

**FINAL REPORT  
OF THE  
SPACE SHUTTLE  
PAYLOAD PLANNING WORKING GROUPS**

**HIGH ENERGY ASTROPHYSICS**

**MAY 1973**

**NATIONAL AERONAUTICS & SPACE ADMINISTRATION  
GODDARD SPACE FLIGHT CENTER  
GREENBELT, MARYLAND 20771**

(NASA-TM-X-69407) THE SPACE SHUTTLE  
PAYLOAD PLANNING WORKING GROUPS. VOLUME  
3: HIGH ENERGY ASTROPHYSICS Final  
Report (NASA) -97 P HC \$7.00 CSCI 22B

G3/31

Unclass  
15956

N74-15520

VOLUME 3

## GLOSSARY

<u>Abbreviation</u>	<u>Description</u>
AFO	Announcement of Flight Opportunity
AIBS	(American Institute of Biological Sciences)
LSRM	Life Sciences Research Module
CORE	Common Operations Research Equipment/Facility
EC/LSS	Environmental Control and Life Support Subsystem
EVA	Extra Vehicular Activity
FFTO	Free Flying Teleoperator
HEAO	High Energy Astronomy Observatory
HZE	High Z (High Energy) Cosmic Particle
LET-HZE	Linear Energy Transfer
MEM	Micrometeoroid Exposure Module
NMI	NASA Management Instruction
PALIS	Post Apollo Life Sciences
PLSS	Portable Life Support System
Q&A	Quality and Assurance
SR&T	Supporting Research & Technology
TBD	(To Be Determined)

FINAL REPORT  
OF THE  
SPACE SHUTTLE  
PAYLOAD PLANNING WORKING GROUPS

Volume 3  
High Energy Astrophysics

MAY 1973

NATIONAL AERONAUTICS & SPACE ADMINISTRATION  
GODDARD SPACE FLIGHT CENTER  
Greenbelt, Maryland 20771

FOREWORD\*

In January 1972 the United States decided to develop a new space transportation system, based on a reusable space shuttle, to replace the present expendable system.

By January 1973 planning had progressed to the point that through the European Space Research Organization (ESRO) several European nations decided to develop a Space Laboratory consisting of a manned laboratory and a pallet for remotely operated experiments to be used with the shuttle transportation system when it becomes operational in 1980.

In order to better understand the requirements which the space transportation must meet in the 80's and beyond; to provide guidance for the design and development of the shuttle and the spacelab; and most importantly, to plan a space science and applications program for the 80's to exploit the potential of the shuttle and the spacelab, the United States and Europe have actively begun to plan their space programs for the period 1978-1985, the period of transition from the expendable system to the reusable system. This includes planning for all possible modes of shuttle utilization including launching automated spacecraft, servicing spacecraft, and serving as a base for observations. The latter is referred to as the sortie mode. The first step in sortie mode planning was the Space Shuttle Sortie Workshop for NASA scientists and technologists held at the Goddard Space Flight Center during the week of July 31 to August 4, 1972. For the purposes of that workshop, shuttle sortie missions were defined as including those shuttle missions which employ observations or operations (1) from the shuttle itself, (2) with subsatellites of the shuttle, or (3) with shuttle deployed automated spacecraft having unattended lifetimes of less than about half a year.

In general the workshop was directed towards the education of selected scientific and technical personnel within NASA on the basic capabilities of the shuttle sortie mode and the further definition of how the sortie mode of operation could benefit particular disciplines. The specific workshop objectives included:

- Informing potential NASA users of the present sortie mode characteristics and capabilities
- Informing shuttle developers of user desires and requirements
- An initial assessment of the potential role of the sortie mode in each of the several NASA discipline programs
- The identification of specific sortie missions with their characteristics and requirements

---

\*Reprinted from the volume entitled "Executive Summaries".

- The identification of the policies and procedures which must be changed or instituted to fully exploit the potential of the sortie mode
- Determining the next series of steps required to plan and implement sortie mode missions.

To accomplish these objectives 15 discipline working groups were established. The individual groups covered essentially all the space sciences, applications, technologies, and life sciences. In order to encourage dialogue between the users and the developers attendance was limited to about 200 individuals. The proceedings were, however, promptly published and widely distributed. From these proceedings it is apparent that the workshop met its specific objectives. It also generated a spirit of cooperation and enthusiasm among the participants.

The next step was to broaden the membership of the working groups to include non-NASA users and to consider all modes of use of the shuttle. To implement both objectives the working group memberships were expanded in the fall of 1972. At this time some of the working groups were combined where there was appreciable overlap. This resulted in the establishment of the 10 discipline working groups given in Attachment A. In addition European scientists and official representatives of ESRO were added to the working groups. The specific objectives of these working groups were to:

- Review the findings of the GSFC workshop with the working groups
- Identify as far as possible the missions (by mode) that will be required to meet the discipline objectives for the period 1978 to 1985
- Identify any new requirements or any modifications to the requirements in the GSFC report for the shuttle and sortie systems
- Identify the systems and subsystems that must be developed to meet the discipline objectives and indicate their priority and/or the sequence in which they should be developed
- Identify any new supporting research and technology activity which needs to be initiated
- Identify any changes in existing procedures or any new policies or procedures which are required in order to exploit the full potential of the shuttle for science, exploration and applications, and provide the easiest and widest possible involvement of competent scientists in space science
- Prepare cost estimates, development schedules and priority ranking for initial two or three missions

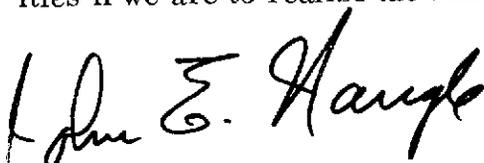
In order to keep this planning activity in phase with the shuttle system planning the initial reports from these groups were scheduled to be made available by the spring of 1973. It was also felt necessary that the individual working group activities be coordinated both between the groups and with the shuttle system planning. As a result, the steering group given in Attachment B was established.

Early in 1973, NASA and the National Academy of Sciences jointly decided that it would be appropriate for a special summer study to review the plans for shuttle utilization in the science disciplines. This summer study has now been scheduled for July 1973. It is anticipated that the results of the working group activities to date will form a significant input into this study.

In the following sections of the summary document are the executive summaries of each of the working group reports. While these give a general picture of the shuttle utilization plan, the specific plan in each discipline area can best be obtained from the full report of that working group. Each working group report has been printed as a separate volume in this publication so that individuals can select those in which they are particularly interested.

From these working group reports it is apparent that an appreciable effort has been made to exploit the full capability of the shuttle. It is, however, also apparent that much work remains to be done. To accomplish this important work, the discipline working groups will continue.

Finally it is evident from these reports that many individuals and groups have devoted appreciable effort to this important planning activity. I would like to express my appreciation for this effort and stress the importance of such activities if we are to realize the full potential of space systems in the 1980s.



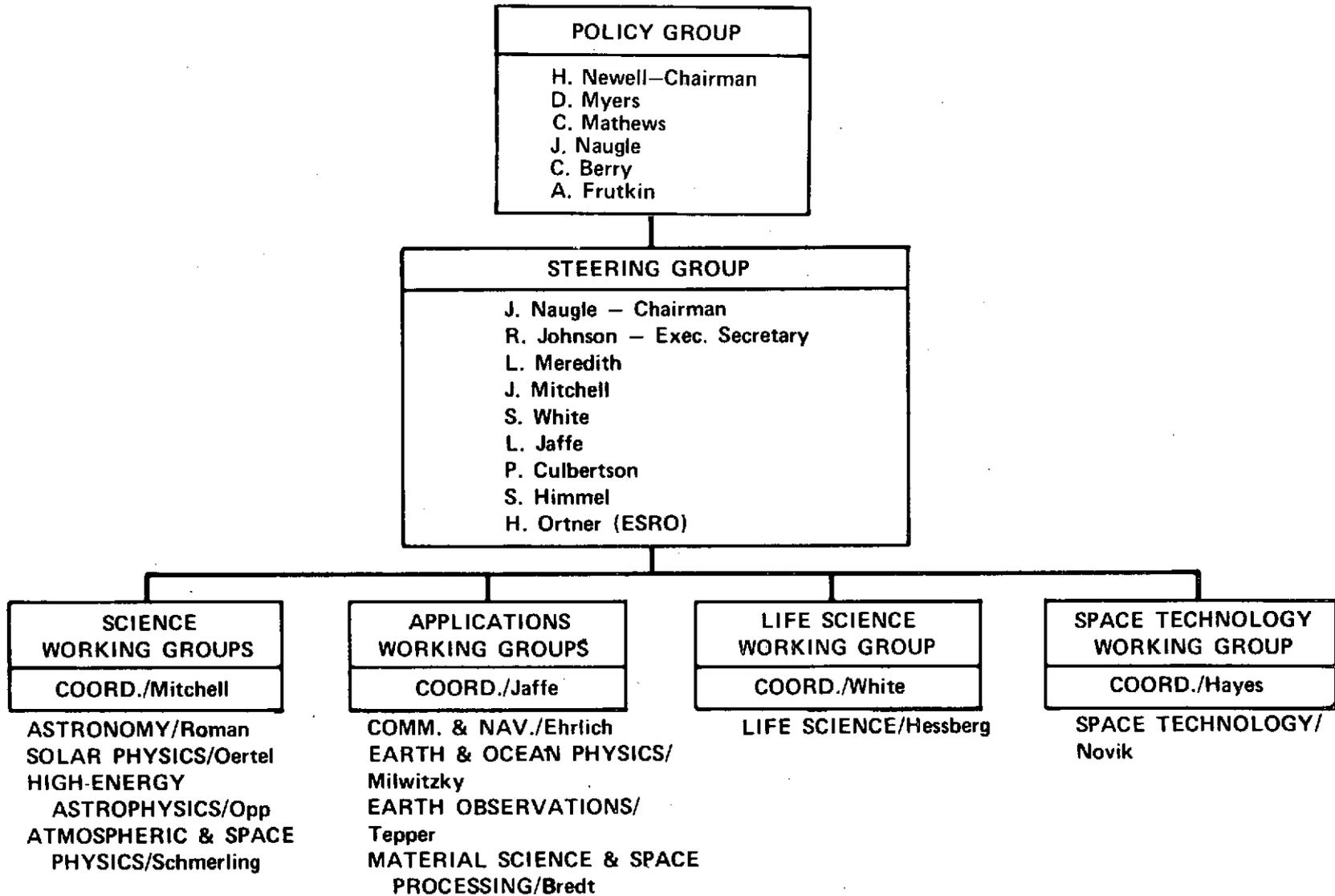
John E. Naugle, Chairman  
NASA Shuttle Payload Planning  
Steering Group

## LIST OF WORKING GROUPS

	<u>GROUP NAME</u>	<u>CHAIRMAN</u>	<u>CO-CHAIRMAN</u>
1.	ASTRONOMY	Dr. N. Roman (HQ)	Dr. D. S. Leckrone (GSFC)
2.	ATMOSPHERIC & SPACE PHYSICS	Dr. E. Schmerling (HQ)	Mr. W. Roberts (MSFC)
3.	HIGH ENERGY ASTROPHYSICS	Dr. A. Opp (HQ)	Dr. F. McDonald (GSFC)
4.	LIFE SCIENCES	Dr. R. Hessberg (HQ)	Dr. D. Winter (ARC)
5.	SOLAR PHYSICS	Dr. G. Oertel (HQ)	Mr. K. Frost (GSFC)
6.	COMMUNICATIONS & NAVIGATION	Mr. E. Ehrlich (HQ)	Mr. C. Quantock (MSFC)
7.	EARTH OBSERVATIONS	Dr. M. Tepper (HQ)	Dr. W. O. Davis (DoC/NOAA)
8.	EARTH AND OCEAN PHYSICS	Mr. B. Milwitzky (HQ)	Dr. F. Vonbun (GSFC)
9.	MATERIALS PROCESSING AND SPACE MANUFACTURING	Dr. J. Bredt (HQ)	Dr. B. Montgomery (MSFC)
10.	SPACE TECHNOLOGY	Mr. D. Novik (HQ)	Mr. R. Hook (LaRC)

LA

# NASA AD HOC ORGANIZATION FOR SHUTTLE PAYLOAD PLANNING



11A

ATTACHMENT B

CONTENTS

	<u>Page</u>
PREFACE . . . . .	xii
<u>EXECUTIVE SUMMARY</u> . . . . .	xiii
<u>STATUS AND OBJECTIVES</u> . . . . .	1
X-RAY ASTRONOMY . . . . .	1
Introduction . . . . .	1
Observational Objectives . . . . .	7
HARD X-RAY AND GAMMA-RAY ASTRONOMY . . . . .	11
Introduction . . . . .	11
Objectives and Rationale . . . . .	12
Status and Development . . . . .	19
COSMIC RAY ASTRONOMY . . . . .	26
Introduction . . . . .	26
Sources . . . . .	26
Interstellar Medium . . . . .	27
Scientific and Observational Objectives . . . . .	28
<u>INSTRUMENTS</u> . . . . .	31
X-RAY ASTRONOMY ( $\lesssim 20$ keV) . . . . .	31
HARD X-RAY AND GAMMA RAY ASTRONOMY . . . . .	35
Techniques . . . . .	35
High Energy X-Ray Survey . . . . .	36
Broad Band X-Ray Spectrometer . . . . .	36
Hard X-Ray Imaging . . . . .	36
High Sensitivity Medium Energy $\gamma$ -Ray Survey . . . . .	37
Nuclear $\gamma$ -Ray Spectrometer with High Resolution . . . . .	37
Developmental Pallet System . . . . .	37
High Energy Gamma-Ray Survey Instrument . . . . .	38
High Angular Resolution Instrument . . . . .	38
High Energy Resolution Detector with Pictorial Device . . . . .	38

## CONTENTS (Continued)

	<u>Page</u>
COSMIC RAY ASTRONOMY . . . . .	39
Magnetic Spectrometer . . . . .	39
Gas Cerenkov Detector . . . . .	39
Electromagnetic Calorimeter . . . . .	39
Nuclear Calorimeter . . . . .	41
Large Area Ionization Hodoscope . . . . .	41
Graded Cerenkov Counter . . . . .	41
<u>SHUTTLE UTILIZATION -- SORTIE MISSION</u> . . . . .	40
<u>MANAGEMENT RECOMMENDATIONS</u> . . . . .	46

## APPENDICES

<u>Appendix</u>	<u>Page</u>
A      Instrument Parameters . . . . .	A-1

## ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1      The X-Ray Sky as seen by Uhuru, January 1973 . . . . .	1
2      Exposure factor required to measure fluxes to an energy E . . . . .	41

## TABLES

<u>Table</u>	<u>Page</u>
1      Satellite Missions Which Have Important $\gamma$ -Ray Experiments . . . . .	20
2      Baseline Shuttle Parameters (Provided to Working Group) . . . . .	42

TABLES (Continued)

<u>Table</u>		<u>Page</u>
3	Spacecraft Carrying High Energy Astrophysics Instrumentation . . . . .	44

## PREFACE

The discipline of High Energy Astrophysics incorporates the fields of X-ray and gamma ray astronomy and particle astrophysics. The report that follows was written by a Working Group in High Energy Astrophysics, which was brought together by NASA to consider the scientific potential of the Space Shuttle to the discipline. Membership in the Working Group was as follows:

- A. G. Opp, NASA Headquarters, Chairman
- F. B. McDonald, Goddard Space Flight Center, Co-Chairman
- S. S. Holt, Goddard Space Flight Center, Secretary
- H. V. Bradt, Massachusetts Institute of Technology
- A. Buffington, University of California, Berkeley
- C. C. Dailey, Marshall Space Flight Center, Consultant
- C. E. Fichtel, Goddard Space Flight Center
- G. Garmire, California Institute of Technology
- R. Giacconi, American Science & Engineering
- R. Golden, Manned Spacecraft Center
- R. Hofstadter, Stanford University
- A. Jacobson, Jet Propulsion Laboratory
- H. Mark, Ames Research Center
- L. Peterson, University of California, San Diego
- K. Pinkau, Max Planck Society
- L. Scarsi, European Space Research Organization
- R. Vogt, California Institute of Technology
- A. B. C. Walker, Aerospace Corporation.

The Working Group met at the Ames Research Center on December 7 and 8, 1972 and at the Goddard Space Flight Center on March 8 and 9, 1973 to discuss the potential uses of the Space Shuttle and to prepare portions of the report. An editorial committee, consisting of H. V. Bradt, A. Buffington, A. G. Opp, and L. Peterson also met at the University of California, San Diego on March 23 and 24, 1973 to complete the writing and editing of the report. The contributions to Section II reflect the particular emphasis of the individual authors and therefore differ somewhat in format.

Contributions to the Working Group discussions and report were also made by:

- H. Gursky, American Science and Engineering
- E. B. Hughes, Stanford University
- D. Mueller, University of Chicago
- R. Novick, Columbia University
- L. C. L. Yuan, Brookhaven National Laboratory.

Albert G. Opp  
Chairman

## HIGH ENERGY ASTROPHYSICS WORKING GROUP

### EXECUTIVE SUMMARY

High energy astrophysics is an important and critical part of the present exciting and explosive growth of our knowledge of the cosmos. It is conducted of necessity from space because the earth's atmosphere absorbs the X-rays,  $\gamma$ -rays, and cosmic rays to be observed. It has profoundly influenced other areas of astrophysics as well as areas of fundamental physics. For instance, the discovery by Uhuru of X-ray binary stars, one or more of which may contain a "black hole" has instigated many theoretical and observational studies of binary systems and of the final compact states of stellar evolution. The existence of black holes would, in certain respects, be the equivalent for general relativity to what the existence of very energetic particles has been for special relativity.

High energy astrophysics is the study of energetic processes within or near compact objects (galaxies, binary stellar systems, quasars, pulsars) and in the diffuse matter between these objects (interstellar hydrogen, the gaseous remnants of supernova and intergalactic space). The field deals with the most energetic and transient phenomena in the Galaxy and Universe. This is apparent from the time scales of these processes, which tend to be short compared to the galactic or Hubble time scale of  $\sim 10^{10}$  years. The high energy particles involved are generally not in thermal equilibrium with the surrounding medium and tend to lose energy rapidly or to escape from a region of confinement ( $10^6$  years for galactic cosmic rays;  $\sim 1$  year for electrons giving rise to X-rays in a supernova remnant). Also the events which accelerate the particles or modulate the observed photons are often of short duration ( $\sim 1$  hour for a binary eclipse of an X-ray star,  $\sim 1$  sec for stellar collapse, 33 msec for the rotation of a neutron star,  $10$ - $100 \mu$  sec for the predicted fluctuations of emission from a black hole).

Cosmic rays detected at the earth (protons, electrons, nuclei) are direct samples of the particles participating in the energetic events. X-rays are emitted by these high energy electrons via processes such as synchrotron radiation and thermal bremsstrahlung. Gamma rays are emitted by nuclear processes such as the decay of excited nuclei or elementary particles (e.g.  $\pi^0$ ) created in proton-proton collisions. In general the scale of the interaction region is set by the energy of the observed photons. Quanta of visible light come from the outer shells of atoms. X-rays quanta come from the inner shells of atoms, closer to the nuclei. Gamma rays of medium energy come from within the nuclei themselves, and gamma rays of high energy come from the individual elementary particles out of which nuclei are made.

