes. The passage of gravitational waves across the antenna changes the difference in length of the two long antenna arms. Lasers with 1-watt beam power are used to measure the arm lengths. Phase-locked lasers at the two outer spacecraft provide the return beams.

This ultra-sensitive interferometric detector would be capable of observing bursts, periodic sources, and stochastic backgrounds of gravity waves in the 10-μHz to 1-Hz frequency range with unprecedented sensitivity. Unless General Relativity is fundamentally in error, observations would "guarantee" detection of gravitational radiation from known sources, e.g., cataclysmic variables, neutron-star binaries, and white-dwarf binaries in our Galaxy. Signals associated with supermassive black holes and a stochastic background of relic gravitons from the Big Bang amplified by inflation would also be sought.

6. Lunar Outpost Astrophysics Program

On July 20, 1989, President Bush announced the Space Exploration Initiative (SEI), embodying the goal of accelerating human exploration of the solar system. Eleven days later, NASA Administrator R. H. Truly commissioned a study of ways to implement this initiative; the study report was delivered to the National Space Council in November 1989. The NASA/OSSA Astrophysics Division was assigned responsibility for producing the astrophysics portion of the report, and the present Working Group reviewed and identified several important opportunities for Ultraviolet, Visible, and Gravity Astrophysics in this connection.

The low surface gravity, high-vacuum environment, and surface stability of the Moon make it a promising astronomical base. It is attractive for the emplacement of high-resolution, long-baseline interferometers and for large-area, high-sensitivity collectors (Figure 32). Moreover, the lunar regolith offers virtually unlimited amounts of radiation shielding for sensitive detectors.

By comparison with Earth orbit, the lunar surface presents the disadvantages of extreme thermal excursions, opportunity for contamination by dust, and potential for damage from micrometeorites, cosmic rays, and magnetotail electrons. It is nevertheless relatively straightforward to counter these effects and to exploit the favorable attributes of the lunar surface for forefront astrophysical research.

The primary criterion for the selection of potential instruments for emplacement on the lunar surface was scientific merit and high priority within the NASA Astrophysics program. Each instrument selected had to possess capabilities beyond those already planned, and the lunar surface had to provide an advantageous site for an investigation.

The NASA science-discipline MOWGs were used as informal peer-review committees to review the scientific credibility of recommended investigations, to define in greater detail the candidate instruments and facilities, and to review the program strategy, instrument priorities, and technology requirements. Individual missions were prioritized by the Astrophysics Subcommittee of NASA's Space Science and Applications Advisory Committee in September 1989.

Three ultraviolet and visible-light missions were selected by the Astrophysics Subcommittee: a Lunar Transit Telescope (LTT), an Optical Interferometer, and a Filled Segmented Aperture Optical Telescope.

In developing the present plan for Ultraviolet, Visible, and Gravity Astrophysics, the Working Group has considered two of these missions—the lunar-based Optical Interferometer and the Filled Aperture Segmented Optical Telescope—to be programmatic alternatives to the Imaging Optical Interferometer in Space and the 16-Meter Telescope discussed above, since it appears unlikely that the nation and NASA will fund both the lunar-based and the space-based versions of these instruments.

As the lunar base matures, a Laser Interferometric Gravity Wave Observatory will be considered for placement on the Moon. This facility is *not* considered to be a programmatic alternative to a Laser Gravitational Wave Antenna in Space because it functions at a much shorter wavelength. It would work with ground-based observatories to obtain much more accurate angular measurements of source positions than could be obtained from ground-based measurements alone.

(a) *Lunar Transit Telescope*

The Lunar Transit Telescope (LTT) is a 1- to 2-meter stationary telescope that will use the motion of the Moon to scan the sky. The charge coupled device (CCD) radiation detectors will be clocked at the lunar rotation rate, permitting superposition of successive views of the same sky area. The lunar motion makes it possible to carry out a long- integration, deep-sky survey at the telescope diffraction limit over a bandwidth that is not possible from the Earth's surface.

LTT will be an imaging survey instrument for observations within five broad bands spanning the ultraviolet, visible, and near-infrared spectral regions (0.1 to 2 µm) with a spatial resolution of 0.1 arcsec. The objective of the LTT is to conduct a deep-sky survey down to 28th visual magnitude, equivalent to the sensitivity that HST was designed to achieve; the LTT survey will thus complement HST measurements.

