GAMMA RAY ASTROPHYSICS TO THE YEAR 2000

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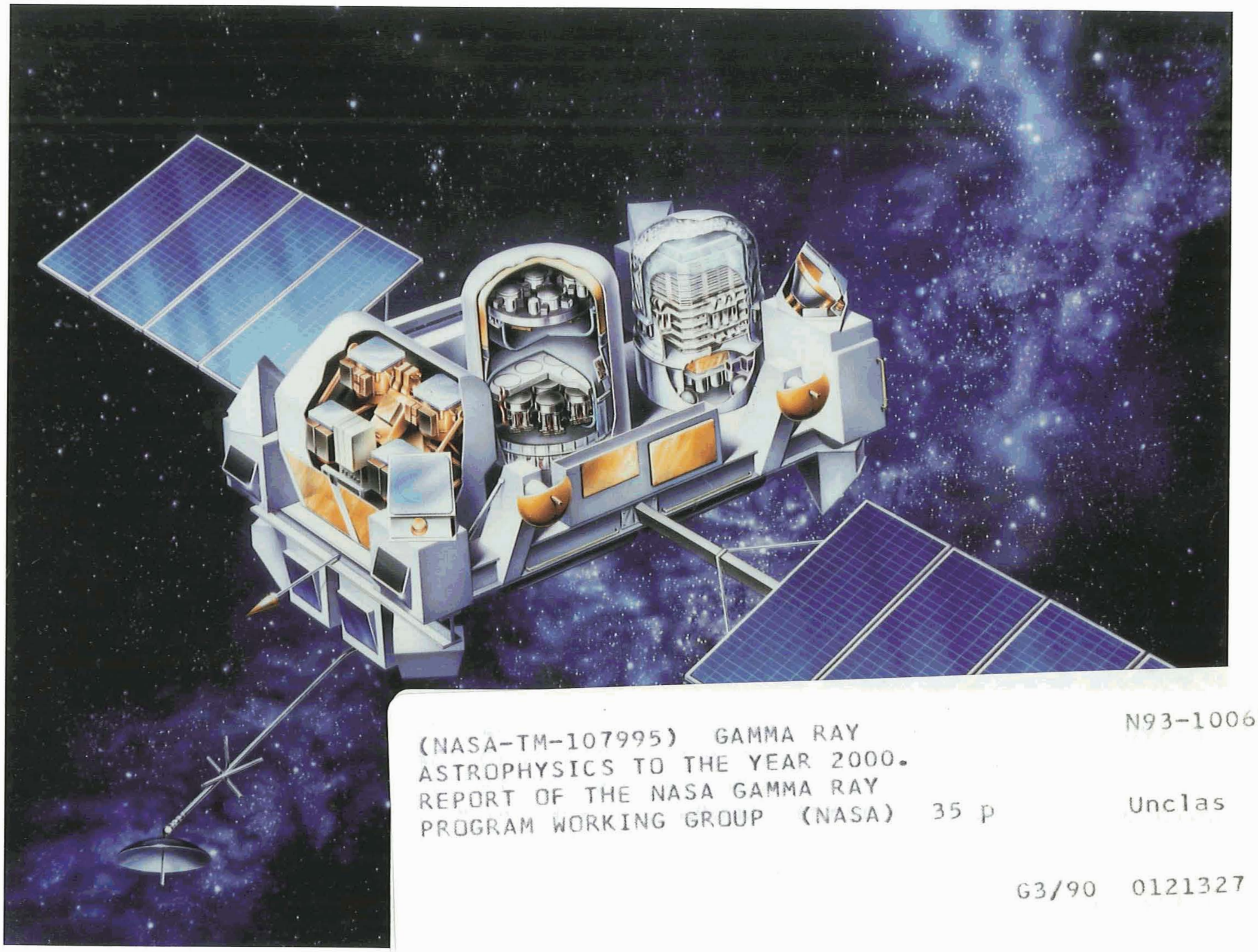

Report of the NASA Gamma Ray Program Working Group

OCTOBER 1988

ORIGINAL PAGE
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PREFACE

This report reviews the important developments in gamma-ray astrophysics up to energies of 100 GeV during the last decade; it seeks to define the major current scientific goals of the field; and it proposes a vigorous program to pursue them, extending to the year 2000.

The recent Space Science Board study *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015 – Astronomy and Astrophysics,* and earlier studies, such as the High Energy Astrophysics Management Operations Working Group's *Program in High Energy Astrophysics for the 1980's* and the reports from the Committee on Space Astronomy and Astrophysics, the Astronomy Survey Committee of the National Research Council, and NASA's Task Group on Astronomy and Astrophysics, have recognized needs in gamma-ray astronomy along with those of other subdisciplines of astronomy and astrophysics. Since the present report deals with gamma-ray astronomy alone, it provides greater detail both in scientific background and in the recommendations. The program recommended here generally encompasses the recommendations of the earlier reports, but in addition to providing greater detail there are important differences in emphasis due to changes and delays in the Gamma Ray Observatory program.

This report has been drafted by the Gamma Ray Program Working Group composed of the following members:

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SUMMARY OF RECOMMENDATIONS

Gamma-ray observations are the most direct means of studying many of the important problems in high energy astrophysics, including explosive nucleosynthesis, accelerated particle interactions and sources, and high-energy processes around compact objects. To pursue a vigorous study of these problems, we recommend the following program:

HIGHEST PRIORITY NEW MISSION

- An Explorer-class high resolution gamma-ray spectroscopy mission, such as the Nuclear Astrophysics Explorer (NAE) concept

HIGHEST PRIORITY MINOR MISSION

- A GAS-can or Scout class multiwavelength experiment for the study of gamma ray bursts, such as the High Energy Transient Experiment (HETE)

CONTINUING PROGRAM

- An Extended Gamma Ray Observatory (GRO) mission, recognizing its role as a Great Observatory with high potential for an active Guest Observer Program
- Continuation of the vigorous program of balloon observations of the nearby Supernova 1987A — a once-in-a-lifetime opportunity to study the nucleosynthesis and dynamics of a supernova at close range
- Augmentation of the balloon program to provide for new instruments and rapid scientific results through more frequent flight opportunities, long duration flights, and southern hemisphere campaigns
- Continuation of support for theoretical research needed to further our understanding of the great variety of gamma-ray sources that have been observed or predicted

LONG TERM NEEDS

- New space missions in the post-GRO/NAE/HETE period using advanced detectors with large improvements in sensitivity and angular resolution to better study sources identified in these and earlier missions and to open new areas for investigation
- Augmentation of the SR&T Program for the development of these detectors
- Continued study of the possibility for the assembly of large detectors in space
- Collaboration with the international gamma-ray astronomy missions initiated by other countries
- Consideration of the Space Station attached payloads for gamma-ray experiments

GOALS OF GAMMA-RAY ASTRONOMY

Gamma-ray astronomy explores the most energetic phenomena that occur in nature. Its observations now span more than ten decades of energy from < 1 MeV to > 10 PeV. They also embrace a great variety of processes – nuclear deexcitation, radiative capture, positron annihilation, pion decay, Compton scattering, bremsstrahlung, synchrotron emission, and curvature radiation – and an even greater diversity of astrophysical sources – solar flares, gamma-ray bursts, nova and supernova explosions, cosmic ray interactions and sources, neutron stars, black holes, active galactic nuclei and the cosmic gamma-ray background.

Gamma rays provide the most direct means of studying many of these sources and processes, not only because gamma rays allow us to see deeper into the objects, but because the bulk of the power radiated by them is often at gamma-ray energies. Moreover there is unique astrophysical information encoded in gamma-ray lines — their energies, shapes, and intensities. Not only do lines indicate the presence of specific nuclei or electron-positron pairs, but the line parameters, i.e. intensities, centroid shifts, widths and profiles, contain information on abundances, bulk velocities, gravitational potentials, densities, temperatures, and accelerated particle spectra. Furthermore, the high transparency of matter to gamma rays allows them to be used as tracers of high-energy processes anywhere in the Galaxy, except for stellar interiors. Thus gamma-ray observations are crucial in unraveling the mysteries of high-energy astrophysics.

In the following, we highlight some of the mysteries that still need to be unraveled before we can understand these objects, and we point out the decisive gamma-ray observations that are required. The discussion is organized into three broad areas which include most of the gamma-ray sources and emission processes: explosive nucleosynthesis, accelerated particle interactions and sources, and high-energy processes around compact objects. We discuss gamma-ray and hard x-ray studies in the energy range from 10 keV to 100 GeV, with emphasis on the 0.1 to 10 MeV range. Investigations at these energies, which can only be studied by experiments on spacecraft and high-altitude balloons, are being carried out by NASA. We do not discuss here the investigations in ultra-high-energy gamma-ray astronomy (> 100 GeV) being carried out by ground-based experiments.

GAMMA RAYS FROM NUCLEOSYNTHESIS

Current observational and theoretical studies indicate that all of the elements heavier than lithium have been produced as by-products of stellar evolution by nucleosynthetic processes that continue even to the present. But many questions still remain to be answered about the current and past rates of nucleosynthesis of various isotopes, about the sites and spatial distribution of nucleosynthesis in the Galaxy, and about many details of the specific models of nucleosynthesis in supernovae, novae and other objects.

Gamma-ray observations are uniquely suited to help provide answers to all of these questions, because of the gamma-ray lines that can be detected from the decay of a rich variety of isotopes covering a wide range of radioactive lifetimes. The principal nucleosynthetic lines are at 0.847 and 1.238 MeV from ^{56}Ni$\rightarrow^{56}$Co$\rightarrow^{56}$Fe decay with a 0.31 yr mean life; 0.122 and 0.136 MeV lines from ^{57}Ni$\rightarrow^{57}$Co$\rightarrow^{57}$Fe decay with a 1.07 yr mean life; 1.275 Mev from ^{22}Na$\rightarrow^{22}$Ne decay with a 3.8 yr mean life; 0.0679, 0.0784 and 1.157 MeV from ^{44}Ti$\rightarrow^{44}$Sc$\rightarrow^{44}$Ca decay with a 78 yr mean life; and 1.809 MeV from ^{26}Al$\rightarrow^{26}$Mg decay with a $1.1\text{x}10^6$ yr mean life. In some fraction of their decays all of these radionuclei also produce positrons, which then annihilate to produce additional line emission at 0.511 MeV.

Explosive Phenomena

Detectable transient gamma-ray line emission at 0.847 MeV and other energies is expected from nucleosynthetic ^{56}Co in extragalactic supernovae for a few years following their explosions — and current observations of the Supernova 1987A are fully confirming that expectation. Measurements of the time-dependent energy profiles of these gamma-ray lines are extremely important because they can provide detailed diagnostics of the supernova explosion and critically test the models that have been proposed to explain them. The time-dependent line profile directly measures the velocity gradient across the expanding supernova ejecta as it becomes transparent to gamma rays. Such time-dependent measurements thus enable us to determine not only the velocity distribution as a function of the column depth and density within the ejecta, but the total mass and energy of the ejecta as well. For such measurements high spectral resolution is, of course, absolutely essential.