The most dramatic recent discoveries have been in X-ray astronomy and have come from the Uhuru satellite (2-20 keV). The discoveries of binary X-ray

stars and diffuse X-ray sources within clusters of galaxies are clearly of fundamental importance. These phenomena alone can be the basis of much future research in X-ray astronomy. Also, we know that young and old supernova remnants, active radio galaxies, a quasar, one (and possibly two) pulsars and at least one Seyfert galaxy, are X-ray emitters. The third Uhuru catalog contains  $\sim 160$  galactic and extragalactic sources. Since the X-rays usually carry a dominant portion of the emitted electromagnetic radiation, studies of this portion of the spectrum are critical to our understanding of these objects.

High energy  $\gamma$ -ray observations have taken on new significance and give promise for major advances with the dramatic discovery of a "ridge" of emission centered on the galactic plane. The emissions are probably due to the production and subsequent decay of  $\pi$  mesons by cosmic rays impinging on the interstellar gas. Discrete  $\gamma$ -ray lines in the MeV range have been measured during intense solar flares. Confirmation of such lines from cosmic sources will open the whole field of observational nuclear astrophysics. An apparently isotropic flux of diffuse  $\gamma$ -rays has been measured over the entire range from  $\sim 1$  keV to 100 MeV. Although complete observational understanding of this complex multicomponent phenomena has not yet been accomplished, it is clear that the total picture will have profound cosmological significance.

Cosmic ray research has focused upon measurements of the charge and energy spectra of its different components (nuclei and electrons). Until very recently the elements were well measured only up to about 10 GeV/nucleon and all components appeared to have similar spectra. In the last two years, however, new measurements in the region above 10 GeV/nucleon have revealed interesting spectral differences between the "secondary" elements (such as Li, Be, B), which probably result from interstellar spallation, and the "primary" elements (such as C, O). In addition, the spectrum of iron appears to differ from that of carbon and oxygen. Detailed analysis of these spectral differences provides us with unique information about the generation, acceleration, and propagation of cosmic rays, and the role they play in galactic dynamics. Individual spectra for the low mass isotopes are also required, since in this form the effects of generation, acceleration, and propagation can be separated. Analysis of the spectra of radioactive isotopes provides a means of direct dating for the cosmic rays. Present experiments have just begun to make isotopic separation. Many of the isotopes to be measured are of low intensity and hence require large area detector systems with long integration times and high discrimination to separate the rare isotopes from their more abundant neighbors. Substantial new progress requires these capabilities. The charge spectrum of high Z cosmic rays is also important as a means of testing concepts of nucleosynthesis. The low flux of high Z cosmic rays requires large area detectors, such as can be carried on the Shuttle, to obtain statistically significant spectral data.

The above examples illustrate the commonality of the astrophysical phenomena of interest to the three subfields of High Energy Astrophysics. The three subfields are at different stages of development and require different types of facilities. This situation has arisen in part because of the relatively low fluxes of  $\gamma$ -rays and certain components of cosmic rays. The interstellar magnetic fields which confine the cosmic rays within the galaxy also diffuse the cosmic rays so the observed individual sources cannot be resolved by virtue of their arrival directions or arrival times. Observations of photons (e.g. X-rays and  $\gamma$ -rays) on the other hand yield temporal and angular information about the source particles. The actual emission process and its physical parameters must be inferred indirectly from this information together with spectral and, in the case of X-rays, polarimetry data.

The working group studied the discipline objectives in a post-HEAO scientific climate within the constraints of the shuttle system. The Working Group finds that an operational Space Shuttle would be a major stimulus to High Energy Astrophysics, given sufficient resources on a timely basis to develop the necessary instrumentation. Fundamental next-generation measurements in the three sub-disciplines (X-ray,  $\gamma$ -ray, cosmic ray) can be carried out by making use of the large weight/area capability of the shuttle. These can and should be accomplished at low cost through a management philosophy modeled, in so far as is reasonable, after the present sounding rocket and balloon programs. Relaxed quality assurance and reliability requirements, minimal external monitoring with a correspondingly greater responsibility placed on the experimenter, and the reuse of common hardware among investigators, should be key factors of such a program.

The requirement for long observing times dictates that the major use of the Shuttle Orbital Sortie will be for the ejection and periodic recovery for refurbishment of free-flying satellites. Most of the requirements of the discipline can be served by a somewhat enlarged standardized mini-HEAO. An important usage will also be made of smaller satellites and of large area passive cosmic ray detectors. The major X-ray telescope facility given high priority herein will require a significantly larger and more specialized spacecraft vehicle. Unattended pallets in the shuttle are important in that they provide the means to make observations of specific celestial objects and to test new instruments and techniques in space. Launches of interplanetary probes out to 10 A. U. are also proposed for cosmic ray and long baseline X-ray observations.

The interaction of man with the experiments aboard the shuttle was discussed extensively. Astrophysics experiments are now routinely designed to operate in space and existing automated technology can be used to perform most of the envisioned required tasks. It is possible that a man in EVA can correct an occasional malfunction, or perform on-board monitoring of an experiment. New,

presently unconceived experimental tasks may also develop as the Shuttle program evolves. It is imperative however that the experiments should be designed and built to relaxed automated standards in order to avoid costly man rating and thus to maintain minimal experiment cost. The experiments presently envisioned are best performed on unattended pallets or free flyers.

# REPORT OF THE HIGH ENERGY ASTROPHYSICS SHUTTLE WORKING GROUP

## STATUS AND OBJECTIVES

### X-RAY ASTRONOMY

#### Introduction

The X-ray satellite Uhuru has provided a qualitative change in our view of X-ray astronomy, even though the general features of the discipline were well established even before Uhuru was launched. The reason for this is that for the first time we have sufficient information to establish the properties of specific classes of X-ray sources and to demonstrate that these objects are of prime importance to astronomy and physics generally, as is exemplified by the discovery of binary X-ray stars in which the X-ray emitting member is apparently a collapsed star.

X-ray astronomy has already resulted in the discovery of new types of objects of fundamental importance in astronomy. The use of the Shuttle promises to greatly expand the impact of X-ray astronomy on a wide range of astronomical problems by allowing significant improvements in instrument sensitivity, and by expanding the repertoire of observational techniques which are available, such as in the area of spectroscopic studies and of very high time and spatial resolution. In addition to the "classical" areas of X-ray astronomy, the traditional astronomical problems on which X-ray observations in the Shuttle era should have the greatest impact include studies of the structure and dynamics of the interstellar medium, the structure of the intergalactic medium, and the structure of stellar atmospheres. In addition, new classes of objects, which may profoundly affect our ideas on stellar evolution and galactic structure, may be discovered in the first Shuttle-supported X-ray sky surveys.

Galactic Sources — Figure 1 shows the distribution of the galactic X-ray sources as seen by Uhuru which reveals the well known concentration in the Sgr-Sco

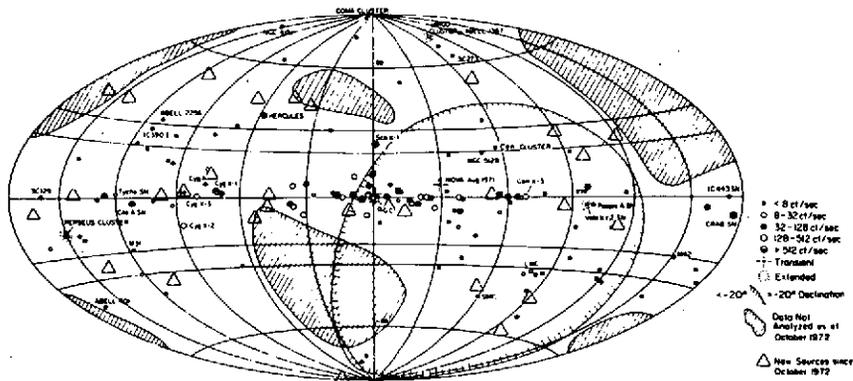


Figure 1. The X-Ray Sky as seen by Uhuru, January 1973

region and less dense concentrations in the spiral arms, particularly those in Cygnus, Serpens and Centaurus. This distribution, by itself, can be used to establish the following "average" properties of galactic X-ray sources:

- Most of the X-ray sources apparently represent a new class of stellar systems. The only recognizable known class of sources are the supernova remnants, and these comprise fewer than 10% of the total number of sources. The remainder show no correlation with established kinds of stars or stellar systems.
- The luminosity of the X-ray sources lies in the range  $10^{36}$  -  $10^{38}$  erg/sec, based on the discovery of single sources in the Magellanic Clouds and on the distribution of sources in our own galaxy.
- The sources show a high degree of concentration in the outer spiral arms.
- The total number of sources in the galaxy is no more than about 100, based on the deficiency of faint sources and the weak strength of the diffuse, galactic ridge in the 1-10 keV energy range.

These characteristics must be accountable from the properties of the individual objects in the galaxy.

- Supernova Remnants — At least eight supernova remnants are detected as X-ray sources (Crab, Tycho, Cas A, Cygnus Loop, Vela SN, Puppis A, IC 443, Lupus Loop), all displaying a great variety of X-ray characteristics. Considering the corresponding variety of optical and radio properties, it is not likely that the same physical process is giving rise to the X-ray emissions in the different sources. For example, the only plausible account of the X-ray emission of the Crab nebula is the synchrotron radiation of high energy electrons. In the Cygnus Loop, on the other hand, the evidence points to thermal emission originating at the boundary of an expanding shock wave. Correspondingly, there seems to be a strong dependence of the spectrum of the radiation on the age of the remnant, the younger ones having appreciably harder spectra than the older ones. Also, at least one (NP0532) and possibly a second (Vela) Pulsar associated with active supernova remnants are seen in X-rays.
- Binary X-Ray Stars — The findings that X-ray sources are members of binary systems and that the source itself is likely to be associated with a collapsed star — either a neutron star or a black hole — is one of the great discoveries in astronomy. The evidence is very compelling by

now, and is limited as much by the lack of optical as by X-ray observations. At least eight X-ray sources are seen to be binary systems with periods ranging from 5 hours to 7 days, based on a combination of X-ray and optical data. In two of these, the pulsing X-ray sources Cen X-3 and Her X-1, we see directly the orbital motion of the X-ray source through the Doppler shift of the X-ray pulse period. In others, such as Cyg X-1 and 2U0900 - 40, we see an optical candidate that is a spectroscopic binary, and for others we find periodic X-ray variations that can only be interpreted as eclipses.

The common thread running through these observations is the combination of a bright, early type star and a small compact X-ray source. But also, these objects illustrate an extraordinary richness and complexity of detail that is typical of close binary stellar systems. Nowhere is this better illustrated than in Hercules X-1, an object which most certainly will take its place in the Stellar Hall of Fame beside Algol, Sirius, the Crab nebula, and other objects which have provided the information for fundamental advances in stellar astronomy. In Her X-1, the observable X-ray emission takes the form of pulses with a period of 1.24 seconds. The pulses are sharp (20% duty cycle) and show significant changes in shape on a time scale of hours. The pulse period displays a periodic Doppler shift corresponding to a velocity change of  $\pm 169$  km/sec in a time of 1.7 days. Also, the X-ray emission is fully eclipsed for about three hours out of this time period. The X-ray emission undergoes yet another cycle — this time of 35 days — during which time it comes on within about one hour and remains on for about 12 days.

The optical companion to Her X-1 is positively identified as HZ Herculis, a star incorrectly known in the literature as an irregular variable. The light variations are in fact regular, showing a change of more than one magnitude in the 1.7 day orbital period. The peak in the optical emission occurs when the side facing the X-ray source is in view, leading to the idea that the excess light results from the stellar surface being heated by UV and X-ray emission from Her X-1. The optical emission does not show the 35-day period as does the X-rays; therefore, there must be present from Her X-1 an emission which is more continuous and of greater power than is indicated by the X-ray observations themselves. However, HZ Herculis is revealing other complexities; studies of historical material reveal that on a number of occasions the periodic optical variations have disappeared for several years leaving only the object we now see at minimum light.

There are even other details — narrow temporal absorption features in X-rays, systematic spectral changes in optical — that as yet defy simple

explanations. But the truly exciting feature of this system is that Hercules X-1 can only be plausibly understood as a neutron star accreting matter from its larger, normal companion. Thus, we now have a new tool for studying the nature and evolution of neutron stars and of close binary systems generally.

Hercules X-1 is not alone as at least one other X-ray source is seen to be pulsing and the light from the optical counterparts of two non-pulsing X-ray sources show variations reminiscent of HZ Herculis. But the most important X-ray binary system is Cyg X-1, one that seems normal in every respect, except that it may contain the most elusive of all stellar objects — a black hole. The X-ray emission is characterized by nothing more than a high degree of short-term, irregular variability down to times of about 50 msec. The optical counterpart is apparently a +9<sup>m</sup> BO supergiant that is a double-line spectroscopic binary with a period of 5.6 days. A straightforward analysis of the spectral lines, taken with the normal appearance of the observed star leads to a mass of the unseen companion of between 10–15  $M_{\odot}$ , much greater than is expected for a white dwarf or neutron star. Thus, the most likely possibility is that we are seeing a black hole.

This conclusion is by no means unanimously accepted, even though it is by far the simplest interpretation of the available data. However, there are several other X-ray sources that display characteristics similar to Cygnus X-1; the study of these systems and continued observations of Cyg X-1 will undoubtedly resolve whatever questions remain.

- Other Galactic X-Ray Sources — It is unlikely that all galactic X-ray sources are supernova remnants or binary systems of the kind described above. There are, for example, transient sources, objects that appear in X-rays where none were previously seen. The degree of brightening and decline is at least  $10^3$ . These are naturally compared to optical novae but no optical identification has been made to confirm this view.

Finally, there is Sco X-1, the first discovered and still the brightest X-ray source. It was also the first for which an optical identification was made and still the only one in which X-ray and optical correlations indicate that the bulk of the optical emission originates in or very close to the X-ray emitting region. So far, there is no evidence that this object is part of a binary system; thus, it is possible that Sco X-1 is a very different kind of X-ray source.

Extragalactic X-Ray Sources — At least half the X-ray sources found by Uhuru are convincingly identified as being extragalactic; some on the basis of direct identifications with prominent external galaxies, others on the basis of distributional properties. They can be described in terms of three distinct classes; active galaxies, cluster sources, and X-ray galaxies.

- Active Galaxies — X-ray sources have been identified with some of the most prominent active galaxies of which we have any knowledge. These include NGC5128, NGC4151, 3C273 and possibly Cygnus A and Hercules A. Based on spectral data, it is most likely that the emission originates in a small region within the galactic nucleus.
- Cluster Sources — These represent one of the great surprises of the Uhuru data, that there exist extended X-ray sources associated with the central region of very rich clusters of galaxies. In at least two instances (Virgo and Perseus), the X-ray emission is centered on an unusually active galaxy (M87 and NGC1275, respectively) although the X-ray emission extends far beyond what can reasonably be considered the confines of the galaxy. In other cases, however, (e.g., Coma) no such active galaxy exists even though the X-ray emission displays similar characteristics. Where it can be established, the spectrum of the X-rays is of an exponential shape, favoring a thermal emission process.

Rich clusters and the giant galaxies that inhabit their central regions are coming to the forefront of astronomical research. One can cite the following examples of new information regarding these objects; the detailed study of the kinematics of cluster galaxies which indicates the reality of the "missing" mass, the continuing failure to find optical evidence for intergalactic gas, the discovery of extended regions of low frequency radio emission, the occurrence of radio trails, the occurrence of optical "halos" around specific galaxies.

The X-ray emission may provide the catalyst to tie together these diverse observations. As an example, the following credible model can be advanced. The X-ray emission originates when an active galaxy explodes in the central region of a cluster, releasing a vast amount of energy in the form of cosmic rays. These cosmic rays heat the intergalactic gas by a magnetohydrodynamic process and produce the X-ray emitting plasma. The X-ray emission persists long after the activity in the parent galaxy dies away. Whether or not this is the correct picture, we are for the first time "seeing" the intergalactic medium, and it is proving to be as complex as the interstellar medium.

- X-Ray Galaxies — At least half the extragalactic X-ray sources cannot be credibly identified with known external galaxies. In a few cases, the brightest galaxy or blue star present in the field is of  $16\text{-}17^m$ , leading to the hypothesis of the existence of X-ray galaxies; i. e., a class of galaxies in which the X-ray power exceeds the optical power by at least a factor of ten. In order that the cumulative flux of these objects does not exceed the observed diffuse X-ray background, the nearest of these objects must be at least 100 Mpc distant. The comparison to the weak unidentified radio sources found during early radio surveys is inevitable.

Soft X-Ray Astronomy — Traditionally, X-ray astronomy lies in the domain 1-20 keV; indeed, the bulk of the information on which the above picture emerges originates in this energy range. Below 1 keV the picture of the X-ray sky changes radically, and nature has yielded up its secrets only grudgingly. Only the old supernova remnants (Cygnus Loop, Vela) stand out clearly as soft X-ray sources; otherwise, there are few, if any sources, seen below 1 keV which are not also known to exist above 1 keV. Overall, an intense background of soft radiation is seen that has a substantial galactic origin.

Features, such as the North Polar Spur and excess point-to-point fluctuations, are beginning to show through. However, it is not clear whether this background is a superposition of weak, point sources or a truly diffuse emission. Also, it is not yet known what fraction of this soft background is extragalactic. In this energy range, we observe interstellar absorption and it is likely that the emission will be dominated by spectral lines.

Soft X-ray astronomy is still in an exploratory stage, but promises to provide tools for the study of several critical astronomical problems. Examples of these tools are the study of the interstellar medium, and of the coronae of late type stars by the direct observation of their XUV emission. In addition, new classes of objects, such as defunct pulsars or white dwarfs which by accretion of interstellar material become XUV sources, have been predicted. If these sources are found, they will have important implications for such studies as the dynamics of the interstellar medium. The prospects for soft X-ray astronomy have been greatly enhanced by the realization that the interstellar medium is highly inhomogeneous, with dense clouds of relatively low volume contained by low density H II regions. The density of the interstellar medium may be as low as 0.1 hydrogen atom per cubic centimeter ( $N_H \sim 0.1\text{ cm}^{-3}$ ), in selected directions in the sky, rather than the typically larger values derived from 21 cm studies. This means that for a significant volume of the galaxy containing large numbers of stars, observations can be extended to 100 Å and beyond.

The Diffuse Background — Because of its isotropy, the diffuse background above 1 keV is clearly extragalactic. However, the discovery of increasing numbers of discrete extragalactic sources makes it likely that a significant fraction of this background, if not all of it, must represent the superposition of more distant unresolved sources.

### Observational Objectives

There are two kinds of observational objectives in X-ray astronomy. One simply relates to completeness within the field; it can be characterized as an attempt to describe as completely as is feasible, the contents of the sky in X-rays. The second one relates to providing information on specific problems in astronomy, cosmology, galactic evolution and structure, stellar evolution, etc. X-ray astronomy has advanced to the point that both kinds of objectives can be described with some definiteness.