The lunar orbit allows the telescope to be operated with no moving parts. The lunar site also offers long integration times, passive cooling, and a high-vacuum environment. Either lunar-surface material or man-made shielding can be used to shield the CCD detectors, which can be passively cooled on the lunar surface down to 100 K. The attractive possibility of making LTT a soft-lander is worthy of study.

(b) *Optical Interferometer*

The lunar-based Optical Interferometer is an extremely high angular resolution instrument that will operate in the wavelength range from 0.1 to 10 µm. The interferometer will be particularly useful for resolving both the broad-line and narrow-line regions in active galactic nuclei and will provide data that can be used to study the isotropy and uniformity of the Hubble flow to an accuracy of 1%. Investigators will also be able to use this facility to measure the parallaxes of objects out to tens of megaparsecs, to image white dwarfs, and to image accretion disks around stellar objects, neutron stars, and black holes.

The Optical Interferometer is planned as a modular instrument incorporating individual collectors with apertures of about 1.5 meters. It will consist initially of four such collectors, together with a signal combiner. Later, the initial 4-meter element of the 16-meter Filled Aperture Segmented Optical Telescope (see below) will be deployed: the 4-meter telescope will thus serve as the fifth element of the Optical Interferometer in addition to performing its imaging objectives. A final, sixth element of the interferometer will eventually be added.

When completed, the interferometer will have a total collecting area of about 21 square meters. The projected baseline is 1-10 km. The low-seismic-noise environment of the Moon provides an ideal base for the Optical Interferometer because the lunar surface serves as a highly stable optical bench for the placement of the interferometer components.

(c) *Filled Aperture Segmented Optical Telescope*

The Filled Aperture Segmented Optical Telescope is a passively cooled, diffraction-limited telescope with a diameter of 16 meters and a field of view of approximately 1 arcmin (Figure 33). It will have a pointing accuracy of about 10 mas and be able to track an object within 1 mas. The telescope's greatest strength will be spectroscopic obser-