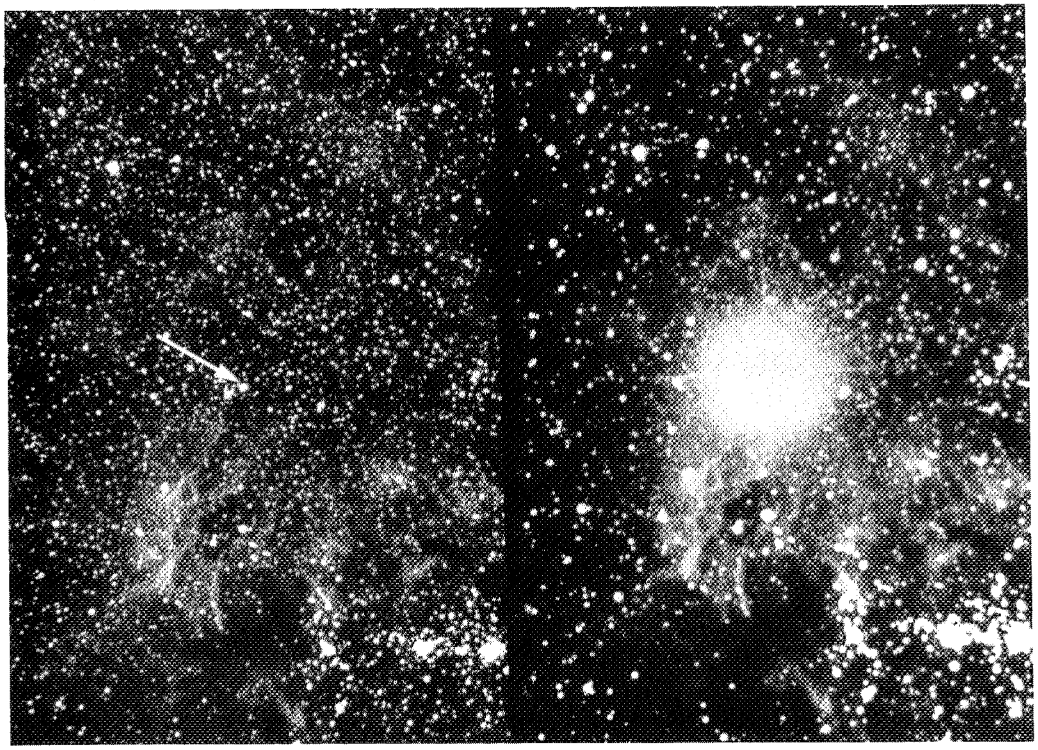

FIGURE 1. SUPERNOVA 1987A IN THE LARGE MAGELLANIC CLOUD

Such gamma-ray measurements can also shed new light on the origin of the different classes of Type I supernovae that have been distingushed by their light curves and spectra. Types Ia and Ib are definitely distinct. The latter group is relatively faint near optical maximum and lacks silicon absorption lines seen in the former. Still more telling is the presence of strong oxygen emission in the spectrum of Type Ib at late times. Type Ip, or "one-peculiar", may be yet a third class distict from both Ia and Ib. It is generally agreed that Type Ia, the "classic" Type I supernovae, originate from carbon deflagration (*i.e.*, a subsonic flame) in carbon-oxygen white dwarf stars approaching the Chandrasekhar mass, but controversy exists regarding the nature of Ib's and even the existence of Ip's. They could be the hydrogen stripped cores of massive (Wolf-Rayet) stars, that are either in binaries or that have lost their envelopes by stellar wind, helium detonation in the outer layers of a white dwarf having a core of carbon and oxygen, helium detonation commencing in the center of a helium white dwarf, or a simple variation (flame speed?) on the carbon deflagration scenario for Type Ia. All these models give differing amounts of and different velocity distributions for the ^{56}Ni that, in each case, powers the light curve. Thus gamma-ray spectroscopy should aid in distinguishing different classes of events and assigning each to a unique theoretical model. This in turn would give greater confidence to those who would use Type I supernovae as the best available standard candle for getting the Hubble constant.

Similar measurements of Type II supernovae can also greatly increase our understanding of these events, because they can not only provide diagnostics of the explosions, but can also give for the first time a direct determination of the mass of the exploding star. The optical light curves of these supernovae vary from event to event and are thought to be strongly dependent on the mass of the exploding star, but the masses of the presupernova stars are not known. Since the expected gamma-ray line strengths, profiles, and time histories from these supernovae are uniquely dependent on the mass and energy of the exploding star, both can be determined for each supernova. Thus for the first time we will be able to test supernova model calculations for a particular mass star with the optical and gamma-ray observations of its supernova.

The occurrence of the Type II Supernova 1987A in the Large Magellanic Cloud – the closest supernova seen since Kepler's in 1604 – has given us a unique opportunity for studying such supernovae and an extensive observing program has been mounted. The Solar Maximum Mission (SMM) and the ROENTGEN/KVANT module of the Mir space station are monitoring the supernova gamma-ray line and continuum fluxes and balloon-borne spectrometers are obtaining high-resolution line and continuum spectra. These observations have already excluded a number of proposed models and they have shown that there is considerable mixing of the ^{56}Co into the overlying ejecta. Since the balloon-borne detectors should continue to observe the 0.847 MeV and other lines through 1989, they should eventually enable us to determine the ejecta mass versus velocity distribution and hence the total mass and energy of the explosion. Moreover, the launch of GRO in 1990 should enable us to look for line emission at 0.122 MeV from longer-lived ^{57}Co, providing additional information on the neutron capture and r-process nucleosynthesis in the supernova.

SN 1986G, a Type I supernova, also occured in a relatively nearby galaxy, Cen A; but unfortunately SMM was not able to observe it until the fall of 1986, some 120 to 225 days after the optical maximum. By that time the ^{56}Co line intensities were about 0.25 of their maximum values and the SMM detectors were only able to set a 3σ upper limit on the combined flux of the 0.847 and 1.238 MeV lines corresponding to a ^{56}Co mass of < 0.74 $M_\odot$. This is just slightly greater than the 0.4 to 0.6 $M_\odot$ of ^{56}Co expected from recent models of Type I supernovae.

Further diagnostic studies of explosive nucleosynthesis in supernovae and novae clearly require both high sensitivity and high spectral resolution. To study Type I supernovae in other galaxies one needs a gamma-ray line sensitivity considerably better than 10^{-5} photons/cm^2 sec and energy resolution < 10 keV FWHM. To study lines from novae and Type II supernovae, still better energy resolution is required, approaching 1 keV. The required sensitivity for detecting gamma-ray lines from novae is unknown and depends strongly upon model parameters.

Gamma-ray observations of the 1.275 MeV line from the decay of ^{22}Na produced in the explosions of classical novae may be visible from white dwarfs at distances up to about a kiloparsec, and could provide important diagnostics on both the nucleosynthetic yield and the nature of the explosion. ^{22}Na is a direct consequence of explosive hydrogen burning, and its time-dependent line profile gives a direct measure of the ejection velocity of the nova and, perhaps, its time history. The abundance of ^{22}Na is very sensitive to both the time scale and the degree of convective mixing in the burning region and to the composition of the white dwarf, whether it is predominantly carbon and oxygen, or neon, oxygen, and magnesium.

Rates and Sites of Nucleosynthesis

Diffuse galactic gamma-ray line emission at 1.809 MeV from the decay of ^{26}Al with a flux of 4x10^{-4} photons/cm^2 sec per radian of galactic longitude has been discovered by the high resolution Ge spectrometer on HEAO-3 (Fig. 2) and confirmed by detectors on SMM. These observations reveal that there is about 3 $M_\odot$ of ^{26}Al dispersed in the interstellar medium. This requires an average galactic production rate of about 4x10^{42} ^{26}Al/sec. However, the origin of the ^{26}Al is still unknown; the observed flux is roughly 10 times that originally predicted from supernova nucleosynthesis. Thus, the gamma-ray observations point to other possible sources, such as novae, red giants, and Wolf-Rayet stars.

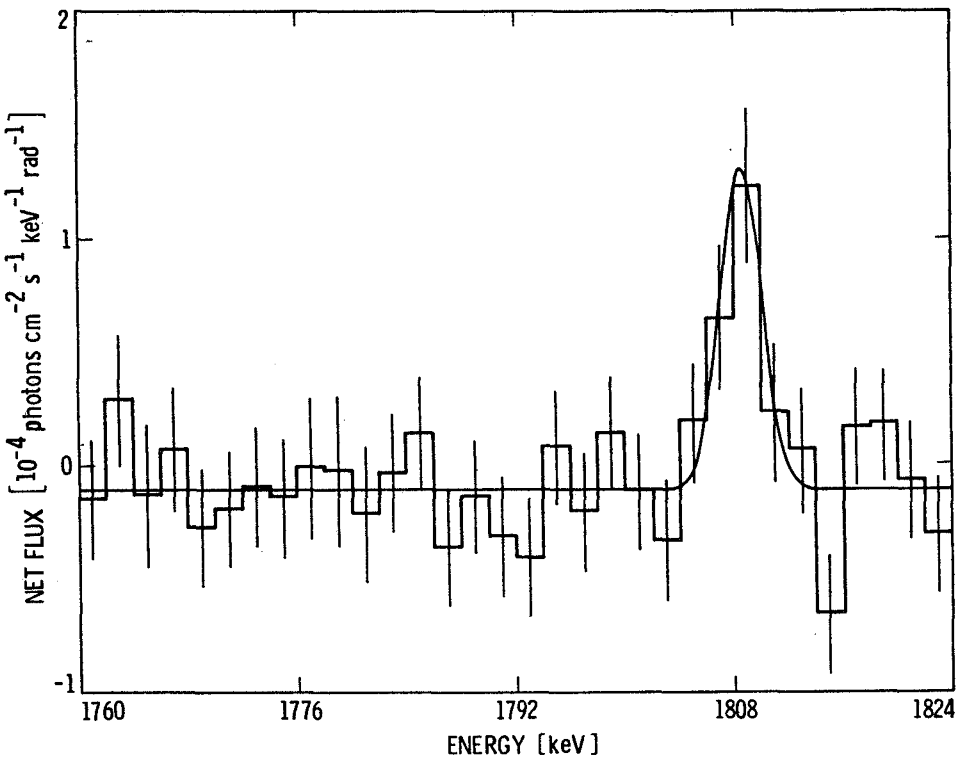

FIGURE 2. HEAO-3 SPECTRUM OF GALACTIC 1.809 MeV LINE

Detailed measurements of the galactic longitudinal distribution of this line should distinguish between these possible sources, using their differing spatial distributions. A recent Compton telescope observation of the 1.8 MeV emission suggests that it is strongly peaked toward the Galactic Center, and narrower than that expected from Type II supernovae. Within the large uncertainties of this measurement, the reported distribution is also consistent with a point source at the Galactic Center, but that is not consistent with other observations. More sensitive measurements are required with an angular resolution of a few degrees or better.

The recently discovered diffuse galactic emission in the positron annihilation line at 0.511 MeV with a flux of 1.6x10^{-3} photons/cm^{2}sec rad may also result from the β^+ decay of nucleosynthetic radionuclei. If so, these observations can also provide a measure of the rate of nucleosynthesis, averaged over the positron lifetime of as much as 10^7 yr in the interstellar medium. The most likely source of these positrons is either the decay of ^{56}Co or ^{44}Sc made in Type I supernovae, as the contribution of all non-nucleosynthetic sources is thought to be $< 20\%$. Detailed measurements of the galactic distribution of this line will play a key role in determining the origin of this emission.

Detectable fluxes of 1.157, 0.0784 and 0.0679 MeV line emission from $^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$ decay should also be observed from young galactic Type I supernovae up to several hundred years old – thus revealing the locations of the most recent supernovae in our Galaxy, which were undetected optically because of the obscuration in the galactic disk. Moreover, a measurement of the line profiles, especially that at 1.157 MeV, can provide a unique determination of the age of each supernova. This is possible because the light-travel time across the nebula becomes comparable to the 78 yr decay mean life, thus leading to an increasing redshift of the line peak with age. Such measurements require a line sensitivity of $< 10^{-5}$ photons/cm^2 sec and an energy resolution $E/\Delta E$ of 100.

Measurements of the distribution of these lines in the Galaxy will thus allow us to determine not only the sites of the most recent galactic supernovae, but also the history of supernova activity over the last several million years. Mapping the galactic distribution of ^{26}Al and positrons requires a sensitivity of $\leq 10^{-5}$ photons/cm^{2}sec and much better angular resolution than previous detectors (HEAO-3 had a 42° FWHM and SMM 130° FWHM). Angular resolution of less than a few degrees is required to distinguish stellar populations, and still finer resolution will be needed to usefully determine the positions of the most recent supernovae in our Galaxy.

GAMMA RAYS FROM ACCELERATED PARTICLES

The acceleration of charged particles to relativistic energies is ubiquitous in high-energy astrophysical processes, occurring in such diverse sources as solar flares, the interstellar medium, pulsars, accreting compact objects and active galactic nuclei. The underlying processes may be quite similar, or may vary significantly. Understanding these acceleration processes is thus a fundamental problem in high energy astrophysics, and hard X-ray and gamma-ray observations are proving to be an important diagnostic tool for their study.

Observations of gamma rays from the interactions of accelerated particles are providing unique information on both the acceleration processes and their sites - especially for solar flare particles and for cosmic rays.

Solar Flares

Solar flares enable us to study at close range particle acceleration processes in high energy plasmas, similar to those that occur on a much larger scale elsewhere in the universe. In a plasma environment with $\sim 10^3$G fields, electrons and nuclei are accelerated to relativistic energies. Gamma rays produced by the interaction of the particles with the solar atmosphere provide a direct probe of the flare acceleration process. Gamma-ray line observations by SMM enable us to study the solar abundances, energy spectrum, time history, and angular distribution of the accelerated particles at the Sun. High resolution spectroscopic measurements, however, are needed to better determine solar abundances in the flare region, and high resolution imaging can also provide great advances in our understanding of flare physics.

Galactic Cosmic Rays and Their Sources

The high energy (> 50 MeV) gamma rays observed from the galactic disk by the SAS-2 and COS-B detectors include contributions both from discrete objects and from diffuse processes. Much of the diffuse component is presumed to arise in collisions of cosmic rays with interstellar gas nuclei. In these collisions, the cosmic ray nuclei (mostly protons and alpha particles) generate gamma rays via the production and subsequent decay of neutral pions, while the cosmic ray electron (and positron) component produces gamma rays via bremsstrahlung. Additional gamma radiation is produced via Compton scattering by cosmic ray electrons on optical and infrared photons.

Considerable success has been achieved in modelling these processes to reproduce the observed gamma-ray distribution, using the results of HI and CO surveys and assumptions concerning the galactic distribution of cosmic rays. From this work has come preliminary information on the cosmic ray distribution, and on the large scale ratio of atomic to molecular hydrogen. Through better statistics and angular resolution, future gamma-ray observations from the Gamma Ray Observatory and Gamma-1 missions should contribute toward a fuller understanding of the distribution of cosmic rays and gas within the Galaxy. If the nucleonic cosmic ray gradient is found to have a scale length significantly greater than the 15 kpc now indicated, it will severely restrict theories of cosmic ray propagation.