High Sensitivity Surveys — The present limit of surveys is  $10^{-4}$  Sco X-1. It is necessary ultimately to extend this to about  $10^{-8}$  Sco X-1 in order to detect X-ray emitting galaxies in the farthest reaches of the Universe, discrete sources in galaxies to at least 10 Mpc, X-ray emission from ordinary stellar coronas, and mapping of the diffuse background on a fine scale. The survey range can be divided into three energy ranges; 0.2 - 2 keV, 2 - 20 keV and 20 - 200 keV. In at least one of these energy ranges, the surveys must have the following capability:

- Location precision of point source to 1 arc second.
- Angular resolution of extended sources to several arc seconds.
- Broad-band spectral information ( $\lambda/\Delta\lambda \sim 1 - 5$ ) over the entire range.

High Resolution Spectroscopy of Selected Sources — The observation of X-ray emission lines and absorption edges is one of the few unambiguous means we have for identifying the physical process generating the X-ray emission and the conditions within the emitting region. The sensitivity must be sufficient to obtain data on a representative sample of X-ray sources.

Polarimetry of Selected Sources — Polarized emission is expected when the synchrotron process operates. A positive measurement of polarization would not only be a positive indicator of the synchrotron process (although a small

degree of polarization can be produced by other means) but it would also lead to information on the direction of certain axes within the source.

Study of Time Variability — There are a number of different time domains which need to be investigated.

- Short Periodic Variability — Periodic components of the emission in the range 1 ms to several seconds are expected based on our present knowledge of pulsars and pulsating X-ray sources.
- Short Aperiodic Variability — Certain sources exhibit erratic fluctuations on a short time scale which is important to study. It may be necessary to make measurements in the microsecond range which is the typical rotation period around collapsed stars.
- Eclipse Phenomena — Binary periods are now seen between 5 hours and 7 days. More realistically one must be prepared to search for periodicities down to the shortest known binary periods which are about 15 minutes. The time scale within which the actual eclipse may be is in the second time range, which falls under the purview of short aperiodic variability.
- Long Term Variability — Certain objects, such as supernovae may undergo secular changes in intensity which should be studied in X-rays. Active galaxies also need to be examined for X-ray variability down to the level at which optical variations are now reported. It is quite possible that in these cases the X-ray variability is substantially greater than the optical or radio variability.

The above are all objectives relating to the field in general; the following are topic-oriented objectives that can be identified at this time.

Stellar Structure and Evolution — There is now convincing evidence that many of the galactic X-ray sources are binary systems in which one member is a collapsed star — either a neutron star or a black hole. There are two aspects of the study of these systems. One has to do with the evolution of stars in close binary systems. Because of the possibility of the transfer of large amounts of mass from one member to the other, the evolution of stars in binary systems proceeds very differently than it does for single stars. The other aspect has to do with the physics of neutron stars and black holes. These objects, particularly when they occur in binary systems may yield vast amounts of new

information on the physics of nuclear matter and of highly compressed matter. Furthermore, we have the possibility of examining for the first time dynamical properties in a very intense gravitational field — one in which general relativistic effects predominate. Thus, black holes are the equivalent for general relativity what very energetic particles are for special relativity.

The importance of X-ray observations to studies of stellar structure is not limited to observation of objects which are primarily X-ray emitters. The coronae and chromospheres of main sequence and giant late type stars should be observable with X-ray telescopes. This will allow the detailed study of stellar atmospheres in a broad range of stars in the depth which has been previously limited to the sun. Spectroscopic studies, using crystal spectrometers and grating spectrometers at the focus of the telescopes will be of great importance to these observations. These observations will allow the great advances in our understanding of stellar atmospheres, brought about by X-ray and XUV observations of the sun, to be extended to other types of main sequence stars, as well as to peculiar stars such as flare stars.

Large Scale Galactic Structure — There are a number of X-ray observations which bear directly on the properties of galaxies on a large scale. These include the development of supernova remnants and how they transfer energy and matter to the interstellar medium, the density and atomic composition of the interstellar medium, and the structure and distribution of "clouds" of interstellar material. Furthermore, we know of the existence of an intense background of soft X-rays of galactic origin which must have a bearing on galactic structure if it is truly diffuse.

X-ray observations provide unique capabilities for studying the interstellar medium — its gaseous content and state of ionization and the interstellar grains. The column density of elements such as oxygen, neon, sulfur and iron are directly measured by observation of the appropriate K-shell absorption edges and detailed study of the structure of the edge can actually reveal the state of ionization of the gas. The grains have two effects on the X-rays. For one, small angle scattering occurs which will result in a strongly energy dependent "halo" around point sources and for another, the X-rays will be absorbed in the grains. The latter effect may provide the only direct evidence for the atomic composition of the grains.

Ultimately, these observations can be applied to external galaxies. When looking at very soft X-rays, it is not possible to see more than a few hundred parsecs within the Milky Way thus giving us only a restricted view of our own Galaxy. Looking at external galaxies near the galactic poles, we have the possibility of mapping the entire galaxy in soft X-rays.

Nature of Active Galaxies — The study of the spatial distribution, spectral characteristics and time variations of the X-ray emission from the nuclear regions of galaxies could yield the key to understanding the fundamental processes that give rise to the enormous production of energy going on there. In addition, the inverse Compton reaction between cosmic rays and the microwave background will allow the more definitive studies of the extended radio regions associated with these objects. Tracking these objects backward in time should allow the study of the evolution of active galaxies.

Rich Clusters of Galaxies — Extended X-ray emission regions in rich clusters of galaxies are likely to be a manifestation of a complex intracluster medium. It is necessary that the structure of the regions and their relationship to other features of clusters such as extended low frequency radio emission, radio "trails", and the presence of active galaxies be studied. It may also be possible to study the evolution of these emission regions and of clusters in general by studying very distant members of this class of objects.

Cosmology — The very first published journal article commenting on the significance of the initial observation of cosmic X-rays in 1962 dealt with a question of cosmology. Professor Hoyle noted that the "hot" steady-state universe predicted a much larger flux of background X-rays than was actually observed. A number of observations provide relevant data on cosmology. First, there is the study of galaxies and clusters of galaxies in the very distant past which could reveal density gradations in time. Secondly, there is the study of diffuse background. Thus, radiation must originate in the remote past; however, it is possible that what we are presently seeing results from known sources. It is equally possible that the radiation originates in a different class of sources or is truly diffuse. In either case, it is a probe into a region of redshift  $>3$  and can provide us with data on the nature and structure of the cosmos on this very large scale. It must also be kept in mind that the study of black holes, since it involves directly the general theory of relativity, may have a bearing on cosmological research.

If there is any significant quantity of neutral intergalactic matter, it should be revealed by absorption effects in the X-ray emission from distant galaxies. Also, it is possible that by looking "through" cluster X-ray sources, cluster structure may be revealed. Such problems as the "missing" mass, the primordial He/H and the origin and evolution of clusters of galaxies could be elucidated by such studies.

## HARD X-RAY AND GAMMA-RAY ASTRONOMY

### Introduction

Gamma-ray astronomy provides information which can be obtained in no other way on fundamental interactions on an astrophysical scale. Optical astronomy may be thought of as originating from effects on the outer electrons of atoms and X-rays from electrons interacting deep within the atom. Low energy  $\gamma$ -rays are produced by processes involving the structure of the nucleus; higher energy  $\gamma$ -rays originate from the structure of the nucleons themselves. Thus  $\gamma$ -ray astronomy uniquely measures effects due to processes which involve energetic nucleons. The hard X-ray sky appears quite different from the low energy X-ray sky. An intensive effort during the Shuttle era to determine the origin and spectra of hard X-ray and  $\gamma$ -ray fluxes will set the stage for discoveries which may well parallel the remarkable advances made by Uhuru in recent years.

Broad astrophysical problems include studying the distributions of high-energy nuclei (cosmic-rays) in the universe, which may indicate acceleration, transport, and loss processes quite different from those of the electrons which produce radio waves and low energy X-rays. Extension of the spectra and time variation of X-ray sources into the 100 keV range provides data contributing uniquely to understanding the physics of the source regions. Further extension into the MeV range brings us into the realm of nuclear activities and particle populations which may have energies intermediate between cosmic rays and those producing X-rays. The diffuse component, which spans the range of X- and  $\gamma$ -ray observations, undoubtedly has profound cosmological significance. Detection of discrete  $\gamma$ -rays from excited nuclei will put nuclear astrophysics on an observational basis, and will do for high-energy astronomy what optical spectroscopy has done for stellar evolution.

High energy  $\gamma$ -rays probe directly the size and flux-density product of the emitting region. Once produced,  $\gamma$ -rays pass undeflected through the galactic and intergalactic magnetic fields and reach the earth from any distance, since the absorption of gamma rays becomes important only at very high ( $E \geq 10^{15}$  eV) energies or in unusually dense regions. Gamma-rays of cosmological origin therefore transverse the entire universe, and their observation provides answers to cosmological questions. For example, if antimatter has annihilated matter in sufficiently large quantities during the history of the universe, the resulting  $\gamma$ -rays should still be observable, unless the redshift has been too extreme.

Processes may exist in the universe that are observable only through the  $\gamma$ -ray window, a prime example being the decay of radioactive nuclei which may be produced during explosive nucleosynthesis. Certain theories on supernova also predict that a flash of  $\gamma$ -rays in the GeV range is produced during the explosion, and the observation of these would be a decisive argument for or against certain mechanisms of the supernova process.

Finally, with respect to high energy physical processes, it should be pointed out that up to about 1950, when large particle accelerators became accessible, essentially all the new particles were discovered in the cosmic rays. Indeed, even at the present time, the basic elementary particles remain those that were found in the cosmic rays. From accelerators we can expect energies up to about  $10^{12}$  eV in the next decade. On the other hand, cosmic ray energies extend up to  $10^{20}$  eV. Although the flux at these high energies is exceedingly small, the long observation times made available by space platforms may allow observation in this extreme energy range. For this reason, space-operated laboratories may yet offer an opportunity, through the detection of high energy gamma ray lines, for the discovery of elementary particles more basic than those we now know.

### Objectives and Rationale

In this section we indicate the rationale and scientific objectives for the developing field of  $\gamma$ -ray astronomy as well as its relation to other areas of high energy astrophysics. It is somewhat difficult to give coherence to this many-faceted area, since  $\gamma$ -ray phenomena originate in a variety of source regions, such as discrete and diffuse sources on both galactic and extragalactic scales. Gamma rays may also be characterized by the type of emission such as continuum or discrete (monochromatic) spectra. Finally, the observations may be distinguished by the energy range; hard X-ray (10-300 keV), low-energy  $\gamma$ -ray (0.3-20 MeV) or higher energy  $\gamma$ -rays ( $> 20$  MeV). In each range the interaction phenomena and therefore detection techniques differ. Since any attempt at classification may be somewhat artificial we have used an organization which preserves scientific coherence.

10-300 keV Continuum — The most direct information bearing on the emission mechanisms and ultimately the nature of celestial X-ray sources lies in the shape and variability of their total energy spectra. Indeed, one of the most spectacular astronomical discoveries of modern times, the close binary neutron star-pulsar system in Hercules, is based on the interpretation of the temporal properties of the low energy X-ray emission. Although additional examples have

been found, the story is far from complete since little is known of the details of the spectral behavior of these objects. In the specific case of Hercules X-1, theoreticians had predicted and were quick to interpret the observations as indicative of a close binary system with accretion on a compact object, probably a neutron star, providing the energy source. A simple model predicts that X-ray emission will occur from the region on the secondary object heated by the infalling matter. Observations in the hard X-ray range preclude such a simple interpretation, since the spectrum is now known to be complex and not compatible with a simple isothermal source. More complex theories suggest that the spectra will be governed by such factors as the detailed dynamics of the accretion process, absorption clouds, magnetic fields and even the inclination at which we observe the source. Thus, to model the sources realistically it is important to study the instantaneous total spectrum and its variability for this new class of astronomical objects.

Unfortunately, the majority of known X-ray sources do not exhibit time structures amenable to simple interpretation. Sco X-1 and Cyg X-2, for example, have been extensively observed in hopes of discovering evidence of binary motion. Progress in understanding these and other objects such as the "X-ray galaxies" discovered by Uhuru will clearly depend on more precise wide band X-ray spectra and correlations with observations in other spectral regions.

Certain X-ray sources, the Crab nebula being a notable example, radiate most of their energy at hard X-ray wavelengths. Such "hard X-ray sources" require efficient acceleration mechanisms operating at extremely high energies to create ultra-relativistic particles. The nature of these mechanisms is speculative at present, however, in the case of the Crab nebula, the intense magnetic field associated with a rotating neutron star may be the region of particle acceleration.

Finally, study of the angular size, structure and polarization of certain objects at hard X-ray energies may be most fruitful. The total Crab nebula spectrum, for example, is due to a combination of emissions from the central pulsar and an extensive nebular region. A measurement of the angular structure and polarization of these two hard X-ray components would yield a wealth of information bearing on the relativistic electron and magnetic field distributions and particle diffusion from the nebula. Other interesting objects include the extended extragalactic sources such as the Perseus and Virgo clusters.

Thus, just as optical photometry would be severely handicapped were there only a single photometric band available for observation, interpretation of X-ray measurements in a narrow energy range has definite limitations. Observational programs should be structured to allow access to the widest possible energy range if the maximum return is to be realized in understanding the nature of celestial X-ray sources.

0.3 - 20 MeV Continuum  $\gamma$ -Rays — The original predictions for  $\gamma$ -ray astronomy in 1958 indicated large intensities in this energy range due to such processes as positron-electron annihilation, deuteron formation, non-thermal electron bremsstrahlung, and radioactivity in supernova remnants. Although fluxes from several cosmic sources and the sun have been measured, the intensity has been less than the most optimistic predictions, and the emission mechanisms different, although more spectacular.

Two basic observational possibilities in the MeV  $\gamma$ -ray regime are extension of the spectra of known X-ray emitters, and observation of various theoretically possible objects that radiate most of their energy at very short wavelengths and thus may be characterized as  $\gamma$ -ray sources. Unique information is contained in the spectral signature of an object at higher energies. Whereas X-ray astronomy is concerned with quasi-thermal mechanisms operating at very high temperatures in special configurations of stellar objects, observations in the MeV range relate to manifestly non-thermal effects such as the scattering of ultra-relativistic electrons on magnetic and low energy photon radiation fields. A consistent picture of the MeV-range  $\gamma$ -ray emission mechanisms of an object will in turn lead to a framework for understanding the violent processes which generate energetic particles on astrophysical scales.

The variety of objects amenable to study are large. At least one class of pulsars, such as NP 0532 in the Crab nebula, apparently converts rotational kinetic energy into ultra-relativistic electrons and ultimately to  $\gamma$ -ray emissions with a remarkable efficiency. The active region in our own galactic center has been shown to emit very high energy  $\gamma$ -rays, a measurement which couples cosmic ray production and the matter density of the interstellar medium. As a final example, we expect at some sensitivity level to detect discrete extragalactic sources of gamma rays if they in fact contribute to the diffuse component. In this case it is important to study the stronger local sources if we are to extend our knowledge to apply to distant weak objects at earlier epochs of the universe.

Nuclear  $\gamma$ -Ray Spectroscopy — Emission line spectroscopy will undoubtedly be as significant to gamma ray astronomy as it has been to astronomical research in the optical and radio regions. In this area experimental work has been far outpaced by theoretical nuclear astrophysics. Recently, however,  $\gamma$ -ray line emission during solar flares has been measured, and an indication of a monochromatic 0.47 MeV  $\gamma$ -ray from the galactic center has been obtained. Exploration of these possibilities cannot fail to indicate new phenomena for energetic particles.

Supernova and blast nucleosynthesis theories have been especially fruitful in posing questions to be answered by nuclear gamma ray spectroscopy. Several researchers have suggested that the exponentially decaying light curve of the type I supernova is related to the radioactive decay of isotopes synthesized in the explosion either by the r-process or by silicon-burning. Either process will leave quantities of radioactive materials in the debris and determination of the presence and constituency of these materials could decide between the mechanisms.

In addition to the residual radiation, prompt nuclear emissions from interactions taking place during the explosion could yield information about the supernova interactions themselves.

Prompt and secondary nuclear emissions from extragalactic supernova explosions should also be a significant component of the diffuse cosmic gamma ray background. Since radiation at early epochs will be redshifted, one should see a line profile whose shape is a historical record of the rate of nucleosynthesis in the universe.

Old neutron stars, which should far outnumber active pulsars, will accrete either interstellar matter or matter from a companion star. This infalling matter will produce nuclear reactions in the surface material. Resultant nuclear gamma rays could give valuable information concerning the surface composition and other physical characteristics of the neutron star.

Positrons are produced in the galaxy by pion decays as well as by radioactive decays of unstable carbon, nitrogen and oxygen produced by low energy interactions in the cosmic ray beam. The positrons resulting from the latter process are of energies below about 1 MeV and thus have a greater likelihood of annihilating within the galaxy to produce 0.51 MeV gamma rays. The expected flux of these gamma rays as a function of galactic coordinates has been recently calculated and the detection of these emissions would provide information on the distribution of matter and cosmic rays in the galaxy.

The most exciting recent development has been the discovery by the OSO-7 of nuclear  $\gamma$ -rays at 0.51, 2.2, 4.4, and possibly even 6.12 MeV during intense solar flares due to accelerated protons interacting in the solar atmosphere or its surface. Similar emissions may be expected from objects which exhibit flaring phenomena many orders of magnitude more energetic than that of the sun. These observations herald a major breakthrough and are bringing nuclear  $\gamma$ -ray spectroscopy into a non-speculative realm.

The above examples, while by no means exhaustive, give some indication of the important and intriguing questions which may be answered by the observation of gamma ray line emissions. To achieve sensitivities adequate to make such observations requires the application of recent low energy gamma ray detection techniques to space astronomy.

Diffuse Cosmic Component — The discovery that the entire sky has a uniformly bright background at X-ray and  $\gamma$ -ray energies must certainly rank as one of the most unexpected discoveries of space astronomy. Point sources such as stars, nebulae, and extragalactic emitters, must be measured against this diffuse background. With the exception of the  $3^\circ\text{K}$  radiation measured at millimeter wavelengths (to which these  $\gamma$ -rays seem certainly coupled) no comparable phenomena exists in any other region of the electromagnetic spectrum.

The first measurement of cosmic  $\gamma$ -rays, obtained on the Ranger III in 1962, was in fact soon associated with the diffuse X-ray flux already detected in the early rocket flights, and with a flux at 100 MeV detected on Explorer XI. Since then, spectral measurements have been expanded over the entire X- and  $\gamma$ -ray range and limits on its anisotropy of about 1% at 10 keV have been determined. Because of its extragalactic or cosmological origin, no other X-ray or gamma-ray data set has been as controversial, or has resulted in as much theoretical speculation. It has even been suggested that the  $\gamma$ -rays were produced at 100 MeV when the universe was 1/50 its present age ( $Z = 50$ ) from  $\pi^0$  meson decays, and have now become redshifted to a few MeV!

There are apparently several contributions to the diffuse spectrum. If the uniformly isotropic flux in the 1-20 keV range in fact has a thermal spectrum, it may originate from a hot intergalactic ( $\sim 10^8$  K) medium. Although this explanation was earlier ruled out on density arguments, the recent reduction of the Hubble constant to  $\sim 50$  Km/sec/Mpc has now made this possibility tenable. It may also be that the lower energy part of this spectrum is due to the superposition of many extragalactic sources. Only measurements of the flux and spectrum of additional weak extragalactic sources in the 1-20 keV range can settle this issue.