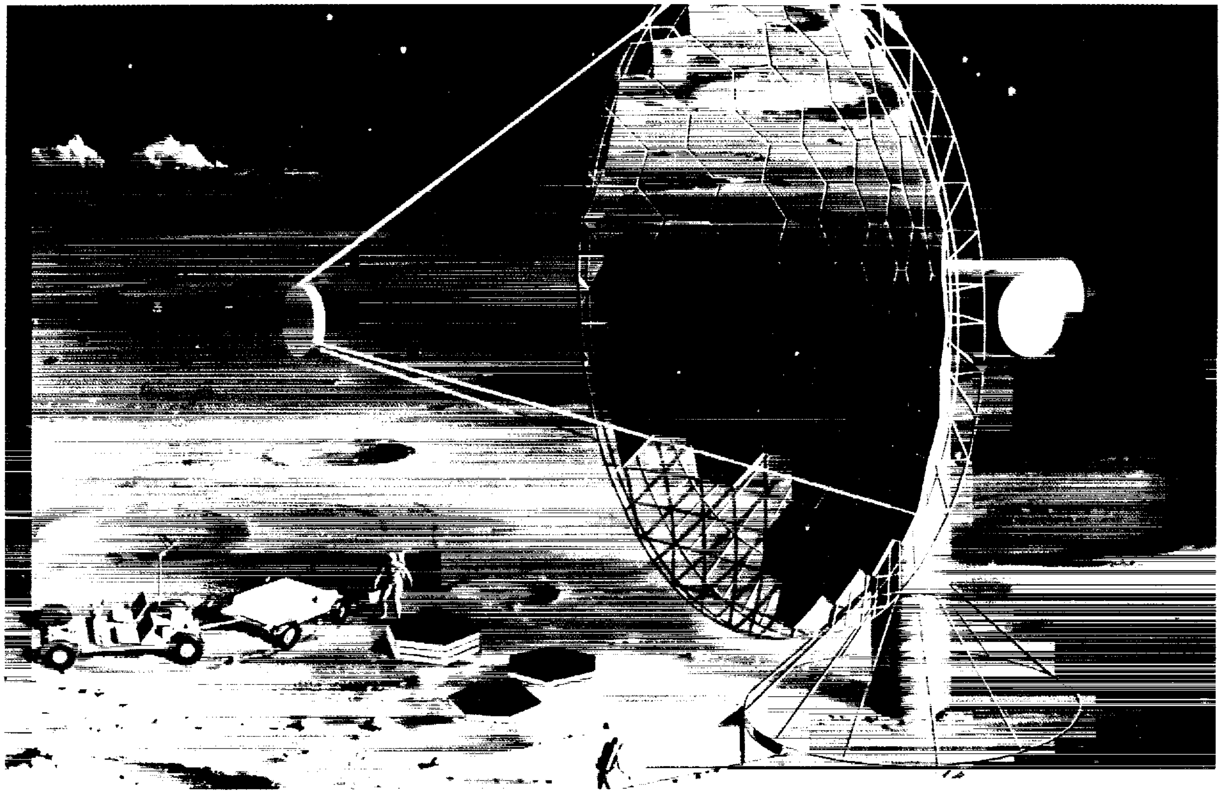

Figure 33. 16-METER TELESCOPE ON THE MOON would be ideally suited to spectroscopic studies of faint sources or objects of low surface brightness. A lunar base provides the stability needed for accurate pointing, tracking, and control. The telescope would be assembled from modular segments, beginning with a 4-m instrument.

vations of faint or low-surface-brightness objects; it will be able to search for Earth-like planets around nearby stars, study the structure of high-redshift galaxies, determine stellar populations, and study star formation. It will represent a major step beyond HST.

The completed 16-meter telescope will have a mass estimated to be 42,000 kg. The full instrument cannot, therefore, be accommodated in the early phases of the Lunar Outpost Astrophysics Program even though it has been recommended by several scientific groups.

The telescope can, however, be constructed in modules. Because of the scientific importance of the instrument, NASA has adopted a strategy in which a 4-meter central module will be deployed and put into operation relatively early in the program (see also discussion of the Optical Interferometer above). The remaining modules, representing an additional mass of 27,000 kg, will be added to the 4-meter telescope as increased weight-carrying capability becomes available later in the program.

The lunar site provides a stable base for high-precision pointing, tracking and control. The high-vacuum environment of the Moon enables broadband spectral observations to be made, and the availability of astronauts and work facilities will make the *in-situ* assembly of the telescope vastly simpler than in orbit.

(d) *Additional Instrument Considered for the Lunar Base*

An additional instrument considered for placement on the lunar surface is the Laser Interferometric Gravity Wave Observatory, which would use a laser interferometer of up to 50-km baseline to search for gravity waves. Seismic test masses connected by laser interferometers in an "L" configuration are capable of measuring fractional changes in the separation of the masses to better than 10^{-21} and are sensitive to gravity waves with frequencies ranging from about 1 Hz to a few kHz.

The low-seismic-noise environment of the Moon is ideal for a gravity-wave detector of this type. A lunar gravity-wave observatory, operated in conjunction with similar instruments on Earth, could locate gravity-wave sources through triangulation. However, the feasibility of the technique must first be proven on Earth before the instrument will be considered for emplacement on the Moon.

C. The Research and Analysis Program

NASA's primary mode of support for space astrophysics is the implementation of missions and the provision of both data and the resources to analyze these data. However, the Research and Analysis (R&A) program is the agency's recognition of the need to maintain a healthy research base from which new and innovative ideas can arise.

Ultraviolet and Visible Astrophysics Branch

Research and Analysis Program, FY 1990

Research Area	Number of Grants	$K
Sounding Rockets	9	3,917
Space Detector Development	5	841
Instrumentation and Technology	8	610
Theory and Data Analysis	13	523
Laboratory Astrophysics	9	510
Gravitational Physics	6	490
Ground-Based Work/NASA Centers	6	295
Space Data Analysis	5	203
Data Cataloging	3	137
Other	1	29
Totals	**65**	**7,555**

1. Background

The purpose of the R&A program is to insure the continued intellectual and technical vibrancy of the field. R&A funds support modest experiments in which high-risk, high-payoff ideas can be tested. The R&A program also supports development of otherwise untested prototype instruments, fundamental laboratory studies necessary for the interpretation of astrophysical data, theoretical and analytical studies that could not otherwise be funded in so timely a way, and the involvement of graduate students in forefront research.