One of the principal uncertainties in this effort is the contribution of discrete sources to the galactic gamma ray flux. About two dozen sources were detected in the COS-B data, which are compatible, given the one-to-several degree resolution of the instrument, with discrete sources. Their spatial distribution indicates that these sources must be mostly galactic. Two are uniquely identified with the Crab and Vela pulsars via their time signatures; the remainder have not been clearly associated with objects seen at other wavelengths, despite considerable effort in the radio and X-ray bands.

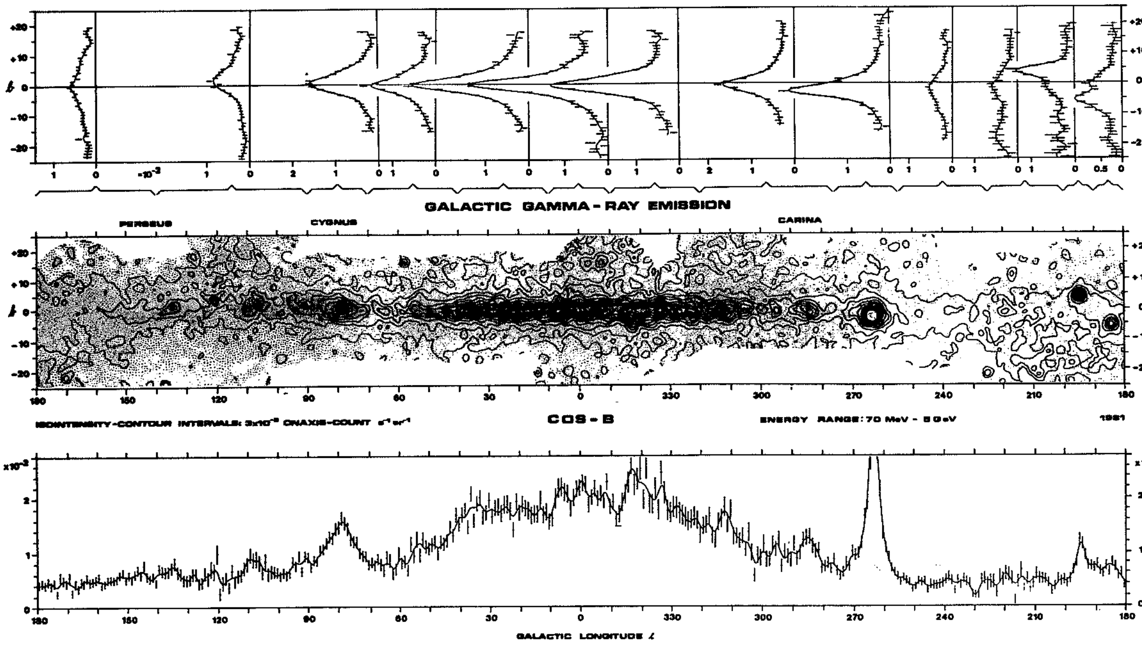

Figure 4

FIGURE 3. COS-B OBSERVATIONS OF 70 MeV – 5 GeV GALACTIC EMISSION

Two emission regions found in the COS-B data seem to be noticeably extended and associated with the dense molecular clouds in Orion and Ophiuchus. This points to the possibility that some of the unidentified sources are also associated with molecular clouds, farther away and therefore unresolved.

Thus the identification of the COS-B sources, which have not yet been associated with objects seen at longer wavelengths, is a high priority for future gamma-ray observations. In addition to the inherent interest in the objects themselves (discussed in more detail below), identification of one or more classes of stellar gamma ray emitters would permit the incorporation of appropriate contributions into the diffuse galactic models.

Lower energy gamma-ray observations can also provide new and unique information on the intensity of low energy ($<$ 100 MeV) cosmic rays. Such charged particles cannot be observed directly near the Earth because they are excluded from the inner Solar System by solar modulation. However, observations of gamma-ray lines resulting from nuclear excitations of interstellar gas and dust by low energy cosmic rays, such as those at 4.438 and 6.129 MeV from $^{12}C^*$ and $^{16}O^*$ can give a measure of the intensity of these cosmic rays. Current limits of about 10^{-3} photons/cm^2 sec per radian of galactic longitude are more than an order of magnitude higher than the fluxes predicted for low energy cosmic rays with an energy density of 1 eV/cm^3, and more than two orders of magnitude higher than derived from recent estimates of the ionization rate of interstellar hydrogen.

GAMMA RAYS FROM NEUTRON STARS

Gamma-ray emission has been observed from a variety of discrete sources, including pulsars, X-ray binaries and gamma-ray bursts, which are thought to be neutron stars, based primarily on their rapid pulsed emission and their spectral features, implying very large (10^{12} gauss) magnetic fields.

Gamma-Ray Bursts

Gamma-ray bursts are arguably the most intriguing, yet baffling class of gamma-ray sources known today. Several hundred have been observed in the energy range from a few keV to 100 MeV and, aside from a few sources, bursts have not been observed to repeat in the same location. Thus gamma-ray bursts are also the most numerous sources of high energy radiation in the sky, rivaling the number of known radio pulsars. Still, with one exception, a controversial association of the March 5, 1979 event with a supernova remnant in the Large Magellanic Cloud, no gamma-ray burst has ever been identified with any known object. An origin on or near magnetic neutron stars is suggested by a variety of circumstantial evidence – the rapid time variability of the burst, its hard non-thermal spectrum, the 8-second periodicity of the pulsing tail of the March 5 event, the similarity of the spectrum of the "soft repeaters" and that of typical X-ray pulsars, and the occasional presence of spectral features near 50 keV and 400 keV that have been interpreted as cyclotron absorption in a 10^{12} gauss field and red-shifted pair annihilation, respectively. Still, often by neglecting one or more of these features or assigning them to a separate class, theorists have been able to devise an exceedingly diverse set of models for the bursters.

Various burst processes have been proposed. Thermonuclear flashes on accreting neutron stars (which would make gamma-ray bursts close cousins to Type I X-ray bursts), transient accretion, and neutron starquakes have been the three favorite models for many years, but other models continue to proliferate so that proposed sources range from neutron stars at 10 parsecs or so to the explosion of cosmic strings near the edge of the universe. Yet neither of these models, which differ in inherent energy by a factor of 10^{14}, can be definitively ruled out. The crux of the dilemma is not knowing where any gamma-ray burster is situated. This inability to associate a frequent phenomenon with any known object is unique to gamma-ray burst astronomy. Precise burst locations are clearly needed to help resolve the nature of these sources.

The highest priority goal should therefore be to identify quiescent counterparts and to constrain the source properties as tightly as possible. This means extracting the maximum amount of information from the burster at the only time it is clearly visible, *i.e.*, when it is bursting. The traditional techniques of studying time variation of the spectrum and its features, at high energy resolution where feasible, will aid in providing these constraints. The GRO's high sensitivity and time resolution, broad energy band and energy resolution of 7% should provide much new information on source properties, in particular the line temporal properties and very short time scale intensity measurements, down to 10μsec. In addition, GRO's angular resolution of approximately 1° will determine many new error boxes and, based upon statistical arguments, will help to distinguish galactic plane and other distributions. However, these error boxes will not be small enough to justify deep searches with large telescopes. After 15 years of study, only three gamma-ray bursts have been localized to better than 1 arc minute, not counting a few more error boxes based upon uncertain identification with archival optical transients. Some of these error boxes are empty to very faint levels. Others have seemingly ordinary stars, but nothing unusual.

The best hope for source identification lies in multiwavelength observations. Gamma-ray bursts are known to emit a few per cent of their energy as soft X-rays, and they may emit as much as 0.1 per cent as optical light. Both X-rays and optical emission can give more accurate locations for a large number of bursts. Moreover, the different time histories and spectral shapes in these two bands can tell us much more about the nature of the site and mechanism. If optical flashes were to be detected by modern instrumentation in conjunction with an observed gamma-ray burst and the timing ($\sim$ 1 sec time resolution), location (few arc seconds angular resolution), and intensity of the flash observed accurately, it would be a major breakthrough in the study of gamma-ray bursts. The location can tell us where to look with other instruments with an error box known to contain a gamma-ray burster and small enough to take full advantage of modern instrumentation, such as the Ten Meter Telescope and Hubble Space Telescope. The timing relative to the gamma-ray emission tells us if the optical emission comes from a disk or companion star, or if it is produced in the magnetosphere. High optical polarization would be definitive evidence for a strong magnetic field. The ratio of L_{opt}/L_{γ} from burst to burst would tell of variations in disk or magnetospheric properties. On the other hand, if optical flashes are not seen down to a level 10^4 times fainter than that inferred from possible archival optical transients, that would also restrict the models and demonstrate the futility of searching for quiescent counterparts in error boxes based upon historical optical transients.

The X-rays themselves could also give accurate positions ($\sim$ 5 arc min), about a factor of 10 smaller in dimension (100 in area) than GRO. Also important is the information carried in the soft "tail" of the X-ray emission. GINGA observations now suggest that the spectrum of the tail approaches a blackbody of limiting temperature around 2 keV from which the ratio of the emitting area to the square of the source distance can be determined. Their initial analyses suggest that the bursts they studied must be closer than 1 kpc. The actual distance scales with the square root of the fraction of the emitting star. In addition the decay time of this thermal tail is determined by the thickness of the cooling layer. Since the accretion and nuclear explosion mechanisms differ by a factor of 100 in the accreted column depth, the X-rays can be used as a diagnostic of the mechanism.

Thus, the highest priority for gamma-ray bursts is an experiment designed to study and localize bursts concurrently across a wide band of emission. This requires a combination of three instruments having large fields of view in the gamma-ray, X-ray, and optical/UV bands.

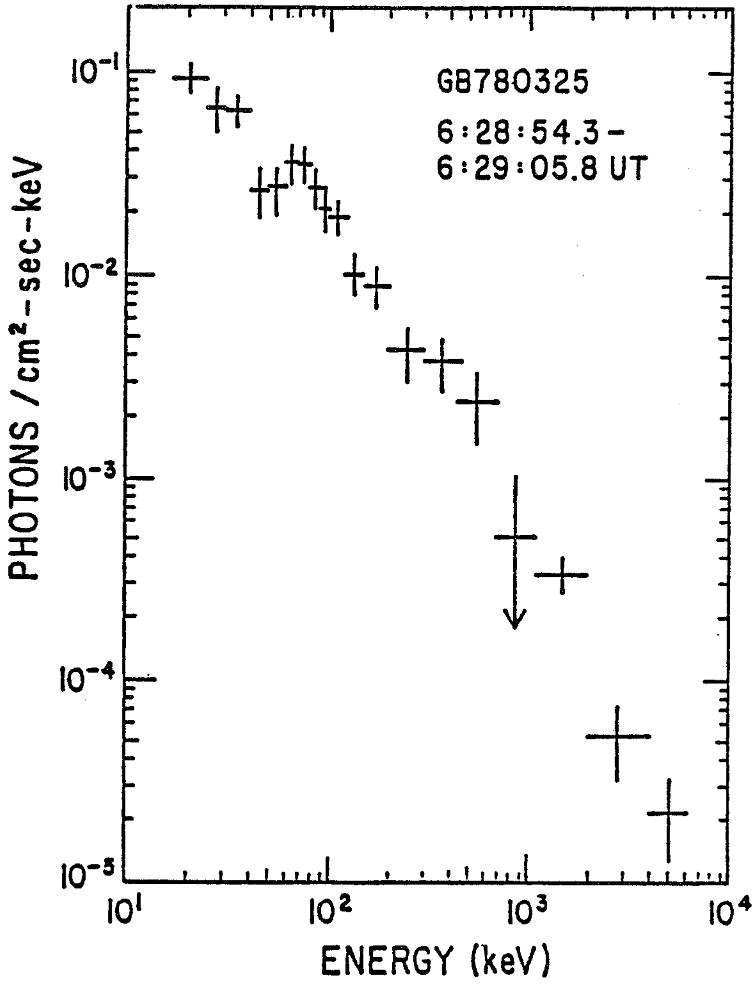

FIGURE 4. HEAO-1 SPECTRUM OF GAMMA-RAY BURST ABSORPTION AND EMISSION FEATURES

To further constrain the nature of the burst sources and emission processes, it is also necessary to observe bursts with sufficient energy resolution and sensitivity to resolve the already known spectral features in the stronger bursts (e.g. Figure 4), measure their temporal properties and search for nuclear lines, which must be present if accelerated ions are part of the burst energy transport. These lines could be quite narrow, FWHM/E $< 10\%$ for ion energies up to 100 MeV/nucleon. The cyclotron lines are known to have widths less than $\sim 10\%$ and their profile must contain detailed information on the magnetic field geometry and the degree to which it confines the burst plasma. Thus high spectral resolution ($E/\Delta E > 100$) observations are necessary.