There is clearly another component which extends as a power law from about 10 keV to well beyond several MeV and most likely even to 100 MeV. This has been suggested as being due to 1 GeV electrons leaking from galaxies into the intergalactic medium and Compton scattering on the  $3^\circ\text{K}$  radiation left over from the primordial fireball, based on a "big-bang" model of the expanding universe. Bends and inflections in the spectrum are associated with the electron distributions and lifetimes in radio galaxies. Finally, there appears to be an excess in

the 1-10 MeV range over the power law interpolated from the  $\sim 0.1$  MeV and 100 MeV observations. This has been suggested as due to nuclear  $\gamma$ -rays emitting from many extragalactic supernovae, redshifted  $\pi^0$  decay  $\gamma$ -rays produced at an earlier, high density, epoch of the expanding universe, or  $\gamma$ -rays from matter/anti-matter annihilation in a baryon-symmetric big-bang cosmology. Definition of these components can only be accomplished with better spectra and isotropy measurements. The resolution of their origin will clearly be of considerable significance to observational cosmology.

High Energy Galactic Gamma Rays — Within our own Galaxy, high energy gamma rays measure directly the presence of energetic protons within discrete sources and in the Galaxy as a whole through the broadly peaked, but distinctive spectrum of gamma rays produced by the high energy nucleons interacting with other nucleons. In this way, the cosmic ray distribution throughout the Galaxy may be studied as well as the high energy particle gas surrounding the individual objects from which cosmic rays originate.

Considering first the diffuse radiation from the galactic plane, the knowledge of the detailed angular distribution of the diffuse gamma rays may be combined with the data on the galactic material obtained from radio astronomy data to provide a detailed picture of the distribution of cosmic rays in our Galaxy. This information provides the basis for the first careful study of the dynamics of the galactic plane.

In this disk, the expansive pressures of the hot cosmic ray gas, the magnetic fields and the kinetic motion of matter are counter balanced only by the gravitational attraction of galactic matter. Of these three expansive pressures, that due to the cosmic rays is the only one which seems likely to have the capability of changing markedly over short periods (less than  $10^4$  years). Since the expansive pressures are thought to be nearly equal, local variations and changes on a broader scale are likely to be driven primarily by the high energy cosmic ray gas pressure.

Consider, for example, the sudden release of a large number of cosmic rays from a source, such as a supernova. The cosmic rays will expand relatively quickly until their energy density falls to the ambient level. The enhanced cosmic ray flux in the general vicinity of the supernova, or other cosmic ray source, will then lead to an increased intensity of gamma rays from the vicinity of the supernova as the cosmic rays interact with the interstellar matter. In addition, the magnetic "bubbles" associated with supernova bursts may carry enough cosmic rays into the halo and may produce a detectable gamma ray flux even in the low density halo region, if the magnetic fields are strong enough to contain the cosmic rays.

It also now seems that the magnetic field of the disk is quite irregular, perhaps being substantially higher in the regions of higher density, and that the cosmic ray gas may also therefore be very non-uniform. A fine angular resolution map of the galactic disk in gamma rays can reveal the detailed distribution of the cosmic rays, and hence provide insight into the density regularity of our Galaxy which speaks directly to theories of matter concentration for star formation.

To illustrate how the gamma-ray information will be characteristically new, one may consider the production of cosmic rays in individual sources. For cosmic ray electrons, these sources have been shown to exist through the observation of the non-thermal radio sources, and the pulsars. Cosmic ray protons produce no other observable signal but gamma rays, and thus their sources have as yet not been established. Yet protons are expected to behave significantly different from electrons. For example, in the Crab nebula, its emissivity in all wave-length bands can be understood by the present production rate of high energy electrons, these electrons having a very short lifetime. If protons have been produced in the Crab, they will not have lost a significant amount of energy since production, and will thus indicate the total energy content in protons that was produced during the entire life of the Crab. Also, it is well known that protons cannot be produced at the Crab in the proton-electron ratio of 100:1 as observed near earth. The question of the location of the sources of protons remains unanswered.

Extragalactic and Cosmological Gamma Rays — The gamma radiation produced in proton-proton collisions is proportional to both the intensity of energetic cosmic rays and the hydrogen density in the source region. Since both energetic particles and matter exist in extragalactic space, gamma radiation should be produced throughout the universe. Even though the source volume is immense, the metagalactic hydrogen density is small, possibly  $10^{-5}$  to  $10^{-6}$  that of the galaxy, and the cosmic ray intensity, from the standpoint of total energy, is probably considerably less than inside the galaxy. On the basis of these simple considerations the metagalactic gamma ray intensity might be expected to be extremely low, and hence undetectable. There are additional features of the extragalactic radiation which make its observation a most important probe into the early stages of the universe.

In an expanding model of the universe, the density of matter is much greater in the cosmological past than is observed at the present epoch. Since the gamma radiation produced at early epochs reaches us from large distances, the energy of the photons is degraded by the cosmological redshift caused by the expansion of the universe. These gamma rays would then have a unique energy spectrum whose peak would be shifted downward from the usual  $\pi^0$  gamma ray peak. This

flux may have already been observed in the diffuse component, and gamma ray astronomy therefore provides information of cosmological significance.

Observations indicate that supernovae are among the most energetic discrete sources in our Galaxy and in other normal galaxies, having estimated total energy outputs of  $10^{49}$  to  $10^{62}$  ergs. Several theories have been propounded to explain supernova development. In the hydromagnetic theory the deposition of the neutrino energy in the outer layers of the star gives rise to a radially outgoing shock wave. As the shock wave propagates to the surface it ultimately reaches a point where the remaining material thickness is less than a photon mean free path and the photons escape. The photons emitted from the moving surface layer will have a very high energy ( $10^2$  to above  $10^3$  MeV) and will be very close together in time (tens of nanoseconds). The prediction of these very energetic pulses is unique to this theory and the determination of whether such pulses exist is crucial for the study of supernovae.

In addition, our own Galaxy is known to be relatively quiet, as compared to the activity that has been observed to occur in other galaxies. One may expect that entirely different situations concerning the high energy particles and the gas may exist in other galaxies, and indeed these may not be in stable equilibrium. Gamma ray observations of extragalactic systems are thus highly interesting.

Finally, it is worth noting that as radio and X-ray astronomy began to explore the sky, there were many unexpected discoveries; in fact, it is not unfair to say that these fields are dominated by the unexpected. As the sensitivity of gamma ray astronomy reaches the level to permit true gamma ray astronomy surveys, it is not unreasonable to suppose that similar surprises may await us, especially since we know even less about the nucleonic processes in our Universe than we do about thermal and electron processes.

### Status and Development

#### 10 keV - 20 MeV

- Present Status — Hard X-rays and  $\gamma$ -rays from cosmic sources in this range are accessible to both high-flying balloons and satellites. Background problems are particularly severe near 1 MeV, where detection technique is also difficult. Table 1 indicates space missions carrying instruments which have contributed importantly to the development of hard X-ray and  $\gamma$ -ray astronomy. The most recent results have come from the OSO-7 and SAS-B.

Table 1

Satellite Missions Which Have Important  $\gamma$ -Ray Experiments

Pre-Shuttle Era			
MISSION	LAUNCH DATE	INSTRUMENT	RESULTS
Ranger III	26 Jan. 1962	70 keV - 3 MeV Isotropic Scintillation Counter	Discovered diffuse $\gamma$ -rays to 1 MeV
Exp. XI	27 Apr. 1961	100 MeV $\gamma$ -Ray Telescope	Limits to galactic and extra-galactic radiation
OSO-I	7 Mar. 1962	50 keV - 3 MeV Scin. Counter, Compton Tel.	Upper limits; Solar X-ray bursts
		50 MeV $\gamma$ -Ray Telescope	Upper limits
OSO-II	3 Feb. 1965	50 keV - 2 MeV Actively Shielded Scin. Counter	Upper limits
		100 MeV $\gamma$ -Ray Telescope	Upper limits
OSO-III	8 Mar. 1967	7 - 190 keV X-ray Telescope	Spectrum & Isotropy of diffuse X-rays; hard solar X-ray bursts; limits on diffuse galactic emission
		100 MeV $\gamma$ -Ray Telescope	Discovered diffuse galactic and extragalactic emissions

Table 1 (Continued)

MISSION	LAUNCH DATE	INSTRUMENT	RESULTS
ERS-17 ERS-18	26 July 1965 28 April 1967	Isotropic Scin. Counters 25 keV - 10 MeV	Measured spectrum of diffuse cosmic $\gamma$ -rays to 6 MeV
OSO-7	29 Sept. 1971	7 - 550 keV X-ray Telescope	Extended spectrum of Uhuru sources; binary X-ray sources; diffuse galactic and extragal. spectra
		50 keV - 10 MeV Scin. Counter	Discovered nuclear X-ray lines during intense solar flares
TD-1	12 Mar. 1972	> 20 MeV Spark Chamber	
SAS-B	16 Nov. 1972	High Energy $\gamma$ -Ray Spark Chamber (Sens $\sim 5 \times 10^{-7}$ ph/cm <sup>2</sup> -sec)	Operating well
OSO-I	1974	0.1 to 1 MeV Shielded CsI(Na) Detector Energy Spectra of Sources Greater Than $10^{-6}$ Photons/cm sec keV	
COS-B	1975	> 20 MeV $\gamma$ -Ray Spark Chamber (Sens $\sim 6 \times 10^{-7}$ ph/cm <sup>2</sup> -sec)	
HEAO-A'	1977	10 - 300 keV Scanning X-ray Telescope	
		0.3 - 10 MeV Diffuse and Point Source Telescopes	

Table 1 (Continued)

MISSION	LAUNCH DATE	INSTRUMENT	RESULTS
HEAO-C'	1979	50 keV - 10 MeV Collimated Ge(Li) Detector for Nuclear $\gamma$ -Ray Spectroscopy (Sens $\sim 4 \times 10^{-5}$ ph/cm <sup>2</sup> -sec)	
		> 50 MeV $\gamma$ -Ray Spark Chamber with Total Absorption Scin. Counter (Sens $\sim 3 \times 10^{-8}$ ph/cm <sup>2</sup> -sec)	

- a. About 25 of the galactic sources listed in the Uhuru catalog have been measured at energies  $> 20$  keV. In only a few cases is the spectrum interpretable in terms of a simple hot gas or a power law distribution of relativistic electrons. Time variations on all scales have been observed, from the 33 ms pulsed component of NP0532 to long term random secular changes of Cyg X-1.
  - b. Only a few extragalactic sources, notably Cen A, M-87, and possibly the Perseus cluster have been detected  $\geq 20$  keV, and no definitive spectral measurements have been reported.
  - c. Only the Crab nebula and the galactic center have been definitely measured in the 0.3 - 1.0 MeV range. The spectrum of NP0532 has been extended to at least several MeV.
  - d. Nuclear  $\gamma$ -rays have been observed during solar flares, and a line at 0.47 keV has been reported from the galactic center. Upper limits of about  $10^{-3}$  photons/cm<sup>2</sup>-sec exist for lines due to possible heavy-element radioactivity in the Crab nebula.
  - e. The diffuse component has been determined to have a complex spectrum extending from 1 keV to 30 MeV. Apparently several components are required to explain this spectrum. Although measurements above about 1 MeV have only been made with omni-directional counters, the isotropy is known to be better than  $\sim 1\%$  at  $\sim 10$  keV.
- ⑥ Planned — During the next few years, there will be considerable activity with balloons. Larger area, more sensitive detectors with sophisticated pointing systems operating in the 20 - 200 keV range will have a sensitivity such that strong extragalactic sources can definitely be observed. Some work toward measuring angular structures in hard X-rays to about  $0.1 \text{ min}$  using modulating collimators on balloon-borne instruments will be attempted. Directional detectors using massive active or semi-active collimators will extend the spectrum of hard galactic sources into the MeV range. Cooled solid-state systems of even larger area will attain a sensitivity of  $\sim 2 \times 10^{-4}$  photons/cm<sup>2</sup>-sec. Development of shielding and collimation techniques, liquid xenon proportional centers, and Compton telescopes will continue. Several space missions are planned:
- a. OSO-I (eye) (1975) will carry a 15 - 300 keV scintillation counter telescope with an active collimator looking along the spin axis.

- b. HEAO-A' (1977) is planned to have a  $\gamma$ -ray telescope complex with modules operating over the 10 - 300 keV and 0.3 - several MeV ranges, designed to observe discrete and diffuse sources. Sensitivity will be about  $10^{-6}$  photons/cm<sup>2</sup>-sec-MeV at 1 MeV, or about 1/20 of the extrapolated Crab nebula spectrum.
- c. HEAO-C' (1979) has under consideration a large area Ge(Li) detection system with  $\sim 50$  cm<sup>2</sup> and a sensitivity of  $\sim 4 \times 10^{-5}$  photons/cm<sup>2</sup>-sec in the 0.05-10 MeV range.
- Shuttle Era — The instruments proposed for the shuttle period are designed to provide increased sensitivity in an orderly manner, and assume the HEAO-A' and C' experiments are implemented.

### Greater Than 20 Mev

- Present Status — Up to the present time, celestial  $\gamma$ -rays  $> 20$  MeV have been observed with satellites and balloon experiments. Balloon experiments are made difficult by the high rate of  $\gamma$ -rays produced by cosmic rays in the upper layers of the atmosphere. For example, the galactic disk provides a matter column density of about  $6 \times 10^{-2}$  g/cm<sup>2</sup> while the highest balloon flights reach altitudes where the amount of overlying atmosphere is 1 to 2 g/cm<sup>2</sup>. Balloon investigations are thus restricted to the observations of features of high emissivity.

Most of the information presently available comes from the  $\gamma$ -ray experiment flown in 1967 on board OSO-III. This experiment provided information with limited angular resolution ( $\Delta\theta \sim 15^\circ$ ) and very limited spectral resolution. The scientific yield of this experiment can briefly be summarized as follows:

- a. The galactic disk, in contrast to the observations of diffuse emission on the X-ray region, shows a strongly enhanced emissivity in  $\gamma$ -rays.
- b. The variation of  $\gamma$ -ray intensity from the galactic disk as a function of galactic longitude is far larger than can be accounted for by the variation of the matter columnar density.
- c. A weak and, within the observational limits, isotropic extragalactic gamma ray flux exists.

The effective geometrical factor of the OSO-III instrument  $G$  ( $\equiv$  Efficiency  $\times$  Area  $\times$  Solid Angle) was about  $1.3 \text{ cm}^2 \text{ sr}$ .

At the time of writing this paper, two  $\gamma$ -ray instruments of the next generation are in orbit. Both instruments employ spark chambers to record the ensuing electrons from the  $\gamma$ -ray to electron pair conversions. They have an angular resolution of  $\Delta\theta \sim 3^\circ$  at energies  $\sim 100 \text{ MeV}$ .

One is the S-133  $\gamma$ -ray experiment on board the European ESRO satellite TD-1 which was launched in March 1972. This instrument has an effective geometrical factor  $G$  of about  $7 \text{ cm}^2 \text{ sr}$ . It has only limited energy resolution like the OSO-III instrument.

The other one is the SAS-B experiment launched in November 1972 with a value of  $G = 33 \text{ cm}^2 \text{ sr}$ . The energy resolution of the latter instrument is somewhat better than that of the other instruments (using multiple scattering). The scientific results of both instruments will be published during this year.

- Planned — In early 1975, ESRO will launch its satellite COS-B which will carry a spark chamber  $\gamma$ -ray experiment. This experiment will also contain a CsI scintillation crystal with a depth of 4.7 rad. lengths to facilitate  $\gamma$ -ray energy measurements. The effective geometrical factor is  $G = 19 \text{ cm}^2 \text{ sr}$ . The angular resolution of this instrument is  $\Delta\theta \sim 3^\circ$ .

The COS-B satellite is spin-stabilized and has an X-ray experiment on board to facilitate pulsar timing. It will observe individual regions of the sky for long observation times in its eccentric orbit.

At the present time, the EGRET experiment originally on board the HEAO-B mission is still one of the payloads considered for the HEAO-C' mission. It has an effective geometrical factor of about  $320 \text{ cm}^2 \text{ sr}$ , an angular resolution  $\Delta\theta \sim 2^\circ$ , and goal energy resolution derived from a NaI-crystal of 10 rad. lengths thickness.

- Shuttle Era — The main thrust of gamma-ray astronomy in the Shuttle era depends on the following considerations.
  - a. What will be known by the end of the 1970's.
  - b. The general scientific goals of  $\gamma$ -ray astronomy.
  - c. The capability offered by the Shuttle.

## COSMIC RAY ASTRONOMY

### Introduction

The same high-energy processes which were responsible for the X-ray and  $\gamma$ -ray emissions described in the previous sections also produce high energy charged particles which are then trapped in the Galaxy for a lifetime of  $\sim 1$  million years by magnetic fields. The resulting energy density of cosmic rays,  $\sim 1$  eV/cc, is comparable with that of the containing magnetic fields, with starlight, and with kinetic motion of bulk matter. The cosmic rays themselves therefore are a major element of galactic structure. The study of high energy cosmic ray particles therefore plays a unique role in modern high-energy astrophysics. It complements and is complemented by radio, optical, X-ray, and  $\gamma$ -ray astronomy, and it has a direct bearing on a variety of basic astrophysical problems.

### Sources

Cosmic rays are associated with — and perhaps largely a product of — extreme non-equilibrium phenomena, sometimes explosive, such as the possible "big-bang" origin of the Universe, collapsing stars, and stellar explosions. In addition, they may well be emitted by white dwarfs and neutron stars with the latter perhaps responsible for acceleration up to the observed energies as high as  $10^{20}$  eV for single particles. Because of breakdown in magnetic containment at about  $10^{16}$  eV, very high energy cosmic rays are likely to be of extragalactic origin. Regarding supernovae and collapsed star formations as the source of cosmic rays, if some reasonable fraction of their lost energy ( $\sim 10\%$ ) were turned into cosmic rays, the leakage losses from the Galaxy would be replenished and we would explain the fact (determined from fossil tracks in meteors) that average cosmic ray fluxes have remained essentially constant through the last  $10^9$  years.

Of fundamental interest is the fact that cosmic-rays are direct material samples from outside the solar system, probably the only ones accessible for generations or perhaps ever. They provide crucial data on the origin of elements, nucleosynthesis, and the possible existence of non-terrestrial elements and quanta, not obtainable through any other kind of observations. For example, since there is a complete symmetry in photon emissions in comparing regions of matter and regions of anti-matter, observation of anti-matter complex nuclei in the cosmic rays may be the only way of establishing whether regions of bulk anti-matter exist in the Universe.