Historically, NASA planning has been oriented toward flight projects and has therefore been focused on hardware. In the case of Ultraviolet, Visible, and Gravity Astrophysics, this emphasis is reflected in substantial R&A support for sounding rockets, detector development, and instrumentation and technology. All of these efforts are essential for a vigorous research program.

Astrophysics, however, depends on the interplay between observation, experiment, and theory, and an optimally productive program must support all three. Laboratory astrophysics, for example, is often the only source of data on atomic and molecular transition probabilities, properties of materials under unusual conditions, reaction rates, and other information crucial to the interpretation of astronomical observations.

Moreover, for their fullest understanding and interpretation, both observational and experimental results require complementary theoretical work. New theoretical ideas are stimulated by new observations and experimental results; theoretical predictions, in turn, help to focus the planning of new observations in the near term as well as to provoke ideas for future missions. The increasingly important field of gravitational physics, among many others, will benefit from the interplay of observation, experiment, and theory during the 1990s and beyond.

We therefore applaud NASA's expansion of support for astrophysical theory during the second half of the 1980s and call for a further strengthening of this effort. In particular, the continuing rapid growth in computational power has had, and will continue to have, a strong influence on the power of astrophysical theory. A complete program of support for astrophysical theory must therefore also include funds for computing at the current state-of-the-art level. Advanced computational capabilities are also essential for effective data analysis and interpretation.

2. R&A Funding

The R&A component of the OSSA Astrophysics Division budget is the portion that most directly affects many scientists. Of the Division's $52 million Fiscal Year 1990 R&A budget, $24 million was devoted to the funding of small and moderate-sized grants. The remainder was used to support early mission studies and larger-scale Advanced Technology Development efforts.

Nearly $7.6 million in grants funding was awarded in FY 1990 through the Ultraviolet and Visible Astrophysics Branch (see box). These funds supported 65 grants in a number of areas, including sounding rockets, detector development, laboratory astrophysics, gravitational astrophysics, space data analysis, and