Gamma-Ray Pulsars

There are two classes of pulsed, gamma-ray emitting neutron stars: the radio pulsars, which are relative young, single, rapidly rotating , highly magnetic neutron stars, and the X-ray binaries, or "X-ray pulsators", which are presumably older, rapidly accreting, magnetic neutron stars with close binary companions.

Pulsed gamma-ray emission has been observed so far only from the two youngest observed radio pulsars - the Crab and Vela. The pulsed gamma-ray emission from both pulsars is double-peaked, but the Crab pulse peaks remain constant in phase from radio to gamma-ray energies, whereas the Vela radio, optical and gamma-ray peaks differ in number and phase. The proposed gamma-ray emission mechanisms for these rapidly rotating magnetic neutron stars include: curvature radiation, synchrotron emission, and Compton scattering. Transient gamma-ray line emission in the Crab spectrum at about 78 keV and 400 keV has been reported at different times by several observers suggesting that cyclotron emission and positron annihilation may also be important at or near the surface of the star.

Time variations are seen in the pulsed intensity from both the Crab and Vela at energies above 100 MeV, possibly extending to 10^{12} eV or higher. Most recently, exciting new evidence has been found in the COS-B data showing that the Vela pulsar gamma-ray emission increased by a factor of two in a period of 30 to 40 days following the October 1975 spin-up "glitch" and then decayed with a time constant of about 100 days. The bulk of this emission occurred in the interpulse phase of the pulsed light curve.

More sensitive gamma-ray observations of these and other pulsars correlated in time with observations at other frequencies, are needed to better understand the nature of isolated pulsars themselves, as well as the process of gamma-ray emission. Moreover, the birth of a neutron star in the Supernova 1987A, inferred from the neutrino observations, may provide us with the unique opportunity of seeing a pulsar in its infancy and studying the development of its emission spectrum all the way from gamma-ray to radio wavelengths.

Pulsed emission from accreting neutron stars in binary systems has been observed primarily in the X-ray and hard X-ray regions. Evidence also exists for transient pulsed emission at energies of 10^{12} ev in a few of the stronger sources. Most of the sources of pulsed gamma-ray emission fall into the category of "massive X-ray binaries", although a small fraction of the "low-mass X-ray binaries" also yield detectable pulsed radiation. The former are usually interpreted as stellar-wind accretion driven sources while the latter are usually considered to be driven by Roche-Lobe overflow.

While both types of X-ray binary systems have been well studied up to about 20 keV, less detail is available about the emission in the next higher decade of energy, from 20 to 200 keV. About 20 X-ray pulsars were detected with HEAO A-4, but most were at the sensitivity limit of the instrument and detailed characterization of transient behavior and pulse-phase spectroscopy was not possible. Time-resolved spectroscopic studies of continuum and line emission will be critical for improvements in the understanding the accretion process in these objects, as well as for understanding of the high temperature thermal plasmas and transient, non-thermal episodes of particle acceleration.

One unique aspect of observations in the 20–200 keV region is the possibility of studying cyclotron emission. Electrons in the accreting plasma can undergo transitions between discrete Landau levels in the intense ($\sim 10^{12}$ gauss) field of the star, giving rise to both hard X-ray emission and absorption lines at the fundamental cyclotron frequency and its harmonics. Observation of these lines would yield a direct measurement of the magnetic field intensity, and the line profiles could be interpreted in terms of the spatial distributions of the field and the accreting matter.

Thus far, three X-ray pulsars, Her X-1, 4U0115+63 and GX1+4 (and possibly the Crab or A0535+26) have had cyclotron features identified in their spectra, at energies between 20 and 80 keV. The best studied of these, Her X-1, has a pulse phase shift in its line emission and measurement of the intrinsic line profile on time scales of hours have yielded a 10 keV width at 35 keV. Changes in the absorption and scattering properties of the pulsar accretion column, as well as changes in the viewing angle with respect to the magnetic field, will appear as changes in the cyclotron emission or absorption profile (and central energy) with pulse phase. Detailed study of the continuum and cyclotron line spectra as a function of pulse phase could provide important new constraints on the origin and evolution of strong magnetic fields in neutron stars, the physics of radiative transfer in strong magnetic fields, and the physical processes operating (e.g., shock formation) in magnetized accretion columns.

There are two critical requirements for future observations. First the brighter sources must be studied with good sensitivity and good spectral resolution, $E/\Delta E > 100$, so that changes in the intrinsic spectral line shape can be resolved and deconvolved from its pulse phase variability. Second, a large sample of X-ray pulsars must be studied with adequate statistics for pulse-phase spectroscopy. The initial work can be with moderate resolution, $E/\Delta E \sim 10$, instruments which can detect spectral lines. Follow-up observations would be done at high resolution. Large area, moderate-resolution detectors with a sensitivity approaching a few times 10^{-7} photons/cm^2 sec keV and high-resolution spectrometers with line sensitivity of approximately 10^{-5} photons/cm^2 sec are required.

Neutron Star Accretion Sources

Not all high-energy emissions associated with neutron star accretion are necessarily pulsed. For instance, low-mass X-ray binaries produce primarily unpulsed, but highly variable, emission. Studies of the low-mass X-ray binaries are of particular interest because of their probable evolutionary link to millisecond radio pulsars and the recently discovered radio pulsars in globular clusters. The spectra of the low-mass binary systems are generally much softer than those of massive X-ray binaries, and those low-mass systems, such as Her X-1, that do exhibit pronounced hard X-ray emission also tend to exhibit pulsed behavior. HEAO A-4 detected about 6 low-mass binary systems with known orbital periods, and about 10 other X-ray bursters in the galactic bulge region, which are also thought to be possible low-mass binary systems. Of particular interest for hard X-ray and gamma-ray observations are the flaring phenomena in these objects, such as that seen for Cyg X-3 and GX13+1. Radio emission and a correlation between spectral hardness and intensity have been observed, providing evidence for particle acceleration during transient outbursts. More sensitive detectors are needed with the ability to obtain accurate spectra over short time periods to advance our understanding of these systems.

Gamma-ray line emission produced by positron annihilation or nuclear deexcitation near a neutron star's surface can be employed to constrain the equation of state of the neutron star. From the spectral decomposition of the line profiles of such emissions, the gravitational redshift can be determined consistently, and consequently the ratio of stellar mass to radius can be derived. Such redshifts alone should place important constraints on models of equations of state. If further information is available, such as neutron star masses, or measurements of neutron star pulsations, an equation of state could be determined essentially uniquely from such redshifts. Potentially observable surface line fluxes as large as a few times 10^{-5} photons/cm^2-sec have been predicted from accreting neutron stars. Thus future gamma-ray line measurements may constrain the equations of state of nuclear matter at high densities and ultimately answer such questions as whether or not a pion condensate exists at the core of a neutron star.

Unidentified COS-B Sources

The COS-B sources not identified with objects seen at longer wavelengths are another mystery in gamma-ray astronomy, although at least some are likely to be neutron stars. The source known as Geminga (CG195+04), discovered by SAS-2, is the prototype in that it is one of the most intense 100 MeV gamma-ray sources, but has no obvious radio, optical or X-ray counterpart within the 1° COS-B error circle. The gamma-ray luminosity of this object thus seems to far exceed that in all other wavelengths combined, so that it appears to be a "gamma-ray star". Although the other unidentified sources are not such obvious paradoxes, some may ultimately fall in the same category. Since a majority of them are closer to the Galactic Center than Geminga, arc minute angular resolution may be required for their unambiguous observation and eventual identification.

GAMMA RAYS FROM BLACK HOLES

Gamma-Ray emission has been observed from a number of sources which are thought to be accreting black holes, based on their large luminosities and small sizes, as inferred from their rapid time variations. These include the active galactic nuclei 3C273, NGC 4151 and Cen A, the Galactic Center, and the X-ray binary Cyg X-1. Spectral measurements of these sources, extending from radio to gamma-ray frequencies, show that all of these sources appear to have peak luminosities at energies around one MeV. They also appear to show great variability at these energies, as indicated by the large variations between measurements.

Cygnus X-1

The gamma-ray variability of these objects has been studied most extensively in Cyg X-1, thought to be a stellar-mass-sized black hole accreting from a close binary companion. Its large temporal variability at $>$ 500 keV has been clearly established by HEAO-3 measurements with the same instrument over the period 1979–80. These and other measurements show flux variations of more than an order of magnitude at energies $>$ 500 keV. They also show an anti-correlation between the gamma-ray and X-ray emission: high gamma-ray fluxes are observed only during periods of low X-ray flux while much lower gamma-ray fluxes are observed during periods of high X-ray flux. When the gamma-ray flux is high the bulk of the power is radiated at energies of about an MeV, while at low gamma-ray fluxes the bulk of the power is radiated at energies $<$ 100 keV. As a result of this anti-correlation, the overall luminosity does not appear to vary as greatly as the flux in the MeV range. There are indications of similar anti-correlations between the gamma-ray and X-ray fluxes in observations of other candidate black hole sources, such as Cen A.

The X-ray and gamma-ray emission up to a few hundred keV may possibly be explained by Comptonized bremsstrahlung from a hot plasma, while the more variable emission at higher energies may be annihilation radiation from a much hotter e^-e^+ pair plasma. The variability may also result from $\gamma\gamma \rightarrow e^+e^-$ absorption leading to an anti-correlation of fluxes above and below an energy of about m_ec^2. In a compact source the luminosity at energies $> m_ec^2$ is controlled by the photon-photon pair production opacity which is proportional to the ratio of the luminosity and the radius. This ratio defines a "compactness" parameter with a critical value at unit opacity. Variations in the emission spectra from gamma-ray dominated emission $> m_ec^2$ to X-ray dominated emission $< m_ec^2$ can thus be correlated with changes in the "compactness". For a small value of the "compactness" where the opacity is $<$ 1, the source is transparent to gamma rays of energy $> m_ec^2$ and it can radiate at such energies. If the luminosity increases, or the radius decreases, such that the "compactness" exceeds the critical value and the opacity becomes $>$ 1, then the source becomes opaque to photon-photon pair production at energies $> m_ec^2$, the emission is suppressed at gamma-ray energies, and must increase at X-ray energies. To test such models, more sensitive measurements are needed of the spectrum as a function of time, especially during transitions between the high and low level of gamma-ray emission.

The Galactic Center

Gamma-ray observations of the Galactic Center region have shown it to be an intense and variable source both of narrow (FWHM $<$ 2.5 keV) 511 keV line radiation from electron-positron annihilation and of gamma ray continuum emission extending to at least a few MeV. It can be in fact the brightest gamma-ray source in the Galaxy with a luminosity of as much as 10^5 $L_\odot$. In 1979–80 its gamma-ray lumniosity in both the line and continuum was observed to decrease by more than a factor of 3 in 6 months, indicating that a single compact object is the source of both the positrons and the continuum. The positron and gamma-ray production mechanisms are not known, but the most likely positron source is $\gamma\gamma$ pair production either near the accretion disk of a modest (10^2 to 10^3 $M_\odot$) black hole or in the relativistic jets from a much larger (10^6 $M_\odot$) black hole dynamo. Our own Galactic Center may in fact prove to be the Rosetta Stone of the physics of active galactic nuclei, with gamma-ray observations playing a decisive role.

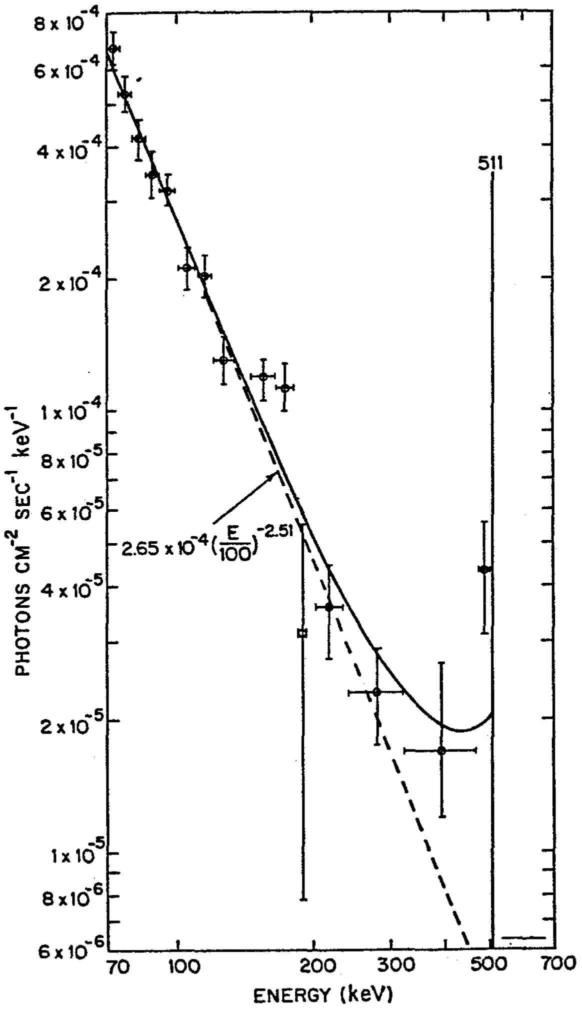

FIGURE 5. BELL-SANDIA SPECTRUM OF GALACTIC CENTER ANNIHILATION RADIATION

Much attention has been focused on the annihilation radiation. Because of its unique nature, it may be a characteristic signature of active galactic nuclei and a key to unravelling the mystery of these sources. The shape of the annihilation line as revealed with high resolution detectors in laboratory simulation experiments and by Monte Carlo calculations is a sensitive function of the annihilation environment and may ultimately allow us to characterize the medium near the central engine.