In the same manner as rock-samples from the moon are revolutionizing our understanding of Earth, Moon, and the origin of the solar system, the elemental abundances of galactic matter will provide data on the origin and nature of the most interesting stellar sources, where cosmic rays are believed to originate. These nuclei, which are observed near earth, will have been synthesized in stellar furnaces, then accelerated, ejected, stored, and propagated in the interstellar medium. While their history complicates the interpretation of source abundances, it is possible to separate these effects and in fact to derive a wealth of additional information. The determination of isotopic abundances will be of particular value, since the isotope source abundances of an element will remain essentially unaffected by acceleration and altered only in a known manner by spallation processes, while the production of secondary isotopes in collisions with interstellar gas can be reliably calculated. After corrections for these propagation effects, the resulting isotopic abundances of cosmic ray sources may be directly compared with predictions from nucleosynthesis theory. The physical environments under which nucleosynthesis takes place impart definite signatures to the isotopic abundances of the manufactured elements. In addition, the discovery of unique radio isotopes, which represent "nuclear clocks", can give direct evidence for presently ongoing nucleosynthesis in the galaxy.

### Interstellar Medium

Once the particles escape from the vicinity of the sources, they are deflected by the microgauss galactic magnetic fields, which both contain them within the Galaxy and erase virtually all memory of original direction. It is therefore generally not possible to distinguish individual sources in the cosmic rays. One sees rather a superposition of many sources in which the galactic cosmic rays are extremely isotropic upon reaching earth. Because of the containment process, cosmic-ray particles are major elements in the structure and dynamics of the galaxy. The thermal and dynamical state of the interstellar gas, the formation of clouds and stars from the interstellar gas, the structure of the gaseous disk and the galactic halo are dominated by cosmic rays and can be understood only on the basis of quantitative observations of cosmic ray charge, energy, and mass-spectra. The overabundance, compared to the "universal" abundance, of light elements (Li, Be, B) is commonly attributed to spallation of heavier nuclei with interstellar H and He. The validity of this conclusion can be checked by a direct comparison of measured isotope ratios with those predicted from detailed spallation processes, now being accurately and directly measured at heavy-ion accelerators. These considerations, at the same time, will determine the total mass of interstellar matter traversed by cosmic rays. Combined with cosmic ray lifetime measurements from radio isotopes with appropriate half-lives (e.g.  $^{10}\text{Be}$ ,  $^{54}\text{Mn}$ ,  $^{26}\text{Al}$ ) this mass number can be refined into an interstellar gas density distribution. Isotopes which decay under electron capture

(e.g.  $^{53}\text{Mn}$ ,  $^{41}\text{Ca}$ ,  $^7\text{Be}$ ) have an effective lifetime proportional to  $\tau_{1/2}$  and the ratio of stripping to pickup cross sections, and thus carry further information on the matter distribution near their source and on their time scale of acceleration.

Electrons and positrons occupy a unique position in cosmic rays because, in their passage through the intergalactic medium, they interact with the microwave background radiation, and their observed spectral behavior places constraints on the universality of this radiation. Also these particles are a source of radio waves through synchrotron radiation, and of X-rays, through the inverse Compton process. The interpretation of interstellar processes must take account of all of these measurements.

Some interesting recent measurements of elemental abundances have shown that the light elements (Li, Be, B) are significantly rarer (compared with carbon and oxygen) at  $\sim 100$  GV/c rigidity than they are at  $\sim 10$  GV/c. This has been interpreted either as a reduction in the galactic containment mechanism occurring at much lower rigidities than previously expected, or as an indication that an appreciable fraction of the matter traversed by the cosmic rays was in a small region immediately outside of the sources. The Space Shuttle provides long exposure times and eliminates large atmospheric corrections from the data. Both of these features are necessary for gathering the precise data required to make unambiguous interpretations of these vital astrophysical measurements.

### Scientific and Observational Objectives

Although the Shuttle will undoubtedly have a function in continued specific investigations and in monitoring activities of solar and interplanetary energetic-particle phenomena, its main impact will be in opening up the study of the high energy phenomena of stellar sources, the interstellar medium, and the intergalactic medium. Cosmic rays will be studied as material samples of these sources as well as probes in exploring the physical properties of the sources and of space (fields and matter).

It would be ill-advised, at this early stage, to narrowly and specifically define the experiments for shuttle-supported investigations in the 1980's. Anticipated new results from the early mini-HEAO and Outer Planets missions undoubtedly will strongly affect the thrust of early Shuttle investigations. Also totally new investigation and instrumentation concepts are certain to surface as soon as the scientific community has an opportunity to seriously participate in the development of Shuttle missions. However, it is possible, even at this early planning stage, to identify a group of crucial experiments which will have high priority in early Shuttle missions, and which are within the state of the art of cosmic ray

instrumentation, although not of present spacecraft. Among these are:

- To determine accurately, from direct measurements, the energy, mass, and charge spectra of the more abundant cosmic ray nuclei (e.g. H - Fe) from about  $10^{10}$  eV to the maximum possible energy, and the charge distribution of nuclei heavier than iron.

The physics of the cosmic accelerators producing the immense energies of cosmic rays is not understood, although a number of theoretical ideas in connection with supernovae, neutron stars, pulsars, and other energetic objects have been proposed. An accurate determination of the energy spectra of different nuclei will provide clues to the nature of the acceleration process. Changes in the shape of the energy spectra and the charge and mass distribution at high energies would have important astrophysical consequences related to the origin of the nuclei, their storage in the gravitational/magnetic fields of the Galaxy, and for their extragalactic history.

- To determine accurately the energy spectra of cosmic ray electrons and positrons above  $10^{10}$  eV.

The shape of the high-energy spectrum should provide important clues on the age of the electrons, their source spectrum, the galactic storage mechanism, and their distribution in the Galaxy. A comparison of the electron-produced galactic non-thermal radio emission (which as a function of frequency and direction averages over different galactic scales) with the local interstellar electron spectrum (which we observe) provides data on the non-uniformity of cosmic ray and magnetic field distributions over the Galaxy. The electron-positron ratio, as a function of energy, provides additional crucial information to the understanding of their sources and the galactic propagation mechanism.

- To search for antinuclei in the primary cosmic rays.

While a small number of antiprotons can be created in p-p collisions in the interstellar medium, the discovery of even one complex antinucleus such as anti-carbon would imply the existence of anti-matter stars and element building, and would have profound significance regarding the nature of the Galaxy and the Universe.

Another objective for the Shuttle usage, probably in a later time frame than the preceding, involves Shuttle-launched space probes:

- To measure the energy spectra and elemental and isotopic composition of low energy nuclei ( $\lesssim 10^9$  eV) and electrons *in situ* in the interstellar medium.

It is not possible to measure the characteristics of the galactic flux of low-energy particles ( $\lesssim$  several hundred MeV) near earth, since the effects of the solar wind prevent their penetration to a heliocentric radius of 1 AU. The particles in this energy range observed near earth are greatly decelerated from their original higher energy. However, in order to reach a complete understanding of the source characteristics and dynamics of galactic cosmic rays, it is essential to extend the spectral coverage to energies as low as  $10^5$  eV. At low energies, because of the ionization range requirements, we are sampling very local distributions of galactic cosmic rays. For example, the range of a 1 MeV proton in the typical galactic magnetic fields is  $\sim 200$  pc, hence with a lifetime of  $\sim 10^4$  years. A comparison of elemental abundances at low and high energies will be crucial to the separation of features related to the cosmic ray production and subsequent propagation in the Galaxy. Possible nearby sources, such as pulsars, may be identified by this technique. The specific details of the low-energy spectra, particularly of heavy-nuclei, are profoundly important with regard to the role of cosmic rays in the dynamics of the Galaxy, in particular the heating of the interstellar medium by ionization loss, and in X-ray and  $\gamma$ -ray production. The bulk streaming patterns of low energy nuclei may show large anisotropies, allowing the probing of interstellar space over different scale lengths as functions of energy. For example, 1 MeV protons with a density gradient of  $L \sim 200$  pc and a typical galactic diffusion mean free path of  $\lambda \sim 20$  pc will show an anisotropy of  $\delta = \lambda/L$  of about 10%.

The galactic electron spectrum below several hundred MeV is unknown. However, the flux is importantly related to the production of the diffuse X-ray and  $\gamma$ -ray background in the galactic disc, to the dynamics of the galactic disk-halo configuration, as well as to the efficiency of the escape from known source regions such as the Crab nebula. The non-thermal galactic radio background is attributed to synchrotron emission by electrons in the galactic magnetic fields. The low frequency galactic radio spectrum is observed to turn over and decrease below about 1 MHz. It is usually assumed that this effect is caused by absorption of the lower energy electrons in interstellar hydrogen. But it is possible that the electron source spectrum itself turns over as well at the equivalent energies. Obviously, the correct interpretation of this feature is fundamental to the understanding of conditions in the interstellar medium (e.g. the presence of cold gas clouds and the temperature of the intercloud medium) and for the understanding of the origin of these electrons and their importance in galactic dynamics.

## INSTRUMENTS

Brief descriptions and justifications of the instruments defined by the individual subdisciplines are included here. The detailed instrument parameters are collected in the Appendix. Individual "payloads" of special instruments are not defined lest they take on unreasonable future significance.

### X-RAY ASTRONOMY ( $\lesssim 20$ keV)

X-ray astronomy had developed to the point where a large national-facility, multi-user high resolution telescope is clearly justified by our knowledge of the X-ray sky. The following paragraph describes such an instrument. It should receive major financial support commensurate with a launch early in the 1980's. The succeeding paragraphs describe more specialized instruments for which priorities have not been assigned. Priorities will depend strongly upon our knowledge at the time of selection. We would presently give high priority to a large area counter array for the study of the known variability of X-ray sources, including "black hole" candidates with  $\mu$ sec timing resolution. All of these instruments should be multi-user instruments. Several of them could be part of an X-ray facility.

High Resolution Imaging Telescope: (0.1 - 4 keV; free-flyer; 15 m x 3 m; focal plane instruments for imaging, spectroscopy and polarimetry)

The fact that practical X-ray telescopes can be built which will reflect and focus X-ray photons to at least 4 keV allows for observational capability comparable to that available to optical astronomers. In terms of sensitivity and resolution, and in terms of the great diversity of measurements that can be made, there is no other single instrument or set of instruments available in X-ray astronomy that can approach the capability of a large X-ray telescope with a compliment of focal plane instruments. Besides the imaging instruments, the devices which can be used in the focal plane include Bragg crystal spectrometers, grating spectrometers, polarimeters and solid-state detectors. In addition, the telescope can be used as an element of an objective spectrometer with either a grating or a Bragg crystal. For each of these instruments, with the possible exception of the Bragg crystal spectrometers, the telescope allows for a qualitative improvement over the equivalent instrument built without a telescope.

The facility can be justified purely on the basis of its imaging capability. Because of problems of source confusion, high angular resolution is required to study any sources in the range fainter than  $10^{-4}$  Sco X-1 or sources present in

crowded regions such as single galaxies, globular clusters or clusters of galaxies. The limiting sensitivity should allow reaching sources as faint as  $10^{-8}$  Sco X-1 ( $\sim 10^{-15}$  ergs/cm<sup>2</sup>-sec), which is a range in brightness comparable to that achieved in optical astronomy and greater by about an order of magnitude than what is now achieved in radio astronomy. This allows the observation of solar-like coronae to about 50 pc, galactic X-ray sources to about 30 Mpc and "weak" extragalactic sources such as NGC 4151 or NGC 5128 to about  $10^3$  Mpc. Other classes of extragalactic sources such as rich clusters of galaxies, which are much more luminous, are observable to the very edge of the universe. Furthermore, this sensitivity is achieved without any sacrifice in angular resolution which should be better than 1 arc second.

The observational capability can best be enunciated in the case of extragalactic astronomy. Literally hundreds of galaxies, of all types, can be studied for their galactic X-ray source content. Besides their position it will be possible to study the spectral and temporal properties of the radiation from these sources. Because of the small number of sources per galaxy, only with this kind of investigation is there any hope to develop the statistics necessary to trace out and sort the evolutionary tracks of these objects which may be the key to understanding their nature. For another, the study of X-ray emission from galactic nuclei may provide the information needed to solve the essential problems of energy production in these regions. Our own galactic center can be seen on a scale of better than 0.05 pc. Furthermore, X-rays, which are efficiently produced by the inverse Compton scattering of relativistic electrons, are an excellent probe for mapping out the cosmic ray fluxes in these regions, especially when combined with radio measurements. We may already be seeing this effect in the cluster sources. Finally, in the energy range below 1 keV, where we can only see for a limited distance in our own galaxy, the observation of external galaxies is the only means for tracing out the diffuse radiation throughout the entire galaxies and for unambiguously determining its relation to galactic structure generally.

This facility has the power to attack virtually every classical problem in astronomy; evolution of stellar systems, the structure of the galaxy, the nature of galactic nuclei, the origin and distribution of cosmic rays, the structure and evolution of clusters of galaxies, the evolution of active galaxies, or the large scale structure of the universe. The only limitation we know of it that it is unlikely that X-rays will be seen from beyond about  $z = 3$  because of electron scattering in the intervening space. This itself may be the only means of studying the intergalactic space at high  $z$ .

Large Area Proportional Counter Array: (1 - 20 keV; 10 - 50 m<sup>2</sup>; pallet and/or free flyer; collimation variable, e.g. modulation collimators for high angular resolution)

A large proportional counter array is the only means known to obtain a large effective area for X-ray detection in the 3 - 15 keV region, where many sources emit most of their energy. The detection of large numbers of photons in short time intervals is essential for the detection and measurement of transient or non-periodic intensity variations. Variations from matter falling into a black hole are expected to have time constants on the order of 10 - 100  $\mu$ sec. The present black hole candidate, Cyg X-1, is known to exhibit aperiodic intensity variations down to  $\sim$ 50 msec time constants. An effective area of 10 m<sup>2</sup> will yield a counting rate of  $\sim$ 10<sup>5</sup> photons/sec for Cyg X-1 or  $\sim$ 1 photon/10  $\mu$ sec. An area of 50 m<sup>2</sup> yields 5 photons/10  $\mu$ sec. Almost every galactic X-ray source is variable and transient irregular phenomena are clearly very common. Angular structure of X-ray sources or the background could be studied with modulation collimators mounted upon the detector array. Such studies might be indicated by unusual or energy dependent angular structure detected at lower energies by the telescope experiments.

Low Energy Telescope: (30 - 300 Å ; 4.5 m x 1 m<sup>2</sup>; pallet/free flyer, 5° x 5° field of view; focal plane imaging, spectroscopy and polarimetry)

The opacity of the interstellar medium, would appear to severely limit observations between 912 Å and  $\sim$ 20 Å. However, the interstellar medium is inhomogeneous, with small dense clouds contained in a low density intercloud medium which can be as low as  $N_H \sim 0.1$  atom/cm<sup>3</sup>. Thus, we can expect to see out of our own galaxy for wavelengths  $<$  100 Å when we look normal to the galactic plane, and even at 304 Å many local sources should be observable. The K and L absorption edges of the most abundant light elements in the interstellar medium are in the XUV. XUV absorption and scattering can allow us to study the chemical composition and size of the interstellar grains. Attempts can be made to detect the intergalactic medium by means of comparative studies of the detailed shape of the long wavelength cutoff and the observation of absorption edges in the spectra of the same class of X-ray sources from nearby galaxies (such as the Clouds of Magellan) and from more distant galaxies. Known or probable discrete XUV emitters which can be studied are chromospheres and coronae of late type stars, supernova remnants, soft extragalactic sources, early type stars and, peculiar stars such as flare stars. More hypothetical candidates are defunct pulsars, UV stars, and galactic halos. A telescope facility optimized for soft X-ray observations provides a greater field of view and is a

compact instrument due to the shorter focal lengths. Focal plane instrumentation would include:

- A high resolution (1 arc second) narrow field detector
- A moderate resolution (3-5 arc second) wide field detector with high sensitivity
- Broad band and narrow band filters
- Grazing incidence grating spectrometers ( $\sim 30 \text{ \AA}$  to  $\sim 350 \text{ \AA}$ )
- A polarimeter

Bragg Crystal Spectrometer: (1 - 30  $\text{\AA}$  , 1.5 m x 2 m x 3 m, effective area 2000-4000  $\text{cm}^2$ )

A separate crystal spectrometer facility, not in the focal plane of a large X-ray telescope, is necessary for several reasons: (1) The hydrogenic and helium-like emission lines and the K absorption edge of iron, as well as of calcium and argon, are at high energies ( $E > 3 \text{ keV}$ ) not accessible to a focusing telescope; (2) a specialized crystal spectroscopy instrument will have a much greater collecting area for a given weight and volume; and (3) telescope scheduling problems which would arise from the required long integration times can be avoided. Although no emission lines or absorption edges have yet been observed, it is clear that their observation would play an extremely important role in the development of our knowledge of discrete galactic X-ray sources, the interstellar medium, and extragalactic sources. The wavelength range from 1 to 25  $\text{\AA}$  will most probably be covered by 3 crystals. For ( $\lambda < \sim 6 \text{ \AA}$ ), the focusing is accomplished by the configuration of the crystal array itself. At longer wavelengths, the focusing is accomplished by the use of grazing incidence optics placed behind (or in front of) the crystal array. These configurations will also permit observations with limited spatial resolution, perhaps as high as a few arc minutes, for the study of extended objects. The extension of the instrument to 100  $\text{\AA}$  could be carried out with a grazing incidence grating spectrometer.

Long Baseline X-Ray Probe: (1 - 10 A. U. , proportional counters, 1  $\text{m}^2$ , 1  $\mu \text{sec}$  timing)

The existence of time variations on the time scale of  $10^{-2}$  to  $10^{-3}$  sec in several of the galactic X-ray sources makes it possible to determine their position by simultaneous measurement from two detectors placed at planetary distances with

a precision greatly superior to any yet achieved in X-ray astronomy ( $1'' - 0.01''$ ). If even faster time variations should occur, the technique could yield positional information to the order of  $0.001''$  to  $0.0001''$ . Such a very large increase in angular resolution makes it possible to perform a variety of experiments having to do with measurement of angular positions as a function of time. Such experiments might lead to precise determination of distance for stellar systems, to the determination of their binary nature, and to refined comparison between structure observed in the X-rays and radio.

## HARD X-RAY AND GAMMA RAY ASTRONOMY

### Techniques

The wide range of energies within the discipline dictate a variety of observational techniques, since different photon interactions occur within various regions of the total spectral range. Hard X-ray observations (10 - 300 keV) use detectors which totally absorb the input photons. Observations in the many MeV range utilize electron/positron pair production. In the intermediate MeV range, Compton scattering is dominant. Various practical factors also dictate techniques depending upon specific observational objectives. Here we describe instrumental techniques applicable to the observational goals in each energy range.

Photometry — This includes sky survey instruments to greater sensitivity.

Spectroscopy — This includes measurements of discrete X-rays and  $\gamma$ -ray lines to on the order of 2 keV, which is the best attainable with solid state detectors. At energy  $> 20$  MeV, the Total Absorption Shower Counter (TASC) is used.

Angular Structure — Measurements of angular structure is hard X-ray to  $\sim 0.5^\circ$  are practical with mechanical collimation techniques. Higher resolution,  $\sim 10$  sec, may be obtained with modulation collimators. Higher energy  $\gamma$ -rays require pictorial representation of each event such as obtainable with spark chamber techniques in a minimum scattering configuration to obtain  $0.1^\circ$  source structure.