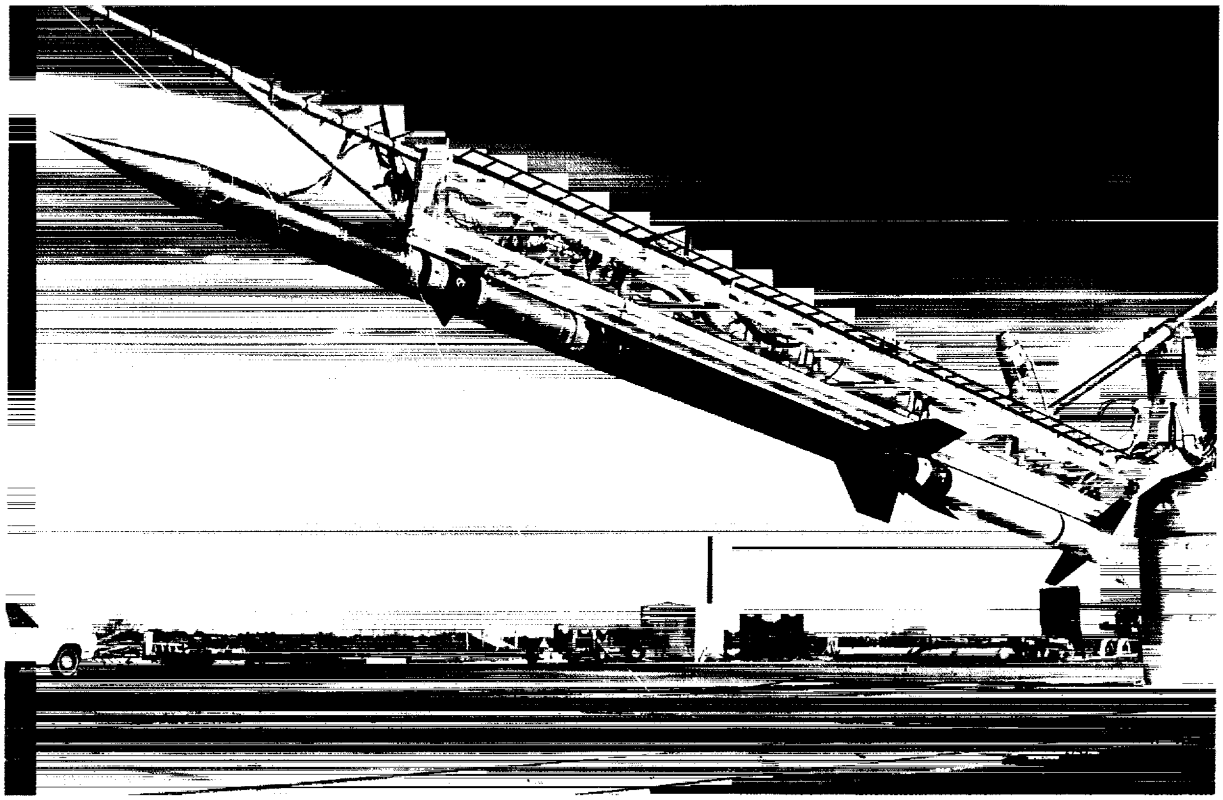

Figure 34. SOUNDING ROCKETS like this stalwart Black Brandt launcher will continue to play a substantial role in the NASA astrophysics program, particularly for observations in the ultraviolet spectral region. Although restricted in duration, rocket flights can provide rapid and comparatively inexpensive access to space for a wide variety of exploratory payloads.

theory. Sounding rockets account for a large fraction of the budget because of their vital role in providing ready access to space for modest experiments.

The Working Group believes that the present division of funds among various research areas of the R&A program is reasonable; the comparatively high level of support for both sounding rockets and detector development reflects the high cost of hardware programs. It is the strong belief of members of the Working Group that R&A support, which has remained at an essentially constant level over the past 5 years, is in urgent need of augmentation.

3. Sounding Rockets

In the 1960s, suborbital missions provided the broadest access to space for conducting research in astronomy. Depending on the observing requirements, sounding rockets, balloons, and high-flying aircraft were the established routes through which astronomers could address the observing challenges that were out of reach from the ground (Figure 34).

In the decade that followed, launch vehicles and spacecraft support systems for experiments in orbit matured and became able to sustain a sequence of large and small observatories that could operate for long intervals of time. On the heels of such advances, some questioned the need for suborbital astronomy missions and, in particular, for sounding rockets.

It was difficult, for instance, to defend the cost-effectiveness of sounding rockets in the simplistic terms of observing time per dollar, since the payloads typically had small collecting areas and were relatively simple. A consequence of this reappraisal was a shift in NASA support from sounding-rocket experiments to small payloads launched by the national Space Transportation System (i.e., the Space Shuttle).

The delay in Shuttle launch opportunities during the late 1980s, together with a reaction against reliance on a single launch vehicle, precipitated an abrupt reversal of NASA's drift away from sounding rockets for space astronomy. At about the same time, the temporary deemphasis of sounding rockets restored an awareness of the program's special contributions, which reach beyond the simple calculation of the amount of scientific data generated per mission. These higher-order benefits are as follows:

SOUNDING ROCKETS

Space astronomy began when simple instruments were installed on German military V-2 rockets captured at the end of World War II and flown on test flights at the White Sands Missile Range in New Mexico. (Rockets in this general size and weight class are popularly known as "sounding rockets" because they have been used extensively to sample or "sound" the upper atmosphere.) Since that time, suborbital rocket flights for scientific research have provided inexpensive access to space for small instruments (usually up to several hundred pounds) and short observing times (typically about 5 minutes).

Even in an era when orbital missions have become commonplace, these suborbital rocket flights are still of special value, since they (a) can be scheduled on short notice, (b) are well suited to highly specialized observations or the testing of payloads featuring new and risky technologies, and (c) serve as an entry mode and training ground for new individuals or groups working on space hardware.

Opportunities to fly specialized or high-risk experiments. Given the infrequent opportunities within a given discipline for access to space, there is an understandable pressure to develop highly reliable, general-purpose instruments that can be applied by a broad community of investigators to a variety of general problems. By the same token, there is a reluctance to fly a technologically or scientifically risky experiment even if the potential payoff is very high. It follows that sounding rockets, by virtue of their simplicity and low cost, are an attractive alternative for much more specialized experiments or those that carry high risk. These vehicles provide an ideal option to pursue objectives that have narrow, but still worthwhile applications in astronomy.