Crucial to the study of this object are sensitive observations over a long time base to determine the correlation between the variable positron source, the gamma-ray continuum source and the radio, infrared and X-ray sources at the Galactic Center. A fundamental observational problem has been the lack of gamma-ray detectors with good angular resolution over the energy range of interest. Detectors of sufficient angular resolution have not had the sensitivity to detect the positron annihilation line, while those that detected the line have had angular resolutions poorer than 10°. There are at least five known variable hard X-ray sources within approximately 6° of the Galactic Center. As a consequence, uncontaminated spectra of the Galactic Center source are unavailable due to source confusion, and the location of the positron source itself is unknown to ± 4°. Broad band gamma-ray telescopes with line sensitivity $\leq 10^{-5}$ photons/cm^{2}sec and angular resolution better than 1° and a localization capability approaching one arc minute are clearly needed in the immediate future, while arc second localization will be needed on the long term.

Active Galactic Nuclei

One of the foremost problems of present-day astrophysics is understanding the nature of the central engine in active galactic nuclei. These sources, which include quasars, Seyfert galaxies, BL Lac objects and radio galaxies, are the most energetic objects in the known

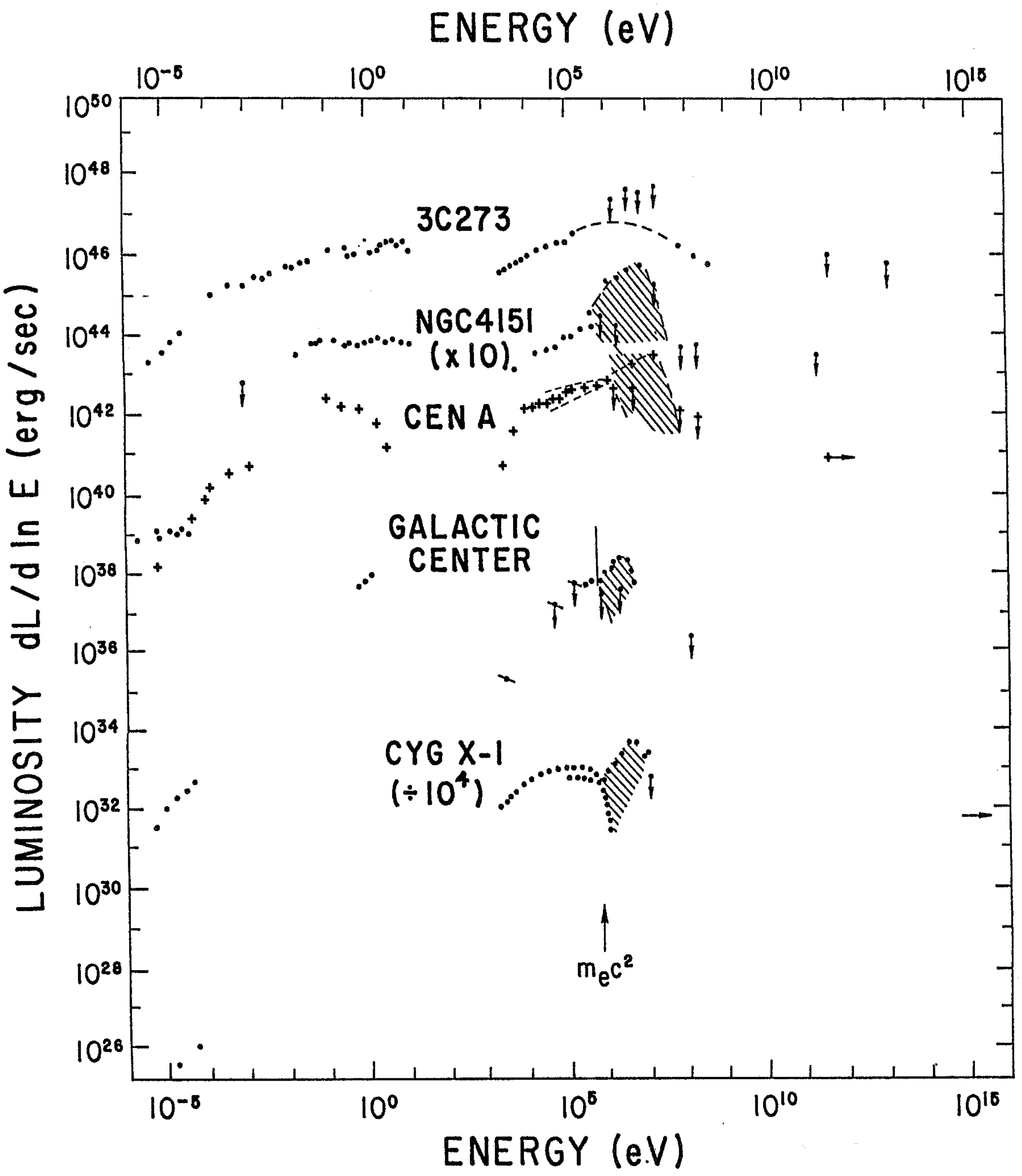

FIGURE 6. ENERGY SPECTRA OF SEVERAL ACCRETING BLACK HOLE CANDIDATES

universe, continuously emitting as much as 10^{47} ergs/sec. Their enormous luminosities, with variability on time scales indicating sizes smaller than the solar system, strongly suggest that they too are accreting black holes with masses as large as 10^9 M_o. The detailed processes involved, however, are not yet understood, although both $\gamma\gamma$ production of e^+e^- pairs and their annihilation are thought to play a major role in the emission and its variability.

Currently, there are measured spectra for about a dozen active galactic nuclei up to energies of 100 keV. At higher energies, spectra have been measured only for the strongest sources: 3C273, NGC 4151, MCG8-11-11 and Cen A. These measurements show, however, that these sources, like Cyg X-1 and the Galactic Center, emit the bulk of their power at energies around one MeV, where they are highly variable. There is also evidence, at least in spectra of Cen A, of an anti-correlation between variations in the flux above and below a few hundred keV.

More sensitive measurements of the time dependent spectra of these and other active galactic nuclei are thus crucial to our further understanding of these objects. Such measurements are needed not only to test specific models and the possible roles of "compactness" and of relativistic jets, but to provide a large enough sample of objects to search for any characteristic differences that might exist between the gamma-ray spectra of the different classes of sources. Simultaneous observations of individual objects at both gamma-ray and other energies are also needed to understand the overall spectrum and to test general emission models, such as synchrotron-self-Compton emission. Finally, a comparison of the spectra of these active galactic nuclei with the diffuse gamma-ray background can enable us to better estimate the contribution of these sources to that emission. Moreover, because their contribution to the diffuse gamma-ray background depends on the range of cosmological redshifts at which they contribute, and thus on their "turn-on" age, we can also gain new information on the evolution of these objects.

To address these and other questions, future instruments must have a sensitivity approaching 10^{-7} photons/cm^{2}sec keV above 100 keV with an angular resolution of about 0.1° over a broad energy range. Measurements are particularly needed from 50 keV, where hard X-ray data currently exist, through the MeV range where strong spectral variability is suggested. Observations should be made over extended periods in order to determine the time scales of sources variability and hence their size scales.

At higher energies (> 100 MeV), sensitivities better than 10^{-8} photons/cm^2 sec will be needed to provide visibility for a large number of active galactic nuclei, and to permit accurate measurements of the spectra of the brighter ones.

DIFFUSE EXTRAGALACTIC GAMMA-RAY BACKGROUND

The existence of a generally isotropic gamma-ray continuum background has been known for about 20 years. However, there is still considerable controversy about both the shape of the continuum spectrum and its origin. From the beginning the gamma-ray background has attracted much attention from both theorists and observers because of its potential cosmological origin. The most intriguing feature of the gamma-ray background radiation is the apparent structure in the spectrum suggesting a second component above a few hundred keV. Theoretical models for such emission include: redshifted π^0 decay gamma rays from matter-antimatter annihilation in the early universe, Compton scattering of relativistic intergalactic electrons by the 3° K background radiation, redshifted gamma-ray lines from extragalactic nucleosynthesis, the decay of cosmological gravitinos at high redshift, and the superposition of emission from many unresolved active galactic nuclei. Clearly some contribution from the latter sources is expected, but their contribution cannot be reliably determined until a larger number of active galactic nuclei have been studied in the gamma-ray regime. Only a few such sources have been studied to date. To accurately determine the contribution of active galactic nuclei to the diffuse gamma-ray background requires the determination of the luminosity function of these sources at hard X-ray and gamma-ray energies. This in turn requires unbiased samples of hard X-ray and gamma-ray selected objects to much lower flux levels than are currently accessible. Instruments with sensitivity significantly better than 10^{-6} photons/cm^2 sec keV at 100 keV can perform the required observations.

The shape of the spectrum above a few hundred keV is also still controversial, so much more sensitive measurements of the spectral shape and also the isotropy of the gamma-ray background around one MeV are required to confirm the existence of spectral structure, before we can even begin to differentiate between the various models. A wide field of view instrument is needed with a sensitivity exceeding 10^{-6} photons/cm^{2}sec ster keV at 1 MeV to make these observations.

For energies above 50 MeV, other cosmological questions can be addressed. For example, if the universe is matter/antimatter symmetric, with "clumps" on the scale of superclusters of galaxies, substantial nonuniformities will be seen in the distribution of high energy gamma-rays due to annihilation radiation at the clump boundaries. Another possibility is the observation of annihilation radiation from exotic supersymmetric particles, if their density is sufficiently great to close the universe, as has been hypothesized. As at lower energies, it is important to determine what fraction of the observed high energy diffuse gamma-ray background is due to emission from active galactic nuclei; this requires high energy gamma-ray observations of a number of such objects.

PRESENT GAMMA-RAY ASTRONOMY PROGRAM

In this section, we describe five components of the currently approved and on-going research program in gamma-ray astronomy in the United States to serve as a guidepost for future directions in the field. In addition to these experimental areas, there is a research and analysis program which supports theoretical studies and the analysis and interpretation of existing data from gamma-ray experiments on HEAO-1, HEAO-3, and SMM.

SPACE PROGRAM IN GAMMA-RAY ASTRONOMY

Gamma Ray Observatory

The Gamma Ray Observatory (GRO) is intended to be the backbone of observational gamma-ray astronomy in the U.S. at least through 1992 and probably beyond. It currently is allocated a major fraction of the resources available from NASA for the discipline. The five experiments originally selected in 1978 have capabilities greatly exceeding those of previous experiments. In 1981, however, the high resolution spectroscopy experiment was deleted from the GRO for programmatic reasons. The four remaining experiments, which are now in late phases of assembly, testing and calibration, include: the Oriented Scintillation Spectrometer Experiment (OSSE), the Compton Telescope (COMPTEL), the Energetic Gamma-Ray Experiment Telescope (EGRET) and the Burst and Transient Source Experiment (BATSE). The GRO will undertake a broadly-based observational program to make significant progress on many important astrophysical problems. These are described further below and include solar flares, gamma-ray bursts, neutron stars, black holes, nucleosynthesis, the interstellar medium, galactic structure, active galactic nuclei and the cosmic background radiation.

The GRO will be placed in a 28.5° orbit at an altitude between 400 km and 450 km by the Space Shuttle. It is scheduled for launch in 1990, having been delayed considerably following the Challenger accident. The current launch date is, of course, dependent upon the schedule for resumption of Shuttle flight operations. Because of its exceptional capabilities and the fact that GRO is the only gamma-ray mission currently scheduled by the United States, there are several persuasive arguments that its operational life must be extended well beyond the presently planned 2 years and into the 5 to 10 year range. The GRO will collect the first high-sensitivity gamma-ray data since the HEAO and COS-B missions, over a decade ago. Its sensitivity and angular resolution are more than an order of magnitude better than previous missions, and we can expect it to produce many discoveries which will require follow-on observations. As it is very unlikely that there will be a new mission of the GRO's scope in the next two decades, these observations will have to be primarily provided by the GRO itself. Many of its scientific objectives require studying variable and transient gamma-ray emission, e.g. supernovae, active galactic nuclei, gamma-ray bursts, black hole phenomena and solar flares. These observations can be expected to lead to the greatest discoveries. However, their random nature will require much more than 2 years to enhance the probability of observing them. In addition, the GRO will be the second of the Great Observatories, and a long operational life will be necessary to allow it to scientifically complement the other Great Observatories, as well as smaller scale space missions such as the XTE and other explorers. A long life will also be necessary to provide for the needs of the international community of scientists that will be served by a vigorous GRO Guest Observer Program. An on-board propulsion system will allow considerable extension beyond the planned two year mission. A lifetime of 10 to 12 years is possible.