Polarimetry — Polarization of  $\gamma$ -rays may be obtained at high energies using Compton scattering. Polarization devices require large arrays of small cell size high resolution detectors such as Ge(Li) or liquid Xe proportional counters.

If either the nuclear gamma-ray spectrometer or the high energy gamma-ray experiment currently being considered for HEAO-C' are not flown on HEAO-C', they should, of course, be the first priority experiments for the Shuttle. These instruments are relatively well defined and have been discussed earlier in the text.

### High Energy X-Ray Survey

This will permit detection of sources to an intensity of  $5 \times 10^{-5}$  of the Crab nebula, and will therefore measure the hard X-ray continuum of many X-ray sources. Such data, which contrasts the spectrum and time variations in such diverse emitters as the binary X-ray objects, supernova remnants, non-periodic but varying galactic sources, and extended and compact extragalactic objects cannot fail to distinguish emission mechanisms and source region properties. Scintillation counters with active or semi-passive shielding configured in modules will be used. An array weighing  $\sim 1000$  kg will have an area of  $\sim 10^4$  cm<sup>2</sup> on a narrow fan shaped field of view if on a scanning mission.

### Broad Band X-Ray Spectrometer

This instrument will be used to study spectra in an effort to identify specific features such as spectral breaks, nuclear gamma ray lines or heavy element K-line emission. The data necessary for an unambiguous determination of such effects involves both the line profile and the continuum since, in most instances, physical conditions within the emitting regions will broaden any features. Thus, the need arises for a broad band spectrometer which will give best possible spectral resolution commensurate with available exposure. An array of cooled Si(Li) detectors will give spectral resolution at least one order of magnitude better than other non-dispersive techniques and afford the best means for identification of the broad spectral features predicted from X-ray sources.

### Hard X-Ray Imaging

Studies of the angular size of extended sources such as the Crab nebula, Perseus cluster, and galactic disc at various energies provide unique information on electron distributions, and distinguish between regions of thermal and non-thermal emission in the same object. In the Crab, for example, the higher energy electrons injected by the central pulsar will diffuse further before being reduced in energy by lifetime limitations. Studies of the Crab require angular resolutions of  $10 \widehat{\text{sec}}$ , while galactic clusters may have structures in the  $0.1^\circ$

regime. At present it appears a modulating collimator on a high sensitivity scintillation counter survey device is the best technique for achieving these objectives. The basic sensitivity should be of the order of  $10^{-4}$  Crab in order to obtain a large number of sources in the Shuttle era. This implies an area of some  $10^4$  cm<sup>2</sup> in a low background configuration.

### High Sensitivity Medium Energy $\gamma$ -Ray Survey

Measuring the spectrum of galactic sources over the 0.3 - 10 MeV range will determine the relative role of non-thermal electrons and nuclear processes in such objects as pulsating binary X-ray stars, supernova remnants and the galactic plane. Gamma-ray fluxes at 1 MeV measure 30 GeV electrons scattering on the 3°K radiation which permeates halos and clusters. Detection of perhaps 50 galactic and extragalactic sources requires a cluster of scintillation counters with active anticoincidence shielding, a sensitivity of at least  $5 \times 10^{-6}$  photons/cm<sup>2</sup>-sec-MeV at 1 MeV, and a total area of 5000 cm<sup>2</sup>. An aperture of 5° FWHM represents a compromise between source confusion and sensitivity. These objectives can only be obtained with massive, large area detectors and long term observations.

### Nuclear $\gamma$ -Ray Spectrometer with High Resolution

Determination of the intensities of  $\gamma$ -ray lines from such processes as radioactivity in supernova remnants, positron annihilation in the galactic disc or in extragalactic interactions, lower-energy cosmic rays passing through dense matter, and nucleosynthesis in violent events in distant galaxies will put nuclear astrophysics on an observational basis. Detection of such lines at a sensitivity of  $2 \times 10^{-6}$  photons/cm<sup>2</sup>-sec (1/10 that of the HEAO-C' instrument) will require a detector of 250 cm<sup>2</sup> with active anticoincidence shielding and collimators, and extreme care to reduce background effects. Present technology indicates that a cooled Ge(Li) system provides the best energy resolution, although other devices are now under development. Extended observing time on single sources or source regions with an instrument of modest weight on a pointed Shuttle pallet or platform is needed.

### Developmental Pallet System

Many experiments in a developing scientific field, such as low energy gamma ray astronomy, require a close and timely interaction between technical developments and scientific discoveries. A system which has basic capabilities for mounting fairly large and massive instruments with modest pointing

requirements is needed during the early Shuttle era. This system serves the same function as rockets for X-ray astronomy and balloons for high-energy X-ray astronomy. Observations which are specific and one-time, such as exploratory polarimetry on strong sources, and observations of new objects found in other wavelengths for phenomena predicted in the gamma-ray regime, might be examples. Technical developments, such as shielding studies, Compton telescopes, or liquid xenon proportional counters can be proven on such a device.

#### High Energy Gamma-Ray Survey Instrument

This will permit sensitivities a factor of ten better than the device being considered for the HEAO-C<sup>1</sup>, or  $\sim 10^{-8}$  photons/cm<sup>2</sup> sec greater than 20 MeV. Although it is impossible to predict the discoveries to be made in a rapidly evolving field, one may speculate that such an instrument will be able to detect galactic and extragalactic point sources, and determine many details of diffuse emission in the galactic plane. The instrument, which must have pictorial readout for each event, will have modest energy and angular resolution capabilities. It may be some form of spark chamber with a total absorption shower counter.

#### High Angular Resolution Instrument

This instrument will permit the precise location of sources of high energy gamma radiation and to correlate these with X-ray, optical and radio objects. The time resolution of the instrument will enable one to study variability on a fine time scale. It will also map the diffuse radiation of extended objects so as to understand their dynamic properties. The field of view of the instrument is approximately 0.1 ster and has an energy resolution of 10% over a range of 20 to  $3 \times 10^4$  MeV. Angular resolution of  $0.1^\circ$  to  $0.2^\circ$  will be possible.

#### High Energy Resolution Detector with Pictorial Device

This instrument will investigate in detail the spectra of previously discovered objects to look for unique changes in the spectral shape. This will provide information related to the source mechanism and to previously unknown high energy fundamental particle lines. The instrument has an energy resolution of 3% over a range of 20 to  $10^5$  MeV.

## COSMIC RAY ASTRONOMY

The instruments capable of meeting the scientific and observational objectives listed in the previous section have many of their gross features fixed by the spectra and abundances being observed. Assuming all charged particles have the same power-law behavior, a graph has been prepared in Figure 2 relating the exposure factor (geometry factor times exposure time) to the top energy to be resolved (due to statistics) for the various types of charged cosmic rays. The relationship was drawn assuming it was desirable to gather 100 events above the energy  $E$ . Also shown on the graph are the coverages for various instruments, whose more detailed specifications are contained in the appendix.

Since these instruments represent an interesting cross-section of the techniques which have been brought to bear on charged cosmic-ray measurements, and since each has its particular strengths and weaknesses, it is appropriate here to discuss each one briefly.

### Magnetic Spectrometer

This device measures the deflection angles as the relativistic particles pass through a region of strong magnetic field. This bend angle is proportional to the ratio of charge to momentum (specific curvature  $\equiv 1/\text{rigidity} \equiv \text{charge}/\text{momentum}$ ) of the incident particle. The magnetic spectrometer usually measures charge through  $dE/dX$  in a thin scintillation, and can also employ Cerenkov counters for isotope separation or electromagnetic shower counters for electron separation. For the particles accessible from Shuttle orbit, the magnetic spectrometer provides the only presently viable means of detecting anti-matter and of separating negatrons and positrons.

### Gas Cerenkov Detector

This instrument provides the means, with modest size and weight, of measuring the velocity spectrum of nuclei up to a maximum of  $\gamma \simeq 200$  set by the Cerenkov medium, its viewing optics, and photomultiplier technology. Coupled with a separate charge measurement, and knowledge of the average isotope mixture for each element, this then can be transformed into the usual energy spectrum form.

### Electromagnetic Calorimeter

Here the incident electron showers in heavy absorber radiators. The particle count is sampled frequently with interspaced scintillators. Since the device is

sufficiently thick to contain the shower (up to a maximum energy of  $10^4 - 10^5$  GeV) the total scintillator response is a measure of the incident energy. This technique is the only one presently capable of covering the interesting and vital spectral region from  $10^3$  to  $10^5$  GeV for electrons — a region in which the spectrum is expected to steepen significantly due to interaction of the electrons with the universal 3°K black-body photons.

### Nuclear Calorimeter

As with the electromagnetic calorimeter, the particles interact and shower, and the device is large enough to contain the incident energy. This device provides the only means of measuring the energy spectrum of nuclei in the  $10^3$  to  $10^5$  GeV/nucleon energy range.

### Large Area Ionization Hodoscope

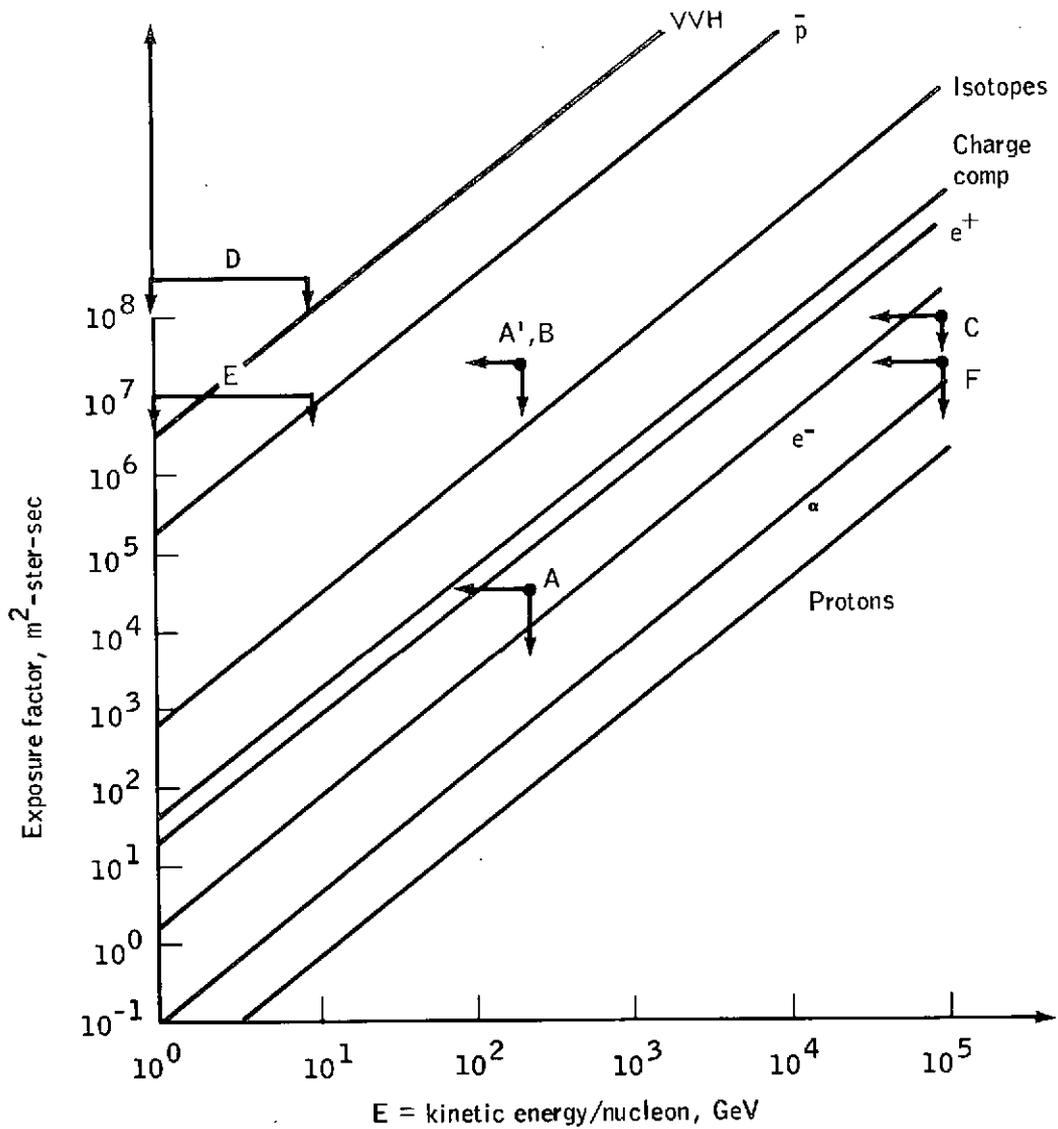
Figure 2 shows, for very heavy, rare elements that very large exposure factors are necessary. This instrument provides the necessary coverage, providing charge measurement on elements all the way from iron up to the interesting trans-uranic elements that have only recently been observed in cosmic rays. If an "island of stability" in the nuclear table exists around charge 115, as many nuclear theorists now believe, we would expect these elements to be made through nucleosynthesis and to be observable in the cosmic rays.

### Graded Cerenkov Counter

This device uses the earth's magnetic field as an analyzer and also makes an accurate velocity spectrum for each charge. When the velocity spectra for the elements are compared, the rigidity dependence of the earth cut-off can be eliminated and the isotopic mixture of each element determined. Reasonable separated isotopic coverage extends over the vitally interesting rigidity range from 1 to 10 GV/c. This is the range in which the radioactive isotope  $\text{Be}^{10}$  is expected to vary from mostly decayed to mostly survived, due to the relativistic time dilation in the decay.

## SHUTTLE UTILIZATION — SORTIE MISSION

The working group considered a Shuttle with the parameters listed in Table 2. Within the guidelines set by these parameters the group found the Shuttle could



- A = Sortie magnet spectrometer
- A' = Free flying magnet spectrometer
- B = Gas cerenkov detector
- C = Nuclear calorimeter
- D = Large area ionization hodescope
- E = Graded cerenkov detector
- F = Electromagnetic calorimeter

Figure 2. Exposure factor required to measure fluxes to an energy E

Table 2

## Baseline Shuttle Parameters (Provided to Working Group)

Volume Available	Cylindrical, dia. 4.5 m, length 18 m
Weight Available	20,000 Kg
Power Required*	1-5 K watts for all experiments on shuttle
Data System*	50 K bits/sec for all experimenters on shuttle
Shuttle Orientation Stability	1°
Modes Available	(a) Fixed open pallet (b) Pointable open pallet (c) Pressurized container pallet, not man-rated (d) Pressurized "shirt sleeve" man-rated lab (e) Shuttle launched "free-flyer", recoverable (f) Shuttle launched rocket for deep space probes
Flight Duration	(a) 5 → 30 days sortie (b) 6 mo. free flyer
Orbital Parameters	Altitudes 150 Km to 250 Km Orbital inclinations: 28° favored; 55° → 90° if possible
Shuttle Availability	Starting in 1980, with pallet space "as available" and free-flyer launch and/or recovery on ~ 6 month intervals
Availability of Man	(a) Part- or full-time within shirt sleeve lab, or from crew compartment (b) Occasional EVA to pallets

\*Specified by Working Group

provide a major stimulus to high energy astrophysics, if sufficient additional support were available for instrument development to have flyable packages ready at the beginning of the Shuttle launch time frame. The volume, weight,

power, and data parameters appeared to be an adequate match to present needs. Of the available modes, the pallet modes and the Shuttle-launched free-flyer appeared to be the most useful, with some interest also shown in the Shuttle-launched deep space probes.

The pallet modes would be useful for instrument checkout and for trying new ideas. Some experiments, such as detailed studies of a few celestial objects with specialized equipment, could be completed in the pallet mode. The group considered the pallet to be most useful if provided in a standard size, such as 4-1/2 x 2 meters, with standard mechanical attachment points and power/data buss. Experimenters would be encouraged to interface their equipment to these standard resources. In addition, for X- and gamma ray experiments, a modified pallet with an experimental platform capable of pointing to  $0.1^\circ$  accuracy shall be provided, since the Shuttle itself probably will not be oriented with respect to specific astronomical objects. We would expect the platform to mount a  $\sim 3$  m cube experiment. Three or more units shall be available, so experiments could be prepared on the ground while others are in flight, or to fly co-linear pointing instruments.

The free-flyer mode would generally be the one in which definitive experiments are carried out, by virtue of its long exposure time. Considerable cost savings could be realized by having standard free-flyer frames and interfaces. We would envisage the free-flyer as a somewhat enlarged mini-HEAO, sized to take advantage of the weight and size capabilities of the Shuttle. Generally the instruments would be recovered, to recycle the spacecraft and instrument or to remedy equipment failures. We also envision the use of small single experiment free-flyers. The large X-ray telescope described in the previous section would probably have to be a specially designed type of free-flyer.

The working group felt that man in the spacecraft need not play a major role in deploying and operating these instruments, since data interpretations usually require large computer-calculation support, and since most control could adequately take place from the ground. Man-rating the instruments could furthermore have a major impact on the experiment cost. However, use of astronauts for unforeseen repair or for activities within a closely controlled man-equipment interface (such as changing photographic film on emulsion plates) should not be excluded. The experiments we presently envision do not require the use of a manned, "shirt sleeve" laboratory.

To place the Shuttle mission requirements in perspective, a brief description of the presently approved flight program is provided in Table 3. Spacecraft now in orbit and providing useful data are also listed. The instruments carried on these spacecraft are typically less than 20 lbs. Spacecraft whose primary mission is other than High Energy Astrophysics, but which carry instruments of interest to the discipline are also included in the table.

Table 3

## Spacecraft Carrying High Energy Astrophysics Instrumentation

SPACECRAFT	OBJECTIVE	LAUNCH
Small Astronomy Satellite (SAS-A) "UHURU (Explorer 42)	X-Ray survey (2-20 keV)	Dec. 1970
Interplanetary Explorer IMP-I (eye) (Explorer 43)	Cosmic ray composition	March 1971
Orbiting Solar Observatory (OSO-7)	Solar gamma rays and X-rays survey	Sept. 1971
Pioneer-10	Cosmic ray composition and gradient	March 1972
TD-1 (ESRO)	Celestial gamma ray survey	March 1972
Orbiting Astronomical Observatory-C "Copernicus"	Soft X-ray telescope ( $< 4$ keV)	August 1972
IMP-H (Explorer 47)	Solar and galactic cosmic ray composition	Sept. 1972
SAS-B (Explorer 48)	High Energy gamma ray survey	Nov. 1972
Pioneer 11	Cosmic ray gradient and composition	April 1973
Mariner Mercury	Solar cosmic ray composition and gradient	1973
IMP-J	Solar and galactic cosmic ray composition	1973
United Kingdom (UK-V)	Low energy gamma ray survey and X-ray spectra, polarization and survey	1974
HELIOS (w/Germany)	Solar cosmic ray gradient	1974

Table 3 (Continued)

SPACECRAFT	OBJECTIVE	LAUNCH
OSO-I	Soft X-ray survey, hard X-ray spectroscopy, polarimetry	1974
American-Netherlands Satellite (ANS)	Soft and medium energy X-rays	1974
SAS-C	Galactic and extragalactic X-ray source study	1975
CORSA-II (Japan)	X-ray source variability (0.45-20 keV)	1975
High Energy Astronomy Observatory (HEAO-A')	Large area X-ray source survey and location	1976
HEAO-B'	Pointed X-ray telescope	1977
International Magnetospheric Explorer (with ESRO)	Cosmic ray isotope analysis, composition and gradient	1977/1978
Mariner Jupiter Saturn	Low energy galactic cosmic ray composition and gradient	1977 (2 missions)
HEAO-C'	High and medium energy gamma ray survey or cosmic ray isotopic composition and charge of very heavy cosmic rays	1978
High Eccentricity Lunar Occultation Satellite (HELOS), ESRO	Source position variability and structure of X-ray sources	1978

## MANAGEMENT RECOMMENDATIONS

The Space Shuttle provides the potential to conduct new and exciting scientific investigations at costs and on a time scale not previously possible on spacecraft. The realization of this potential requires the modification of many accepted management practices and the implementation of new practices. The large weight lifting capability, recoverability and short turn-around time to reflight are the characteristics that will contribute most to the realization of the high scientific potential at low cost from the shuttle.