Encouragement of new instruments and technology. Sounding rockets encourage the development of new and innovative instruments, often ones that incorporate enterprising technological concepts. Who will spend extensive time creating and perfecting an instrument, especially one with special design challenges, if there is some doubt that there will be an opportunity to use it? The expectation that an instrument can be flown on a rocket within a few years of its initial development is a powerful incentive, even if the scientific return will be modest because of the short observing time.

An important corollary is that a sounding-rocket mission is a simple enough undertaking that its launch schedule can be relatively flexible. When an experimenter encounters unforeseen difficulties, as is often the case with a new instrument, it is a simple matter to reschedule the flight to a later time. Furthermore, a scientist often has access to the payload right up to the day before launch. These alternatives are not provided by the Space Shuttle or major expendable-launch-vehicle missions.

Realistic testing of prototype instruments. Sounding rockets provide realistic tests of prototype instruments intended for longer-term space missions. In fact, the environment of a rocket flight is, in several respects, more brutal than that associated with an orbital mission. Many experiments that have been flown on Shuttle flights or are now manifested for such flights were originally flown on sounding rockets. In several cases, valuable lessons were learned which influenced the designs of the instruments.

Training of young investigators. A vigorous program in space astronomy must be sustained by an influx of young astronomers who are proficient in designing, building, and flying space hardware. Suborbital missions are an ideal training ground for graduate students and post-doctoral fellows. People in such positions must be able to fly their experiments within a few years of the time they begin building them. The low cost of sounding-rocket research is an important characteristic which permits the support of a reasonable number of young investigators. A high proportion of the scientists who are now developing major space-astronomy instruments "cut their teeth" on sounding rockets early in their careers.

Entry of new scientific groups. An additional consideration, related to that mentioned directly above, is the fact that sounding-rocket grant programs provide an excellent entry mode for new space-astronomy groups with fresh approaches to research. Some turnover and evolution in the complexion of the institutions that carry out space astronomy is an important prerequisite for avoiding stagnation and continuing true progress in science.

In summary, the Working Group urges that NASA continue an energetic program of astronomical research using suborbital vehicles. Sounding rockets are ideal for those experiments that must operate above virtually all of the atmosphere but that can achieve their technical or scientific goals within a brief flight. It is vitally important that sufficient funding be restored to the Goddard Space Flight Center at the Wallops Flight Facility to support the required frequency of flights for astronomy and assure good mission reliability. Under most circumstances, a frequency of one operationally successful flight per year for a research group of average size is appropriate.

Appendix A: Participation

A.K. **Dupree** (Chairperson), Harvard-Smithsonian Center for Astrophysics (1988-1991)
J.W. **Armstrong**, Jet Propulsion Laboratory (1987-1990)
P. **Bender**, JILA/University of Colorado (1989-1992)
C.S. **Bowyer**, University of California at Berkeley (1988-1991)
W.C. **Cash**, Jr., University of Colorado (1988-1991)
J.T. **Clarke**, University of Michigan (1989-1992)
F.B. **Estabrook**, Jet Propulsion Laboratory (1990-1993)
R.J. **Harms**, Applied Research Corporation (1985-1988)
P.D. **Hemenway**, University of Texas at Austin (1989-1992)
J.G. **Hoessel**, University of Wisconsin at Madison (1989-1992)
G.D. **Illingworth**, University of California at Santa Cruz (1986-1989)
E.B. **Jenkins**, Princeton University (1988-1991)
J.H. **Krolik**, The Johns Hopkins University (1988-1991)
R.F. **Malina** (Chairperson Elect, 1991), University of California at Berkeley (1990-1993)
J.T. **McGraw**, University of Arizona (1988-1991)
J.R. **Mould**, California Institute of Technology (1990-1993)
M. **Shara**, Space Telescope Science Institute (1988-1991)
P. **Szkody**, University of Washington (1989-1992)
A. **Tokunaga**, University of Hawaii (1986-1989)
B. **Woodgate**, NASA Goddard Space Flight Center (1988-1991)

Management Operations Working Group—NASA Members *ex officio:*

G.C. **Clayton**, NASA Headquarters (1988-1990)
D.P. **Huenemoerder**, NASA Headquarters (1990-1992)
J.M. **Mead**, NASA Goddard Space Flight Center
R.V. **Stachnik**, NASA Headquarters
E.J. **Weiler**, NASA Headquarters