Figure 7 shows the configuration of the GRO spacecraft and the location of the experiments. Table 1 lists some key parameters of the four experiments.

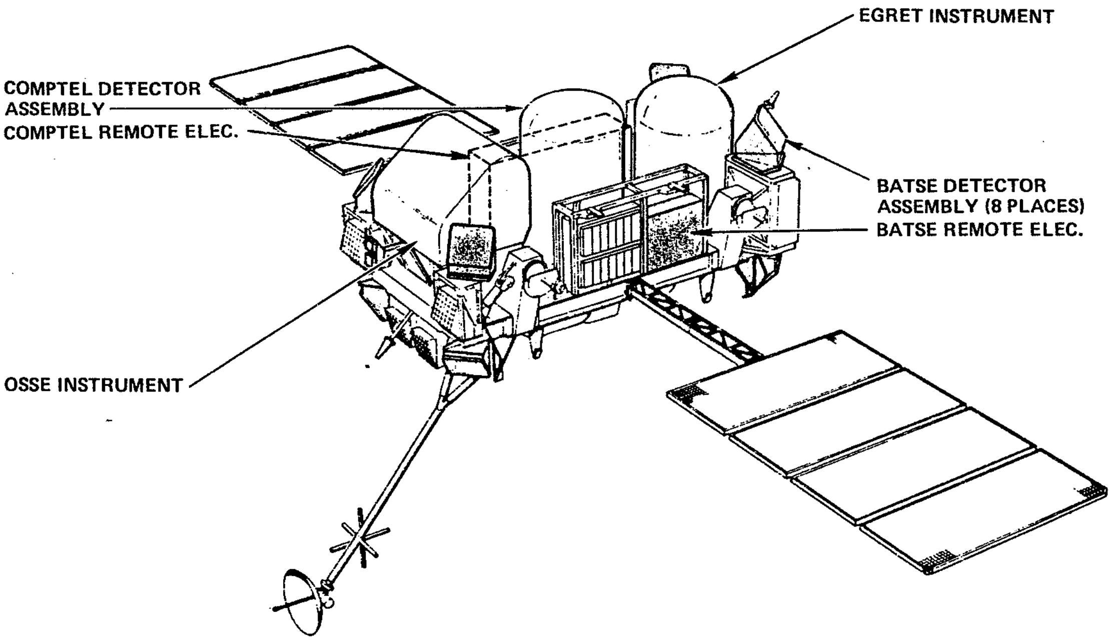

FIGURE 7. GAMMA RAY OBSERVATORY (GRO)

The EGRET instrument, with an energy range of 20 MeV to about 30 GeV, is the primary high energy gamma-ray experiment on GRO; it will expand on the initial discoveries of the SAS-2 and COS-B spacecraft. EGRET has roughly ten times the effective area of the earlier instruments and includes a large calorimeter module to obtain accurate gamma-ray energy measurements lacking in previous instruments of this type. The incoming gamma-ray is converted to an electron-positron pair in a large spark chamber module; the track of the pair is then determined by the spark chamber and will be used to located sources to an accuracy of $\sim$ 5 arc minutes. Its energy is measured by the scintillation crystal calorimeter at the lower end of the instrument. A large number of plastic scintillators provide triggering, anticoincidence, and time-of-flight signals for the detector system. EGRET will provide vital contributions to the understanding of several of the topics mentioned earlier, including identification of the COS-B sources, gamma-ray emission from radio pulsars and other compact objects, galactic structure and cosmic-ray dynamics as revealed in high energy gamma-rays, and the relationship between active galactic nuclei and the extragalactic gamma-ray background.

The COMPTEL instrument is a low-background imaging telescope, optimized for the energy range 1 to 30 MeV. Two arrays of scintillation detectors are used to characterize the incoming gamma rays. The gamma-ray is first Compton-scattered by one of the seven upper liquid scintillation detectors; the scattered photon is then detected by one of the fourteen lower NaI(Tl) crystal scintillation detectors. Both sets of detectors can localize the gamma-ray interaction to within a few centimeters. The energy losses and the interaction locations are used to constrain the arrival direction to an annulus on the celestial sphere. The intersections of numerous annuli within the field-of-view are used to build a flux map or "image" of the region. The primary topics to be addressed by COMPTEL include discrete galactic and extragalactic objects such as pulsars and other neutron stars, supernova remnants, molecular clouds, active galaxies and nearby normal galaxies, diffuse gamma radiation, both galactic and extragalactic, and moderate-resolution gamma-ray spectroscopy.

TABLE 1. GRO EXPERIMENT CAPABILITIES

EGRET	
Energy Range	20 MeV to 30 GeV
Energy Resolution (FWHM)	15% (100 MeV - 10 GeV)
Maximum Effective Area	2000cm^2 (200 MeV)
Position Resolution	5 arc min(strong source)
Maximum Effective Geometric Factor	1000 cm^2 sr

COMPTEL	
Energy Range	1.0 to 30 MeV
Energy Resolution (FWHM)	8% (@ 1 MeV)
Maximum Effective Area	50 cm^2
Position Resolution	7.5 arc min
Maximum Effective Geometric Factor	30 cm^2 sr

OSSE	
Energy Range	0.1 to 10 MeV
Energy Resolution (FWHM)	8% (@ 0.66 MeV)
Effective Area	1950 cm^2 (@ 0.5 MeV)
Position Resolution	10 arc min (strong source)

BATSE	
Energy Range	20 keV to 10 MeV
Energy Resolution (FWHM)	8% (@ 0.66 MeV)
Effective Area	3840 cm^2
Position Resolution	1° (strong burst)

The OSSE instrument consists of four large, collimated scintillation detectors. Both active and passive collimators are used to reduce background. The passive collimators have a field-of-view of 3.8° x 11.4°. The thick NaI(Tl) detectors are optimized for moderate resolution spectroscopy in the nuclear gamma-ray region, 0.1 to 10 MeV, although observations can be made at lower and considerably high energies. Charged particle active shielding completely surrounds each central detector. Offset pointing between source and background regions on minute time scales is used to minimize systematic effects associated with instrumental background variations. The OSSE instrument is designed to undertake high-sensitivity observations of discrete galactic and extragalactic sources and to map the diffuse galactic features with an angular resolution of several degrees.

The BATSE experiment is an all-sky gamma-ray monitoring experiment designed primarily for the detection and detailed study of gamma-ray bursts and other transient sources in the energy range 20 keV to 10 MeV. Eight uncollimated detector modules are positioned around the spacecraft to provide an unobstructed view of the sky. Bursts are detected onboard the GRO, and signals are sent to the three other GRO instruments so that additional data on bursts can be obtained. The BATSE instrument will provide more sensitive measurements of rapid spectral variability in gamma-ray bursts and the celestial distribution of gamma-ray burst sources than has been possible with previous experiments.

Other Gamma-Ray and Hard X-ray Experiments on Spacecraft

The Gamma-Ray Experiment on the Solar Maximum Mission (SMM) is a wide-field, actively shielded scintillation experiment designed primarily for solar gamma-ray observations. However, due to its long lifetime it has been able to make significant contributions to celestial gamma-ray astronomy through observations of gamma-ray bursts, the Galactic Center region, SN1987A and diffuse emission from the plane.

The small gamma-ray burst experiment on the Pioneer Venus Orbiter (PVO) consists of two scintillation detectors, data system and burst memory. It has been an important component of a interplanetary gamma-ray burst network which has operated intermittently since 1978. Ginga, a Japanese spacecraft, contains a U.S.-provided proportional and scintillation burst detector. Launched in February 1987, the instrument is considerably larger than that flown on PVO.

A large area (1600 cm^2), collimated (1° FWHM) scintillation detector (HEXTE) will be part of the X-ray Timing Explorer (XTE), to be launched about 1994. This experiment will perform important observations in the energy region 15 keV to 200 keV, simultaneously with a coaligned proportional counter array that covers 2-60 keV, thus bridging the X-ray and gamma-ray regions. The all sky monitor on XTE will be able to alert observers to changes in the x-ray sky within a few hours of their occurrence.

The Wind spacecraft, part of the complex, multi-spacecraft GGS mission to study interplanetary and solar-terrestrial effects, also will carry a gamma-ray transient spectrometer. This passively-cooled germanium instrument was selected because of the unique planned orbital location at the first Lagrangian point. It is a sequel to the earlier, ISEE-1 experiment of that design, and although it is an improved design in many respects, due to weight constraints it will not provide a significant increase in sensitivity. This mission and this experiment now appear to be firm parts of the NASA program, with a launch in the 1990s.

The Mars Observer mission also includes a germanium spectrometer for the orbital mapping of the Martian surface composition. Astrophysical transients such as gamma-ray bursts and solar flares can also be studied with the instrument for energies > 20 keV with msec timing for durations up to 300 sec.

BALLOON PROGRAM IN GAMMA-RAY ASTRONOMY

High Resolution Gamma-Ray Spectroscopy

In 1982, NASA initiated a program to develop high resolution detector systems for gamma-ray astronomy. Balloons would be used to develop and optimize the detector systems as well as to provide scientific data during relatively brief balloon flights. It is intended that detectors and techniques developed in this program would be available for future spaceborne experiment opportunities. Two teams of investigators were selected to proceed with the development of balloon-borne systems comprising arrays of germanium detetctors and initial balloon flights of the systems occurred in 1988. The detector systems consist of arrays of cooled germanium detectors. The individual detectors are segmented and use electronic techniques to minimize various types of internal and external background. Imaging is performed by aperture masks; dense, active shielding defines the front aperture. The progress under this program was responsible, in large measure, for the strong proposal for the Nuclear Astrophysics Explorer Concept Study, which is discussed below.

New Experiments

Balloon-borne instruments have historically been the forerunner of spaceflight experiments in gamma-ray astronomy. All of the gamma-ray instruments for HEAO-1, HEAO-3, and GRO had their origins in balloon experiments. Several hardware development programs, begun in the 1982-1984 time frame have begun to yield new results with improved instrumentation. The NASA program has sponsored the development of imaging, high-resolution detector systems, discussed below. The NASA SR&T and balloon programs have also supported development of imaging hard X-ray and gamma-ray detectors. Coded-aperture imaging instruments developed during this time have yielded the first gamma-ray images in the energy range 50 keV to 1 MeV. These instruments are presently achieving angular resolutions on the order of 20 arc minutes, and coded-aperture techniques will allow resolution as good as one arcsecond in the future.

Development of imaging and modulation techniques in gamma-ray astronomy is an important step for advanced instrumentation in the post-GRO /XTE era.

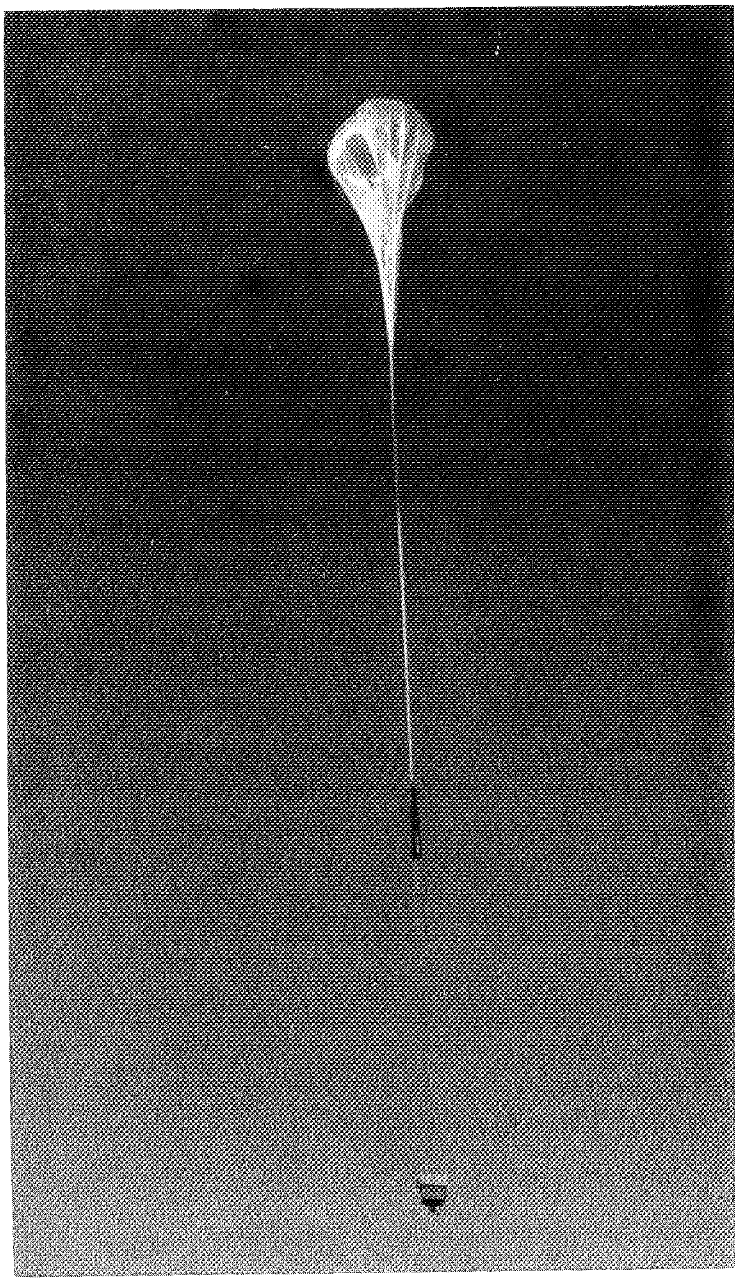

FIGURE 8. BALLOON LAUNCH OF GAMMA-RAY ASTRONOMY EXPERIMENT

In addition to the development programs in high-resolution and coded-aperture imaging, the NASA balloon program has also supported efforts in Compton telescope and gamma-ray burst instrumentation, as well as instruments for solar gamma-ray astrophysics.