The balloon and sounding rocket programs have proven highly effective in carrying low cost, but scientifically valuable, payloads into space. The Working Group recommends extending the balloon and rocket experiment philosophy to the Space Shuttle. Adopting this philosophy requires acceptance of relaxed quality assurance and reliability standards, greater reliability on the performance of the principal investigator (PI), and standardization of most systems interfaces. For example the TTL logic elements of the Texas Instrument 54L family cost approximately \$45.00 when bought to MSFC 85 MO specifications for high reliability space flight use. Plastic encapsulated circuits in dual-inline packages cost only \$1.00 to \$2.00 each. These low cost circuits have been used with great success in balloon and sounding rocket payloads. Acceptance of a relaxed quality assurance philosophy infers also the tacit acceptance of occasional in-flight experiment failures. The ability of the Shuttle to check out an experiment in space and to return a failed instrument for repair and reflight reduces the potential loss from such a failure to an acceptable level.

Achievement of the goal of performing valuable scientific research at a low cost infers placing greater responsibility for development and testing on the PI. That is, the burden of providing a tested, functioning instrument to NASA for integration must be with the PI. At the present NASA monitors the activities of the PI through a large in-house organization. A more practical and economical approach appears to be to provide the PI with an experiment handbook in which standardized electrical and mechanical interfaces, safety requirements, and launch environment are provided. The burden of meeting these requirements would be on the PI, not on the NASA contract monitor. NASA would, however, assure that the intent of the requirements is being met through one or more design reviews early in the development of an instrument. The frequency of review would be determined by the complexity of the instrument. At delivery of the instrument, the integration center would perform functional tests, inspection for adherence to safety requirements and simple, flight level vibration and thermal tests. If the instrument fails, the flight opportunity would be lost to the PI. When it passes, the instrument would be integrated and launched. The Working Group recognizes the necessity for NASA to maintain accountability over public

resources. At the present this is done by the previously mentioned monitoring of the PI. To replace this, we recommend the establishment of Boards of Inquiry to investigate and rectify failures. In this situation, after-the-fact monitoring of failures would replace close pre-launch monitoring of all efforts. The PI's reputation would be clearly compromised by a failure within his sphere of responsibility. A system of instrument evolution discussed later, should further minimize the probability of inflight failures.

A major cost factor in present manned spacecraft operation is the requirement to "man rate" all equipment. Acceptance of the low cost philosophy discussed in the preceding paragraphs infers acceptance by NASA of the elimination of man rating of the experiment instrumentation. We recognize that the basic safety of the Shuttle crew cannot be endangered. The Working Group proposes to achieve the safety objectives by minimizing the manned interface with the experiment. Investigations on the pallet would be automated to as large a degree as possible. The mission specialist would be required for monitoring functions from the crew compartment or for EVA to perform simple alignments and repairs. The design of the pallet and payload would have to assure that no single malfunction could cause damage to the Shuttle or crew or that the payload would not create a hazard during an abort landing. The payload would have to provide malfunction signals and electrical fusing to the crew compartment.

Experiment selection and development and the long lead time from selection to flight are major factors in increasing experiment costs. Under the present system an announcement for flight opportunity is issued. Interested investigators submit proposals, which are evaluated by a NASA committee and a number are selected for flight. Selection is often tentative and is made final only after a 6 month or longer definition study. Following formal selection, the PI is funded for major hardware fabrication. The hardware is delivered to the integration center for integration, test, and finally launch. This entire procedure from proposal to launch can often extend over a period of four or more years. During this period the PI's staff is being funded, the spacecraft contractor has a major design, fabrication, and testing effort in progress and the NASA management center has a staff monitoring the activities of all participants. The Working Group proposes a modification of this system into an evolutionary instrument program from Supporting Research and Technology (SR&T) funding through pallet flight into flight on a free flying spacecraft. Under the proposed system, a potential PI would be given an agreed upon sustaining level of SR&T funding. The level would probably be higher than present day SR&T levels and would be supplemented on occasion when new construction or modification is required. Within this fixed budget the PI would develop a new instrument concept and construct the instrument to the relaxed quality assurance standards, much as he does today for a balloon flight. If the instrument is flown successfully (scientifically as

well as technically) on the pallet, the same instrument would be upgraded and the interfaces modified as necessary for flight on a free flyer. It is recognized that an impartial selection committee must be interposed at various stages to advise NASA on specific selection actions. The ability of the Shuttle to check out spacecraft in space, recover malfunctioning spacecraft, refurbish standardized spacecraft, and refly instrumentation enables an investigator to carry through from development to spacecraft flight with a single basic instrument. The PI would, under this system, carry out a complete research program over the period of a decade without the major perturbations of specific flight instrumentation construction or the long and expensive lead times from proposal submission to spacecraft flight.

The requirement for a PI to operate on a fixed budget over an extended period of time will also have the beneficial effect of requiring long term planning of a research program, sharing common components with other PI's and integrating design and development into a standardized form that does not require major expenditures for relatively small modifications necessitated by spacecraft interfaces or man rating. Particle physicists using accelerators, for example, often borrow detectors or other major pieces of equipment rather than build an entirely new module for an experiment. The practice of sharing equipment and data output at an accelerator has often been necessitated by funding limitations under which an experimenter must operate. The same philosophy should be applicable to investigations in space.

The implementation of many of the preceding procedures and the extension of these procedures to the management of national facilities such as the Large X-ray Telescope argue strongly for bringing the PI more directly into the decision making process. The HEAO Timeline Committees worked well in this sense. The Working Group considers that a committee consisting of PI's on a multiexperiment investigation or guest observers on a national facility, NASA personnel and outside consultants could perform a valuable service in evaluating change requests and assisting in distributing resources such as power and telemetry. It was suggested that the outside consultants be selected from the original committee which evaluated investigations for the particular mission. The reliance to a greater degree on the PI, the acceptance of relaxed quality assurance standards and the implementation of an evolutionary instrument development and flight program should together serve to provide a scientifically valuable research program in the Shuttle era at a lower total commitment of national resources than can now be realized.

APPENDIX A  
INSTRUMENT PARAMETERS

X-RAY ASTRONOMY

X-1

Type

High Resolution X-ray Telescope Facility.

Objective

The instrument comprises a very large X-ray telescope with a complement of focal plane instruments (imaging detectors, spectrometers and polarimeters) which can perform a wide array of observations with great sensitivity. The instrument would be operated as a national facility.

A variety of objectives can be described including high sensitivity surveys, detailed studies of external galaxies, structure of the X-ray background, spectrometry and polarimetry of single sources.

Parameters

- Energy Range — 4 keV to  $\sim 0.1$  keV.
- Sensitivity — To  $10^{-8}$  Sco X-1 for point sources.
- Field of View —  $1^\circ$
- Resolution —  $1/2$  arc second.
- Weight — 10,000 Kg.
- Dimensions — 3 meters by 15 meters.
- Power — 500 watts.



## Parameters

- Wavelength — 1-20 keV.
- Area/Weight — 10-50 m<sup>2</sup>/2, 500-12, 500 kgm.
- Depth — ~1/2 meter.
- Field of view — 1° x 1°.
- Absolute timing — ~1 μ sec (for correlated ground based observations).
- Data rate — 10<sup>5</sup> bits/sec average.  
10<sup>7</sup> bits/sec short periods.
- On board data storage — ~10<sup>10</sup> bits.
- Pointing — 0.1°; stability — ~1'/sec.
- Gas System — Cheapest counter system may entail gas supply. This could reduce low energy threshold to 1/4 keV.
- Modulation Collimators — Increase depth to ~1.5 m and add ~50% to weight when used.
- Power — 150 watts.

## Payload Carrier

Sortie mission on unmanned but pointable pallet is appropriate for observation of specific objects. Free-flyer status might be appropriate for more complete surveys with a well developed system.

## X-3

### Type

Low Energy X-ray Telescope.

### Objective

The study of individual sources, and of the interstellar and intergalactic media at wavelengths from  $\sim 30$  to  $\sim 300$  A can best be carried out with a dedicated grazing incidence telescope with the capability of placing imaging, spectroscopic and polarization instrumentation in the focal plane.

### Parameters

- Wavelength Range —  $\sim 30$  A to  $\sim 300$  A.
- Collecting Area — Pallet/Free Flyer  $\lambda > \sim 20$  A,  $600 \text{ cm}^2$ ,  $\lambda > 30$  A  $\sim 1600 \text{ cm}^2$ ;  $\lambda > 70$  A  $\sim 4800 \text{ cm}^2$ . Observatory  $\lambda > \sim 20$  A;  $3000 \text{ cm}^2$ ;  $\lambda > 30$  A  $\sim 8,000 \text{ cm}^2$ ;  $\lambda > 70$  A  $24,000 \text{ cm}^2$ .
- Field of View —  $\sim 5^\circ \times 5^\circ$ .
- Resolution — Angular 1 arc second. Spectral  $\lambda/\Delta\lambda \sim 1500-8000$ .
- Weight/Size — Pallet/Free Flyer  $1500 \text{ kg } 1 \text{ m}^2 \times 4.5 \text{ m}$ . Observatory  $7000 \text{ kg } 2.2 \text{ m}^2 \times 10.0 \text{ m}$ .
- Power — Pallet/Free Flyer 150 watts. Observatory 300 watts.
- Data Rate — Pallet/Free Flying 10 kilobits. Observatory 100 kilobits.
- Contamination — This instrument is extremely sensitive to contamination of the lens, and great care must be taken in the sortie mode to control this problem.

### Payload Carrier

Pallet and free flyer, possibly as part of a "national facility".

### Mission Characteristics

- Shuttle orbit is acceptable for Free Flyer.
- Recovery and refurbishment will be required.
- Pointing Accuracy: 1 arc minute for Free Flyer.

- Stability:  $0.1^\circ$  arc sec/sec for Free Flyer.
- Pointing accuracy for Sortie Missions  $0.1^\circ$ .
- Real Time Data Links are desirable but not mandatory.
- Data storage is required.
- In Flight Computer will be incorporated in both Sortie and Free Flyer.
- No photographic film will be used.
- Timing:  $10 \mu$  seconds absolute timing is required.

#### X-4

#### Type

High Resolution Crystal Spectrometer.

#### Objective

Spectroscopy of individual sources and the study of the composition of the interstellar medium can be best carried out by crystal spectrometers independent of major telescope facilities, or with their own dedicated optical systems.

#### Parameters

- Wavelength Range — 1 to  $\sim 30 \text{ \AA}$  (to  $\sim 100 \text{ \AA}$  with grating spectrometer).
- Collecting Area —  $\lambda < \sim 10 \text{ \AA}$   $4000 \text{ cm}^2$ .  
 $\lambda > \sim 10 \text{ \AA}$   $2000 \text{ cm}^2$ .
- Field of View —  $15^\circ \times 15^\circ$ .
- Resolution —  $\sim 5$  arc minutes angular resolution.  
 $\lambda/\Delta \lambda$  7000 at  $2 \text{ \AA}$   
 7000 at  $6 \text{ \AA}$   
 3000 at  $12 \text{ \AA}$   
 500 at  $25 \text{ \AA}$   
 1000 at  $100 \text{ \AA}$

- Weight/Size — 1.5 m x 2 m x 3 m.  
1000 kgm.
- Power — 100 watts.
- Data Rate — 5 kilobits.
- Contamination — This instrument is sensitive to the contamination of reflecting surfaces, and care must be taken in the Sortie mode to control this problem.

### Payload Carrier

The instrument should be flown on the Sortie Pallet mode. This is particularly important if an instrument of this nature cannot be accommodated on a pre-Shuttle mission. The instrument would then be developed for an early Shuttle launched Free Flyer.\*

### Mission Characteristics

- Shuttle orbit is acceptable for Free Flyer.
- Recovery and refurbishment will be required.
- Pointing Accuracy: 1 arc minute for Free Flyer.
- Stability: 1 arc sec/sec for Free Flyer.
- Pointing accuracy for Sortie Missions  $0.1^\circ$ .
- Real Time Data Links are desirable, but not mandatory.
- Data storage is required.
- In Flight Computer will be incorporated in both Sortie and Free Flyer.
- Raster scan — 1' steps  $3^\circ \times 3^\circ$  field.

---

\*A similar instrument should be part of an x-ray national facility.

## X-5

### Type

Proportional counter array on long baseline probes (1-10 AU).

### Objective

Perform correlated studies with an earth orbiting Large Area Proportional Counter Array experiment.

- To determine the binary nature of certain important X-ray emitters such as Cyg X-1.
- To measure the apparent angular size of the orbits of other objects known to be in binary systems such as Her X-1, Cen X-3 and hence their absolute distance.
- To measure by parallax the distance of nearby X-ray objects.
- To position variable X-ray sources to 0.1 to 0.01 arc seconds.

### Parameters

- Wavelength -- 1-20 keV.
- Area-Weight --  $\sim 1 \text{ m}^2/50$  to 100 kg.
- Depth --  $\sim 20$  cm.
- Field of View --  $3^\circ \times 3^\circ$ .
- Absolute Timing --  $\sim 1$  microsecond.
- Data Rate --  $10^4$  bits/sec average.  
 $10^6$  bits/sec short periods.
- On-board Data Storage --  $10^9$  bits
- Pointing --  $0.5^\circ$  stability  $0.1^\circ/\text{sec}$ .
- Power --  $\sim 50$  watts.

## Payload Carrier

A deep space-probe launched from the Shuttle.

## HARD X-RAY AND GAMMA RAY ASTRONOMY

### G-1

#### Type

High Energy X-ray Survey — Array of 10 large area phoswich scintillation counter modules with partial passive collimation.

#### Objectives

Perform survey in 10 to 300 keV energy range to a sensitivity of  $5 \times 10^{-7}$  photons/cm<sup>2</sup>-sec-keV. Measure spectra and determine location of sources with moderate resolution.

#### Parameters

- Energy Range — 10 to 300 keV.
- Sensitivity —  $5 \times 10^{-7}$  photons/cm<sup>2</sup>-sec-keV (nominal).
- Field of View — 1 deg x 5 deg.
- Energy Resolution — 20% (nominal).
- Effective Area —  $10^4$  cm<sup>2</sup>.
- Weight — 1000 kg.
- Envelope — 1.5 m rectangular x 1 m long array total.
- Power — 100 W.
- Data Rate — 5 to 15 kb/s.
- Temperature Range — 0° to +30° C.

- ⊙ Contamination, Acceleration, Vibration Not Critical.
- ⊙ No Consumables.

### Payload Carrier

Free flyer for extended observation, should be flown co-aligned with 1-10 keV instruments, or 0.3-10 MeV survey experiments.

### Mission Characteristics

- ⊙ Inclination —  $< 28^\circ$  ( $0^\circ$  preferred).
- ⊙ Altitude —  $< 200$  m (minimum consistent with duration of mission).
- ⊙ Operating Life —  $> 2$  years.
- ⊙ Retrieval for Refurbishment Desirable.
- ⊙ No In-Orbit Servicing Required.
- ⊙ Orientation — Scan with  $0.1^\circ$  pointing accuracy available.
- ⊙ Duration — 6 months minimum.
- ⊙ Communications and Data Management.
  - a. Real time transmittal: 10% of data.
  - b. Near real time: All data.
  - c. No voice link.
  - d. Some on board computer processing may be convenient.
- ⊙ Timing Standards —  $10 \mu$  sec/day relative.  
1 ms absolute.
- ⊙ Dedicated Ground Facility Required.

## G-2

### Type

Broad Band Spectrometer — Si(Li) Array with collimator, shield and cooling apparatus.

### Objective

To measure broad-band spectral features such as nuclear gamma ray lines, spectral breaks and heavy element K-line emission.

### Parameters

- Energy Range — 2 to 50 keV.
- Field of View — 2 degrees.
- Resolution — 2% (nominal).
- Area — 100 cm<sup>2</sup> total.
- Weight — 1000 to 2000 lbs (depending on mission length and cooling requirements).
- Power — 50 watts, passive cooling, 150 watts active cooling.
- Temperature — -20° C to +50° C.
- Contamination — Not critical.
- Acceleration/Vibration — Not critical.
- Consumables — May require replenishment of refrigerant.

### Payload Carrier

Pallet for specific limited objectives or free flyer.

## Mission Characteristics

- Inclination --  $< 28^\circ$  ( $0^\circ$  preferred).
- Altitude -- 200 nm.
- Operating Life -- 1 to 6 months.
- Retrieval Desirable.
- Orientation -- 0.1 degree pointing accuracy, 0.1 degree stability.  
Duration: up to 1 day.
- Communication and Data Management -- 10% of data real time, all data near real time.
- Timing Standards -- 10  $\mu$ sec relative, 1 ms absolute.
- Dedicated Ground Facility Required.
- No Crew Support Required.
- No Unique Requirements.

G-3

## Type

Hard X-ray Imaging Detector -- Array of 10 large area phoswich scintillation counter modules with modulation type collimators of differing modulation field.

## Objectives

Determine location, size, and structure of selected X-ray sources in the 10 to 200 keV energy range down to few arc second level.

## Parameters

- Energy Range -- 10 to 200 keV.

- Field of View — 5 deg.
- Angular Resolution — 2 arc seconds.
- Energy Resolution — 20% (nominal).
- Effective Area —  $5 \times 10^3 \text{ cm}^2$ .
- Weight — 2000 kg.
- Envelope — 1.5 m rectangular x 1 m long array.
- Power — 100 W.
- Data Rate — 5 to 15 kb/s.
- Temperature Range —  $0^\circ$  to  $+30^\circ\text{C}$ .
- Contamination, Acceleration, Vibration Not Critical.
- No consumables.

#### Payload Carrier

Sortie pallet, should be on a payload with 1-10 keV imaging experiments, or other co-pointed X-ray instruments.

#### Mission Characteristics

- Inclination —  $< 28^\circ$  ( $0^\circ$  preferred).
- Altitude —  $< 200 \text{ nm}$  (minimum consistent with duration of mission).
- Operating Life —  $> 2$  years.
- Retrieval for Refurbishment Desirable.
- No In-Orbit Servicing Required.
- Orientation —  $\pm 1^\circ$  mini-scan with one arc second determination.
- Duration — 6 to 30 days.