Liaisons:

M.L. **Aizenmann**, National Science Foundation
P.B. **Boyce**, American Astronomical Society

Appendix B: Acronyms and Abbreviations

ACE: Advanced Composition Explorer

AGN: Active galactic nucleus

AIM: Astrometric Interferometry Mission

ASTRO: Space Shuttle Astronomy Observatory

AstroSPAS: German space platform

AXAF: Advanced X-Ray Astrophysics Facility

BBXRT: Broad Band X-Ray Telescope

CCD: Charge coupled device

COBE: Cosmic Background Explorer

Copernicus: Third OAO satellite

CSAA: Committee on Space Astronomy and Astrophysics

ESA: European Space Agency

EUV: Extreme ultraviolet

EUVE: Extreme Ultraviolet Explorer

EXOSAT: ESA X-Ray Observatory Satellite

FGS: Fine Guidance Sensors

FOC: Faint Object Camera

FOS: Faint Object Spectrograph

FUSE: Far Ultraviolet Spectroscopic Explorer

FUV: Far ultraviolet

GHRS: Goddard High Resolution Spectrograph

GP-A: Gravity Probe-A

GP-B: Gravity Probe-B

GRO: Gamma Ray Observatory

H-R: Hertzsprung-Russell

HIPPARCOS: ESA astrometric satellite

HSP: High Speed Photometer

HST: Hubble Space Telescope

HUT: Hopkins Ultraviolet Telescope

IMAPS: Interstellar Medium Absorption Profile Spectrograph

IR: Infrared

IRAS: Infrared Astronomical Satellite

IUE: International Ultraviolet Explorer

ISM: Interstellar medium

LAGEOS: Laser Geodynamics Satellite

LAGOS: Laser Gravitational Wave Observatory in Space

LTT: Lunar Transit Telescope

MAMA: Multi-anode microchannel array

MCP: Microchannel plate

MOWG: Management Operations Working Group

NASA: National Aeronautics and Space Administration

NIC: Near Infrared Camera

NSF: National Science Foundation

OAO: Orbiting Astronomical Observatory

ORFEUS: Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer

OSI: Orbiting Stellar Interferometer

OSSA: Office of Space Science and Applications

P-L: Period-luminosity

PI: Principal Investigator

POINTS: Precision Optical Interferometry in Space

QPO: Quasi-periodic oscillation

R&A: Research and Analysis

SAS: Small Astronomy Satellite

SEI: Space Exploration Initiative

SMEX: Small Explorer

SN: Supernova

STIS: Space Telescope Imaging Spectrograph

STORE: Shuttle Test of Relativity Experiment

STU: Shuttle Test Unit

UIT: Ultraviolet Imaging Telescope

UV: Ultraviolet

UVS: Ultraviolet Spectrometers on Voyager spacecraft

VLBI: Very long baseline interferometry

WF/PC: Wide Field/Planetary Camera

WUPPE: Wisconsin Ultraviolet Photo-Polarimeter Experiment

XTE: X-Ray Timing Explorer

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Appendix D: Acknowledgments

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R.V. Stachnik: MOWG Report Manager

P.A. Blanchard and B. Geldzahler: MOWG Report Editors

Appendix E: OSSA Management

L.A. Fisk: Associate Administrator for Space Science and Applications

C.J. Pellerin: Director, Astrophysics Division

Credits

Ground-based image of M 81 beneath Foreword: National Optical Astronomy Observatories.

Figures
2,3: Space Telescope Science Institute.
7: M. Geller, Harvard-Smithsonian Center for Astrophysics.
10, 11: National Optical Astronomy Observatories.
15: adapted from a diagram by G. Abell in *Exploration of the Universe* (1969).
19: B. Smith, University of Arizona and R. Terrile, Jet Propulsion Laboratory.
22: J. Krolik, The Johns Hopkins University.
25: adapted from a diagram by M. Harwit in *Cosmic Discovery* (1984).
26: Space Telescope Science Institute (WF/PC and FOC images), University of Wisconsin (HSP data), and Lowell Observatory (FGS data).
27: University of California at Berkeley.

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