In addition to instrument development, the NASA SR&T and balloon flight programs also produces important scientific results, as shown recently by the NASA suborbital program for observations of SN1987A. The recent supernova in the Large Magellanic Cloud has afforded an unprecedented opportunity to observe the evolution of a Type II supernova, in particular the role of newly synthesized ^{56}Co produced in the explosion. Observations with satellite and balloon-borne spectrometers spanning a few years can reveal not only the amount of synthesized ^{56}Co and ^{57}Co, but also their degree of mixing in the ejecta and the velocity distribution and the mass of the ejecta itself. Preliminary results from the observations between August 1987 and May 1988 suggest early plumes of high velocity material followed by emission from the core itself as the ejecta become thinner. Two balloon flights have also been made to search for high energy gamma rays resulting from relativistic partcle interactions. The ongoing series of balloon flights should ultimately give us a coherent description of both the nucleosynthesis and expansion dynamics of the supernova.

FOREIGN PROGRAMS IN GAMMA-RAY ASTRONOMY

The KVANT module on the Soviet MIR spacestation was launched on March 31, 1987 and contains two gamma-ray scintillator experiments. The HEXE, supplied by West Germany, observes 15 to 250 keV photons with a 1.6° field of view, and the Soviet-built PULSAR X-1 extends up to 1.3 MeV with a 3° field of view.

Two French/Soviet experiments are scheduled to be launched in 1988. The GAMMA-I experiment is a spark chamber high-energy telescope with an energy threshold of $\sim$ 50 MeV. This experiment will use a coded aperture mask and calorimeter in conjunction with the spark chamber. The expected sensitivity will be better than the COS-B experiment but less than that of EGRET/GRO. The SIGMA experiment on the Soviet GRANAT spacecraft is a coded aperture scintillation telescope for observations in the energy range from 30 keV to 2 MeV. The central, position-sensitive NaI(Tl) detector is actively shielded against background radiation. SIGMA also has considerable capabilities for gamma-ray burst studies by both the central and shield detectors. In addition to the SIGMA experiment, GRANAT contains six other advanced x-ray and gamma-ray experiments utilizing rotation modulators, simple collimators and coded mask imagers. Beyond GRANAT, the Soviets are planning a large gamma-ray facility known as SPECTRUM-GAMMA, planned for launch in 1994.

In gamma-ray burst astronomy, there are three relatively small European experiments planned. Two of them will become part of a burst timing network. The WATCH experiment uses a rotation modulation collimator to provide burst locations on the first EURECA spacecraft to be launched by the Shuttle. The resently launched Soviet PHOBOS spacecraft have French and Soviet gamma-ray transient experiments on board and the ESA-NASA ULYSSES mission scheduled for a 1990 launch will have a French/German/Dutch gamma-ray burst monitor. In addition, Danish and Soviet experiments, SUNFLOWER and another WATCH, will be on board the GRANAT spacecraft to study optical and X-ray transients possibly associated with the gamma-ray busts. With quick turn-around gamma-ray data analysis, these instruments can be pointed by command to provide broad band observations of gamma-ray burst locations at the subdegree level. This procedure will make possible a search for repeated outbursts from a newly detected candidate source direction.

FUTURE GAMMA-RAY ASTRONOMY PROGRAM

The program we recommend is divided into two phases. The first phase is the GRO era. Here, the needs are very clear. The program of space missions consists of an extension of the GRO mission and the addition of two new missions which cover important observational areas not included in the GRO, i.e. high resolution gamma-ray spectroscopy and multiple wavelength-band observations of high-energy transient sources. The balloon program includes a series of crucial observations of SN1987A during the next few years as well as continued observation of other potential gamma ray sources. In addition, the SR&T and balloon programs will provide for detector development and important new scientific results. This, along with strong theory and data analysis programs, will maintain the infrastructure that is necessary to provide for graduate student training and assure the field's viability. The program's second phase is the post-GRO era. Here, anticipating the future needs is more speculative. While it is premature to recommend specific space missions for this phase, augmentation of support for instrumental development is recommended and mission requirements are identified which appear to offer the most promise. We also emphasize an ongoing program of balloon flights, theory and data analysis.

NEW PROGRAM

High Resolution Gamma-Ray Spectroscopy

The most urgently needed new scientific capability is that of high sensitivity to narrow gamma-ray lines in the nuclear line region from 0.01 to 10 MeV. This could be achieved with an Explorer-class mission incorporating a collimated, high-resolution gamma-ray spectrometer, such as the Nuclear Astrophysics Explorer (NAE) concept. The sensitivity must be much better than the HEAO C-1 high resolution spectrometer and better than the medium resolution spectrometer, OSSE, on the GRO. A sensitivity of a few times 10^{-6} photons/cm^{2}sec appears achievable and would be ~ 100 times better than the HEAO C-1 and ~ 10 times better than the OSSE with much higher spectral resolution. The spectrometer would directly measure the information encoded in the lines' energy shifts and profiles, which are expected to be in the 0.1 to 1 percent range in most cases. Thus the resolving power, E/ΔE, must be ~ 1000. The spectrometer would be used to study discrete sources as well as map the diffuse galactic emission. These objectives require

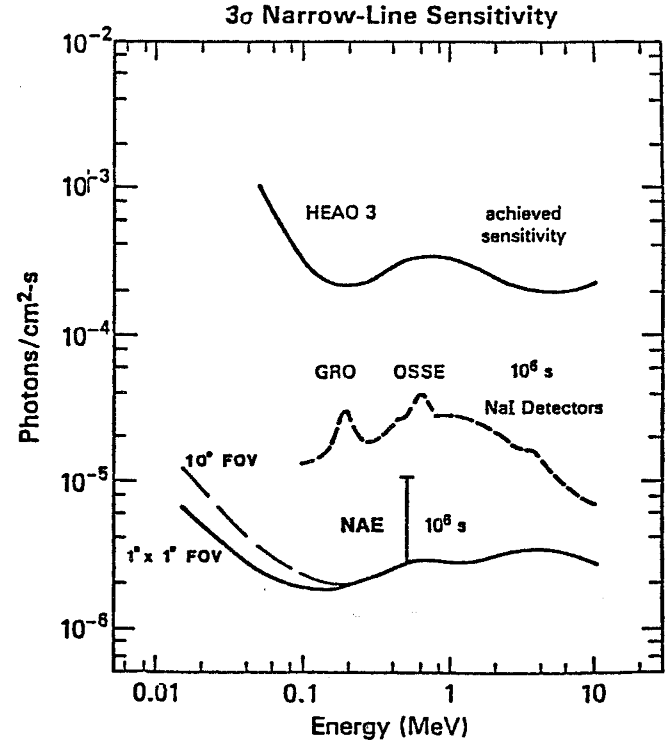

FIGURE 9. PROPOSED NAE SENSITIVITY

an angular resolution of a few degrees while obtaining a diffuse flux sensitivity of a few times 10^{-5} photons/cm^2-s-rad.

With these capabilities the instrument would attack many of the basic astrophysical problems discussed above, such as nucleosynthesis in supernova and novae, the sites and rates of galactic nucleosynthesis, including recent unknown supernovae; compact objects such as accreting neutron stars, black holes, the galactic nucleus and active galactic nuclei; the mixing of the interstellar gas and the elemental abundances of the interstellar dust and solar atmosphere; the acceleration and interactions of solar flare accelerated particles and low energy cosmic rays; and the physics of the intense ($\sim 10^{12}$ gauss) magnetic fields and hot plasmas of accreting neutron stars in X-ray pulsators. This instrument would build on the discoveries that have been made by the HEAO-1, HEAO-3, SMM missions and balloon-borne instruments. It would strongly complement the results expected from the GRO, XTE, AXAF, and SIGMA.

Recently there have been major advances in detector size, detector background reduction, imaging, shielding efficiency and cryogenic cooling. These allow an instrument with a weight that fits within the Explorer envelope. Most of these techniques are incorporated in balloon-borne spectrometers that are in development. These spectrometers will have nearly the necessary combination of background, detector size and energy resolution for the space mission. Due to the limitations on ballons, however, they will be limited $\sim$ 50 hours/year of data, which will allow only a few of the brightest sources to be observed.

High Energy Transients

The second most urgently needed space mission is one dedicated to the broad wavelength study of transient, high energy phenomena, chiefly gamma-ray bursts, such as the High Energy Transient Explorer (HETE) concept. This mission is smaller in scope than the spectroscopy mission and is therefore achievable at a significantly lower cost. It would maximize the information obtained from bursters during the only time they can definitely be seen – during the burst – by simultaneously observing emissions in the optical, X-ray, and gamma-ray region. The required optical/UV sensitivity is $\leq 5\text{x}10^{-10}$ erg/cm^{2}sec (about 12th magnitude) over an area of sky greater than 2 steradians with angular resolution better than 3 arc seconds. Sampling of the optical emission on time scales less than one second is needed to distinguish different optical emission mechanisms and sites. The X-ray monitor, also having an active field of view greater than 2 steradians, would need sensitivity better than 10^{-8} erg/cm^{2}sec in the 2–25 keV range to sample well the relatively faint X-ray tails of bright gamma-ray bursts and concurrently to detect and monitor X-ray bursts in the Galactic Center. The X-ray detector by itself should render source locations for bright gamma-ray bursts accurate to better than 6 arc minutes. The gamma-ray instrument should have a FOV of 2π steradians, and be capable of detecting bursts down to better than $5\text{x}10^{-8}$erg/cm^{2}sec with sensitivity to continuum spectra in the range from 10 keV to $\geq$ 1 MeV. High spectral resolution is not required, and NaI could be utilized to obtain energy resolution of 7% near 600 keV and 40% at 10 keV. Both the X-ray and gamma-ray instruments would need to have timing resolution better than 5 ms.

Such a complement of instruments would detect at least several dozen gamma-ray bursts per year and obtain their time histories, including moderate resolution spectroscopy, in three regions of the spectrum. X-ray observations alone would provide numerous new error boxes smaller than 6 arc minutes for immediate follow up by other instruments at all wavelengths. Locations should be provided within less than one day of the actual event. If the associated optical/UV transient is within 4 orders of magnitude (10 magnitudes) of that suggested by archival events, the mission will additionally provide source localizations of unprecedented accuracy (few arc seconds, again in one day) and unique information regarding the dimensions and/or magnetic field strength of the source. If flown in the same time frame as GRO, HETE would provide timing and positional information complementary to that obtained for the same bursts by the BATSE and OSSE experiments, giving for example, an additional check on locations. As a secondary goal the mission would also search for other sources of transient optical and X-ray emission that previously may have escaped detection because of the limited field of view of earlier instruments.

All three instruments and their mounting platform could weigh only about 200 pounds and the only required attitude control would be a slew rate of less than 0.1 degree/sec. This mission has our highest recommendation as a "Get Away Special" launched out of a GAS can on the Shuttle, or as a Scout launched mission. The low cost of this mission would make it a very cost-effective initiative.