- Communications and Data Management.
  - a. Real time transmittal: 10% of data.
  - b. Near real time: All data.
  - c. No voice link.
  - d. Some on board computer processing may be convenient.
- Timing Standards — 10  $\mu$  sec/day relative, 1 ms absolute.
- Dedicated Ground Facility Required.

G-4

Type

High Sensitivity Medium Energy  $\gamma$ -Ray Survey — High sensitivity survey instrument, 0.3-20 MeV, using actively shielded scintillation counters.

Objectives

To perform survey at a sensitivity of at least a factor of ten better than previous measurements with moderate energy and angular resolution for galactic, and extragalactic and diffuse source structure.

Parameters

- Energy Range — 0.3-20 MeV.
- Active Area — 5000 cm<sup>2</sup>.
- Sensitivity —  $5 \times 10^{-6}$  ph/cm<sup>2</sup>-sec-MeV at 1 MeV.
- Field of View — Angular resolution - 5° FWHM.
- Energy Resolution — 5% at 1 MeV.
- Weight — 5000 kg.

- Size -- 1.5 m dia. x 1.5 meter long.
- Power -- 100 W.
- Data Rate --  $\sim 10^4$  kps.
- Temperature Range -- 0 to  $30^\circ$  C.
- Contamination -- None produced by instrument. Experiment sensitivity determined by local radiation environment, need radioactivity and material controls like HEAO.
- Unusual Acceleration or Vibration -- None.
- Consumables -- None.

#### Payload Carrier

Free flyer since long absolute times required. Pallet or pallet/sortie lab could be used for single observations. Requires other co-aligned X-ray and  $\gamma$ -ray experiments with following priority:

- 10-300 keV survey or spectrometer.
- 50 MeV  $\gamma$ -ray high sensitivity.
- 1-10 keV.

#### Mission Characteristics

Requires low altitude, low inclination orbit to avoid trapped particle and cosmic-ray induced radioactivity. Lifetime -- 6 months to one year, with reflight opportunity desirable.

- Orientation -- Must survey sky, point at selected objects.
- Pointing Accuracy -- Position with celestial sphere known to  $\sim 0.1^\circ$  for scanning, point to  $\sim 0.5^\circ$ .
- Communications -- Need command link, near real-time quick look data for operations. Requires continuous data retrieval.

- Timing Standards --  $\sim 1$  part in  $10^{10}$ /day for pulsar work.
- Dedication Ground Facility -- Mission operations center.
- Crew Support -- None.
- Unique Requirements -- Prefer equatorial orbit.

## G-5

### Type

Nuclear  $\gamma$ -ray High Resolution Spectrometer -- Large area Ge(Li) detectors with active anti-coincidence shielding.

### Objectives

To detect and study sources which emit nuclear  $\gamma$ -rays at a sensitivity of  $10^{-6}$  photons/cm<sup>2</sup>-sec or about 1/10 that of presently planned HEAO instruments. Moderate angular and best energy resolution available.

### Parameters

- Energy -- 0.05-10 MeV.
- Energy Resolution -- 2 keV or 0.2%.
- Area --  $\sim 250$  cm<sup>2</sup>, active.
- Field of View -- Angular resolution: 3° FWHM.
- Sensitivity --  $10^{-6}$  photons/cm<sup>2</sup>-sec.
- Weight -- 1500 lbs.
- Size -- 1.5 m x 1 m dia.
- Power -- 50 watts, passive cooling, 150 W active cooling.
- Data Rate -- 3 Kbps.

- Temperature Range --  $-20^{\circ}$  -  $+50^{\circ}$  C.
- Contamination -- Passive cooling system vents  $\text{LN}_2$ ,  $\text{NH}_3$ ,  $\text{CH}_4$ ,  $\text{CO}_2$ , or some other coolants.

Particularly susceptible to radio-active contamination both natural and induced. Requires low inclination, low-altitude orbit and material control.

- Unusual Vibration -- None.
- Consumables -- Cryogenics, if passive cooling.

### Payload Carrier

Pallet, or platform, to be reflown on 7 to 30 day missions.

### Mission Characteristics

- Inclination & Altitude -- Low as possible to avoid trapped protons and cosmic ray induced radioactivity.
- Operating Life -- Limited to cryogenic lifetime if passive cooling, but can be matched to mission lifetime.
- Pointing Accuracy --  $\sim 20$  arc/min for an integral duration  $\sim 10^5$  sec.
- Communications and Data Management -- Real-time data link for monitoring. Requires on-board storage, and dump to receiving stations for total data retrieval.
- Timing Standard -- Each event must be related to absolute time to  $\sim 10^{-4}$  seconds.
- Dedicated Ground Facility -- None, other than mission operations.
- Crew Support -- None.

Type

Development Pallet System for 10 keV - 20 MeV  $\gamma$ -ray Astronomy — A pointed facility for mounting relatively heavy single observation, exploratory and developmental instruments.

Objective

Make specific, one observation type of measurements on cosmic sources; develop and test new instrument concepts and techniques for implementation in the latter 1980's. Examples might be:

- Liquid He proportional counters.
- Computer telescopes.
- Polarimetry devices.
- New collimation and shielding techniques.

Parameters

- Energy Range — 10 keV - 20 MeV.
  - Sensitivity —
  - Dynamic Range —
  - Field of View —
  - Angular Resolution —
- } To be determined by specific instrument and objective.
- Weight — 500 - 5000 kg.
  - Size — Envelope probably 2 x 2 x 3 m maximum.
  - Power — 500 W should be available.
  - Data Rate — 5 - 10 kps.

- Temperature Range —  $0^{\circ}$  -  $30$  C.
- Contamination — Varies, may be cryogenic or counter gas venting, will require radioactivity and material control of nearby systems in pallet.
- Unusual Vibration or Acceleration — Not usually.
- Consumables — Cryogenics occasionally.

### Payload Carrier

Pallet mounted pointing, data and control system available for general class of heavy, crudely pointed exploratory and development experiments. Should be re-flyable with a different instrument for a 7-day observing period on 2-3 month turnaround.

### Mission Characteristics

- Inclination — Varies, usually low latitude, occasional equatorial may be desirable.
- Altitude — Low altitude to avoid trapped radiation.
- Operating Life — 7-10 days.
- Retrieval, Servicing, etc. — Instrument to be retrieved for reflight with different detector; no in-flight servicing required.
- Orientation — Should have capability of pointing at selected celestial object  $\pm 0.1^{\circ}$ , for at least 1 day ( $10^5$  seconds). More accurate pointing, if needed, will be part of instrument.
- Communications & Data — Near real time data and command link required; data storage for readout over control stations essential. Voice link may be useful if man in control loop.
- Timing Standards — Absolute accuracy  $100 \mu$  sec, relative accuracy 1 part in  $10^{10}$ /day maximum.
- Dedicated Ground Facility — Mission control console, easily adapted to various instrument and operation requirements.

- Crew Support — Varies, man could be used to adjust parameters, set modes, etc.
- Unique Requirement — Many flights of same basic system with experiment.

## G-7

### Type

Large High Energy Gamma Ray Survey Instrument combining Pictorial and Energy Measurement Detectors.

### Objective

To perform a full sky survey at a sensitivity at least an order of magnitude better than instruments flown as of the HEAO. The detector will have moderate energy and angular resolution and good time resolution.

### Parameters

- Energy Range — 20 to  $10^5$  MeV.
- Active Area —  $8 \text{ m}^2$ .
- Field of View — Approximately  $1/2$  sr.
- Energy Resolution — 10%.
- Angular Resolution — About  $2^\circ$ .
- Weight — 6,000 kg.
- Size —  $2.5 \times 2.5 \times 4 \text{ m}$ .
- Data Rate — Uncertain, possibly  $10^4$  bits/sec.
- Temperature Range — HEAO type range or preferably less.

- Contamination — Materials which have outgassing components affecting scintillators should be avoided. Normal satellite requirements for minimizing radioactivity and EMI interference should be met, but there are no special requirements beyond these.
- Unusual Acceleration or Vibration Limits — None.
- Consumables — Possibly spark chamber gas.

### Payload Carrier

Free Flyer.

G-8

Type

High Angular Resolution Instrument using a Picture Type Device.

### Objectives

- a. To locate more precisely previously identified sources of high energy gamma radiation, to correlate them with X-ray, optical or radio objects, and to study them with fine time resolution.
- b. To map diffuse radiation of extended objects in detail so that their dynamic properties can be studied in depth.

### Parameters

- Energy Range — 20 to  $3 \times 10^4$  MeV.
- Active Area — Uncertain, but probably about  $3 \text{ m}^2$ .
- Field of View —  $\sim 0.1$  sr.
- Energy Resolution — 10%.
- Angular Resolution —  $0.1^\circ$  to  $0.2^\circ$ .

- Weight — 3500 kg.
- Size — 3 x 3 x 2.5 m.
- Data Rate — Uncertain, but about  $5 \times 10^3$  bits/sec.
- Temperature Range — HEAO type range or preferably less.
- Contamination — Materials which have outgassing components affecting scintillators should be avoided. Normal satellite requirements for minimizing radioactivity and EMI interference should be met, but there are no special requirements beyond these.
- Unusual Acceleration of Vibration Limits — None.
- Consumables — Possibly spark chamber gas.

### Payload Carrier

Pallet and Free Flyer.

G-9

### Type

High Energy Resolution Detector with Pictorial Device for Positive Identification.

### Objectives

To study the energy spectrum of previously discovered objects in detail to look for unique changes in the spectral shape related to the source mechanism and to search for previously unknown high energy fundamental particle lines.

### Parameters

- Energy Range — 20 to  $10^5$  MeV.
- Active Area —  $A = 3\text{m}^2$ .

- Field of View —  $\sim 0.1^\circ$ .
- Energy Resolution — 3%.
- Angular Resolution —  $1^\circ$ .
- Weight — 3,500 kg.
- Size — 2.5 x 2.5 x 4 m.
- Data Rate — Uncertain, possibly  $5 \times 10^3$  bits/sec.
- Temperature Range — HEAO Type Range or preferably less.
- Contamination — Materials which have outgassing components affecting scintillators should be avoided. Normal satellite requirements for minimizing radioactivity and EMI interference should be met, but there are no special requirements beyond these.
- Unusual Acceleration or Vibration Limits — None.
- Consumables — Possibly spark chamber gas.

### Payload Carrier

Pallet or Free Flyer.

Note: It is possible that instruments G-8 and G-9 might be combined into one instrument that is somewhat larger than either and has a slightly larger bit rate.

## COSMIC RAY ASTRONOMY

### C-1

#### Type

Magnetic Spectrometer

#### Objective

Antimatter search, nuclear spectra, negatron-position spectra, isotopes.

#### Parameters

- Rigidity range —  $1 \leq R \leq 200$  GV/c,  $1000 \text{ cm}^2$  ster ( $30^\circ$  half cone).
- Charge range —  $1 \leq Z \leq 26$   $\Delta Z \simeq .2$ , 5% multiple scattering limits on rigidity.
- Weight, Dimensions — 6000 lbs., cylinder 10' diameter x 12' length.
- Power — Sortie version - 500 watts, Free Flyer - 50 watts, 250 watts additional power required during magnet charge. Magnet charge would be prior to release in case of free flyer.
- Data Rate — 10 K bits/sec.
- Temperature Range —  $10^\circ \text{ C} \rightarrow +40^\circ \text{ C}$ .
- Contamination — Generates: stray mag. field  $\simeq 50\text{g}$ , helium venting  $\sim 3$  lbs/day, neon venting  $\sim 10 \text{ ft}^3/\text{day}$  STP.
- Unusual Acceleration or Vibration Limits — None.
- Consumables — 1000 lbs. LHe (Free Flyer only), spark chamber gas.

#### Payload Carrier

Free Flyer and Sortie.

#### Mission Characteristics

- Inclination — Not critical.
- Altitude — Low.
- Operating Life — 7 days/meet modest objectives (Sortie) - 1 year (Free Flyer)/meets full objectives.

- Retrieval — Optional for Free Flyer - no service, etc., required.
- Orientation — Away from earth, scan (nominal).
- Pointing Accuracy — Aspect info  $\pm 1^\circ$  required.

## C-2

### Type

Gas Cerenkov Detector.

### Objective

Energy spectra and charge composition of cosmic ray nuclei.

### Parameters

- Charge range —  $3 \leq Z \leq 26$ .
- Geometry factor —  $\geq 1000 \text{ cm}^2 \text{ ster.}$
- Energy range — 1 GeV/nucleon to 200 GeV/nucleon.
- Weight, Dimensions — 1500 lbs.; Cylinder,  $\sim 3 \text{ m}$  high, 1.5 m dia.
- Power — 50 watts.
- Data Rate — 10 k bit/sec.
- Temperature Range —  $-10^\circ$  to  $+40^\circ \text{ C.}$
- Contamination — None.
- Consumables — Gas-filling for Cerenkov counters.

### Payload Carrier

Free Flyer.

### Mission Characteristics

- Inclination — Not critical.
- Altitude — Low.
- Operating Life — As long as possible (1 year).
- Retrieval — Optional on Free Flyer. No in-orbit servicing required.
- Orientation — Axis of cylinder should be perpendicular to earth's surface.
- Pointing Accuracy — Not critical, aspect information.
- Timing Standards — Spacecraft clock.
- Ground Facilities — Telemetry coverage.
- Crew Support — None.
- Unique Requirements — None.

C-3

### Type

Electromagnetic Calorimeter using shower detector (electronic counter detector).

### Objective

Electron energy spectrum.

### Parameters

- Geometry factor — 12,000 cm<sup>2</sup> sr.
- Energy resolution — ~ 10% range -1 GeV to 10<sup>4</sup> GeV. No separation between negatrons and positrons.

- Weight, Dimensions — 3000 lbs. Cylinder, ~ 2.5 m high, 1.5 m dia.
- Power — 50 watts.
- Data Rate — ~ 10 k bit/sec.
- Temperature Range — -10 to +40° C.
- Contamination — None.
- Consumables — None.

### Payload Carrier

Free Flyer.

### Mission Characteristics

- Inclination — Not critical.
- Altitude — Low.
- Operating Life — As long as possible (1 year)
- Retrieval — Optional on Free Flyer. No in-orbit servicing required.
- Orientation — Axis of instrument should be perpendicular to earth's surface.
- Pointing — Not essential, aspect info  $\pm 10$  required.
- Timing Standards — Spacecraft clock.
- Ground Facilities — Telemetry coverage.
- Crew Support — None.
- Unique Requirements — None.

C-4

Type

Nuclear Calorimeter.

Objective

Nuclear charge and energy spectra.

Parameters

- Energy range —  $10^1 - 10^5$  GeV,  $\frac{\Delta E}{E} = .2$
- Geometry factor —  $2 \text{ m}^2$  ster.
- Charge range —  $1 \leq Z \leq 30$   $\frac{\Delta Z}{Z} \leq .5$  @  $Z = 30$ .
- Weight and Dimensions — 12,000 lbs. 1 m x 1 m x 1 m spectrometer.  
Total volume 4 m x 4 m x 4 m.
- Power — 100 watts.
- Data Rate — 5k bits/sec.
- Temperature Range —  $-10^\circ$  to  $+40^\circ$  C.
- Contamination — Generates 1/2 MeV of  $\gamma$ -ray background due to large mass.
- Consumables — Gases for spark chambers, ionization chambers, proportional counters.

Payload Carrier

Free Flyer.

## Mission Characteristics

- Inclination —  $28.5^\circ$ .
- Altitude — As low as possible, consistent with operating life.
- Operating Life — 1 year lifetime.
- Orientation — Away from earth.
- Pointing — Aspect info  $\pm 1^\circ$  required.
- Timing — Spacecraft clock.
- Dedicated Ground Facilities — Minimal.
- Crew Support — Minimal.

C-5

## Type

Large Area Ionization Hodoscope.

## Objective

Elemental abundances for charges  $Z > 20$ .

## Parameters

- Energy range —  $> 10^9$  eV integral (set by geomagnetic cutoff)  $10^9$  eV -  $10^{11}$  eV differences.
- Charge range —  $20 \leq Z \leq 130$ ,  $\Delta Z = .3$ .
- Field of view — Geometry factor  $\sim 10 \text{ m}^2$  ster, area  $\sim 10 \text{ m}^2$  in modules of  $1 \text{ m}^2$  each.
- Weight, Dimensions —  $\sim 400$  lbs./ $1 \text{ m}^2$  module, total  $\sim 4000$  lbs.,  $1 \text{ m} \times 1 \text{ m} \times .75 \text{ m}$ /module.

- Power — ~ 50 w.
- Data Rate — 2 Kb/sec.
- Temperature Range — +10 - +40° C, must be monitored to 1° C.
- Contamination — None.
- Unusual Acceleration or Vibration Limits — None.
- Consumables — Ionization chamber gas.

### Payload Carrier

Free Flyer.

### Mission Characteristics

- Inclination — Determines cutoff and data rate, e.g., 45° orbit ~ 10<sup>9</sup> eV 1/2 year; 0° orbit ~ 10<sup>11</sup> eV 1 year.
- Altitude — Low.
- Operating Life — 1 year.
- Orientation — Away from earth.
- Aspect Info — ±1° post fact info, no active.
- Data — Telemetry + recording occasional quick-look.
- Timing Standards — Spacecraft clock.
- Ground Facilities — Telemetry coverage.
- Crew Support — None.

C-6

Type

Graded Cerenkov Counter.

Objective

Statistical isotopic separation using earth's magnetic field.

Parameters

- Rigidity range — 1 → 10 GV/c.
- Geometry factor — 1000 cm<sup>2</sup> ster; 30° half cone.
- Charge range —  $1 \leq Z \leq 26$ ,  $\Delta Z \simeq .1$ .
- Weight, Dimensions — 1000 lbs.; 5' cube.
- Power — 50 watts.
- Data Rate — 10 k bits/sec.
- Temperature Range — -10° C → +40° C.
- Contamination — Generates: neon venting ~ 10 ft<sup>3</sup>/day STP.
- Unusual Acceleration or Vibration Limits — None.
- Consumables — Spark chamber gas.

Payload Carrier

Free Flyer.

## Mission Characteristics

- ④ Inclination — 55° preferable.
- ④ Altitude — Low.
- ④ Operating Life — 1 year.
- ④ Retrieval — Optional on Free Flyer. No in-orbit servicing required.
- ④ Orientation — Scan with 1° aspect info.
- ④ Communications and Data Management — Telemetry and recording + occasional quick look.
- ④ Timing Standards — Spacecraft clock.
- ④ Dedicated Ground Facilities — Normal.
- ④ Crew Support — None.
- ④ Unique Requirements — None.

The following are the contents of each volume of this series:

EXECUTIVE SUMMARIES

VOLUME 1 — ASTRONOMY

VOLUME 2 — ATMOSPHERIC AND SPACE PHYSICS

VOLUME 3 — HIGH ENERGY ASTROPHYSICS

VOLUME 4 — LIFE SCIENCES

VOLUME 5 — SOLAR PHYSICS

VOLUME 6 — COMMUNICATIONS AND NAVIGATION

VOLUME 7 — EARTH OBSERVATIONS

VOLUME 8 — EARTH AND OCEAN PHYSICS

VOLUME 9 — MATERIALS PROCESSING AND SPACE MANUFACTURING

VOLUME 10 — SPACE TECHNOLOGY