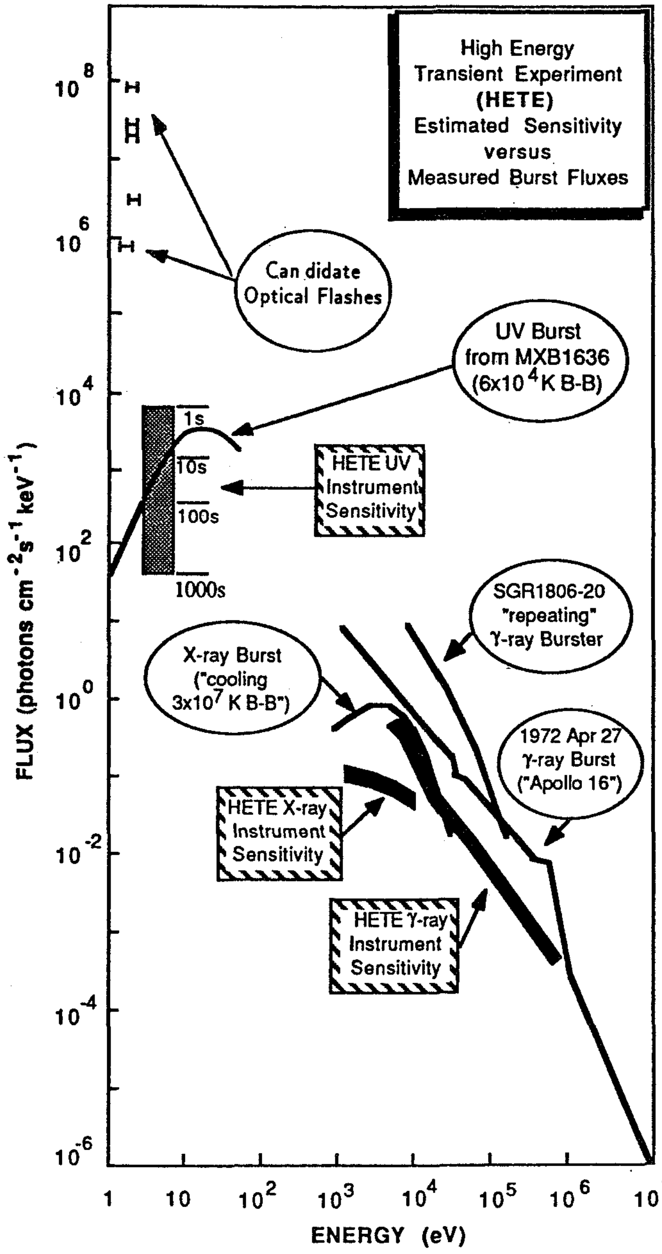

FIGURE 10. PROPOSED HETE SENSITIVITY

High resolution observations of gamma-ray absorption line features in burst spectra could provide valuable information on the physical conditions and emission processes near neutron stars, unobservable by other means. To complement the GRO observations of these line features, a high-resolution, wide-field instrument with comparable line sensitivity should be flown. Such an opportunity may be afforded by the Space Station attached payload using existing detector technology at a relatively low cost.

CONTINUING NEAR TERM PROGRAM

Balloon Program

The balloon program will continue to be the backbone of gamma-ray astronomy's ability to develop new instrumental techniques, train graduate students and obtain scientific results rapidly. Balloons make possible frequent, low cost access to a space-like environment.

The development of a truly operational capability in long duration ballooning has the next highest priority. This capability should allow payloads of ~ 2000 pounds to be carried up to $\sim$ 130,000 feet for several weeks with continuous data recovery at $>$ 1 kb/sec and global command capability. Four long duration flights from Australia to Brazil have been conducted in 1987 and 1988. Although three of these were successful, the flights experienced a number of problems (e.g. ballasting, solar cell recharging of batteries, termination and operational control.) We estimate that these could be solved with 1 to 2 years of additional development. The scientific return from long duration balloon flights can be an order of magnitude greater than conventional balloon flights. For many experiments they will be superior to Space Shuttle deployment since the radiation environment is stable for long periods and the observing program is under the complete control of the scientists. Instruments carried on long duration balloons will obtain sufficiently long exposures that collaborations which provide data sharing with other research groups will be practical. We envision joint programs among groups to exploit this possibility and note that it could make high quality data from the best instruments available to many groups. We urge that high priority be given to negotiating with China and the USSR for balloon overflight permission, so that long duration flights can be conducted in the northern hemisphere, thereby making the other half of the sky accessible and doubling the opportunities for long duration flights.

Conventional balloons will still have an important role to play. They will be essential for instrument testing and the flights of heavier payloads, and at seasons when the winds do not allow long duration flights. The development and maintenance of a reliable capability for the flights of payloads $>$ 5000 pounds, and the ability to utilize remote launch sites have high priority.

In both long duration and conventional balloon flights, frequent flight opportunities are essential. Gamma-ray astronomy requires at least 10 flights per year. These would be used for scientific observations and instrument development, would provide crucial new data in the otherwise data-starved period between the HEAO era and the GRO era, and would compliment the GRO with high angular resolution measurements, as well as with high spectral resolution measurements prior to the NAE. These flights can be expected to produce important new results on a number of important sources including SN 1987A, the Galactic Center, the diffuse galactic gamma-ray line emission from e^+-e^- annihilation and radioactive ^{26}Al, accreting neutron stars, and solar flares.

Supporting Research and Technology

The Supporting Research and Technology (SR&T) program has provided for the development of new instrumental techniques which lead to the space experiments of the past three decades. The successes of the series of experiments on OSO, SAS-2, HEAO-1, HEAO-3 and SMM are testimony to its effectiveness. The continuation of the SR&T program is essential. As space instruments inevitably become more complex and sophisticated, the role of laboratory and balloon flight development and understanding of new techniques becomes more important. The SR&T program provides the foundation for the generation of well-conceived proposals and spaceflight hardware developments which carry a minimal risk.

The goals of the near term SR&T program are derived from the scientific and observational goals of the long term program. The SR&T goals include 1) the development of very low background detectors which will allow source limited observations down to very low flux levels, and thus better sensitivity with instruments of acceptable scale, 2) improved energy resolution in order to resolve spectral features, and 3) imaging with an order of magnitude, or better, improvement over current capabilities, i.e. $\sim$ 10 arc minutes, for source identification.

Theory and Data Analysis

Although theory and data analysis are traditionally funded separately from detector development activities, we believe that scientific progress can be enhanced if they are logically linked through the definition of broad program themes. Theory and data analysis proposals would be evaluated in the light of these themes. Some examples which have high priority are supernova explosions and nucleosynthesis, diffuse galactic emission, processes on or near neutron stars, active galactic nuclei and the diffuse background. Continuing analysis of the numerous data bases from past missions should be well funded. This would help maintain the field's viability in the long periods between space missions and complement the planning for, and scientific results from future missions. For example, the GRO will rely heavily on results from balloons, the HEAO-1, HEAO-3 and SMM. In a similar manner, the HEXTE experiment on the XTE will rely on the HEAO-1, EXOSAT and Ginga results. These data are far from fully analyzed and the trend toward funding the analyses at a low level threatens their completion. The Astrophysics Data Program (ADP) program is an important step in reversing this trend, and we recommend that it be expanded to include more longer-term analysis involving graduate students.

Graduate Student Training

As the space program has progressed, spaceflight instruments have become more complex and flight opportunities less frequent. The increasingly long cycle, greater than 10 years, from instrument/mission concept to scientific results is incompatible with the graduate student education process, and is a strong disincentive for young astrophysicists. It leads to PhDs with specialization in only one facet of astrophysics and thus does not provide for the broad experiences necessary for a strong community in the future. However, the balloon and theory and data analysis programs outlined above would allow graduate students to have a broad education. Frequent balloon flights and the development of new instruments would provide hardware development experience and allow scientific observations with the latest instruments. Similarly, the theory and data analysis programs make possible the analysis and interpretation of data from previous satellite and balloon experiments.

Ground-Based Observations

Ground-based observations also play a very important role in gamma-ray astrophysics. The very highest energy gamma rays are only observable with ground-based instruments, and a coordinated observation program with GRO is strongly recommended.

In addition, optical searches for extragalactic supernovae and optical emission from gamma-ray bursts,and monitoring of active galaxies and other variable sources can also be of great value to the GRO, XTE, NAE and HETE missions. If the optical transient experiments – presently under construction and planned for implementation at Kitt Peak National Observatory – are successful, their further use, in coordination with the spacecraft gamma-ray experiments, could be of great importance. Support for the maintenance of such SR&T projects as the Explosive Transient Camera and the Rapidly Moving Telescope as observatories for monitoring optical bursts, even with their reduced duty cycle, should be continued throughout the active lives of GRO, the Hubble Space Telescope and the other missions of the '90s. This will ensure that the occasional gamma-ray burst event seen both on the ground and in space can be studied with exceptional thoroughness. Unexpected phenomena may also occur, such as the discovery of the soft galactic repeater, that produced over 100 gamma-ray bursts in a month. Clearly, interdisciplinary benefits will accrue from multiple wavelength monitoring – intentional or unintentional; the most famous example would be the observation of neutrinos from SN1987A. Thus it remains obvious that the continued monitoring of astrophysical transients, of as many kinds and over as many energy bands as possible, is highly desirable.

LONG TERM PROGRAM

Space Missions

The new space missions after the late 1990s will be following up on the discoveries of the GRO, and related missions, such as XTE and AXAF, as well as foreign missions. We also expect that the NAE and HETE will be flown in the mid 1990's so that their initial discoveries will be known. In this context it is difficult to make specific mission recommendations. Rather, we have considered the instrumental and mission requirements that are likely to be necessary. We note that a vigorous SR&T program must be commenced as soon as possible in order to assure that the necessary developments occur during the next 5-10 years.

Instruments of the next decade will range from major national facilities with broad objectives to modest instruments with limited objectives. Since the all-sky surveys will be completed, we expect that most of these will be designed for in-depth studies of specific objects and regions. It is certain that they must utilize new technologies to meet the scientific requirements.

The technologies necessary for such instruments will clearly require a very substantial development effort over a period of years. The requirements are sufficiently demanding that an attempt to condense the development into a few years would be inefficient, and would almost certainly lead to less than optimal instruments. If these technologies are to be available when needed in the post-GRO era, it is essential that their development be pursued beginning immediately.

The following subsections describe the performance parameters which are likely to be needed in gamma-ray instruments in the period after GRO. In order to facilitate this discussion we divide the gamma-ray regime into three overlapping bands, characterized primarily by the available gamma-ray interaction processes (and therefore the available detection techniques):

High Energy	30 MeV - 100 GeV	(pair production)
Medium Energy	1 MeV - 50 MeV	(Compton scattering)
Low energy	0.01 MeV - 5 MeV	(photoelectric absorption)

Since gamma ray burst studies span a broad range of energies and require unique instruments, they are discussed separately.

For the purpose of the following discussion, we assume a successful GRO mission of at least 3 years duration and the realization of missions with the characteristics of NAE and HETE.

High Energies

The EGRET instrument on GRO will have a sensitivity of about 0.02 of the Crab intensity, angular resolution of about 0.5° at 1 GeV, and point source location capability of 0.1°– 0.2° (see Table 1). A follow-on instrument would be expected to have roughly an order of magnitude greater sensitivity, angular resolution at 1 GeV of roughly 0.1°, and source location capability better than 1 arc minute. A 5° field of view should be adequate for the types of observations required in that time period. The 15% FWHM energy resolution of EGRET is probably sufficient for most observations. However, better energy resolution would enhance searches for annihilating massive particles which have been suggested in some astrophysical settings. The large collecting area of such an instrument could require in-space assembly, and studies of this approach should continue. Some development effort has already begun on several innovative detectors for post-EGRET use, such as large-area drift chambers, with or without a coded aperture mask, or a large-volume, focusing gas Cerenkov detector. The GRITS instrument, which is presently being studied, is an example of the latter method. Also, studies are being performed on innovative uses of the proposed ASTROMAG experiment to achieve high gamma-ray spectral resolution.

Medium Energies

The COMPTEL instrument on GRO will have a sensitivity about 0.03 of the Crab, angular resolution of a few degrees, and source location capability under 1° (see Table 1). In this extremely difficult energy range, several types of developments could substantially improve this capability. Probably the most dramatic improvement would be the ability to determine the direction of the electron leaving the site of the Compton scatter, which would reduce the position uncertainty of a detected gamma-ray from a large area annulus to a small area circle. The background would be reduced by more than an order of magnitude and the instrument would have true imaging capability. Other important improvements for both sensitivity and angular resolution would result from better energy and spatial resolution in the individual detectors within the Compton telescope. Needless to say, the improved energy resolution is valuable in its own right. Studies of the polarization of astrophysical gamma rays may be of great value in understanding the emission processes. Gamma-ray burst studies in particular may benefit greatly, given the great likelihood of polarization to characterize most transient processes. The measurement of polarization can be carried out most efficiently in the MeV region where instruments can be built to achieve the required directional scattering and total absorption with high efficiency, using the appropriate materials and geometry. With major improvements along these lines, it is likely that dramatic increases in overall instrument capabilities could be accomplished with little increase in overall telescope size compared with COMPTEL. Some technologies which appear promising are highly segmented detectors, either scintillators or germanium, and liquid or high pressure noble gas chambers.

Low Energies

The OSSE instrument on GRO will have a sensitivity of about 0.03 of the Crab at 1 MeV, an angular resolution of about 4°, and a strong source localization capability of 0.2° (see Table 1). Other space missions planned for the next decade in this energy range are XTE, with its 10–200 keV HEXTE instrument, and the French/Soviet SIGMA experiment operating in the 0.03–2 MeV region. Both are expected to achieve sensitivities of $\sim 10^{-3}$ Crab at 100 keV in long observations. HEXTE will perform high time resolution (< 1 msec) studies of bright sources, while SIGMA will perform imaging observations with a resolution of 0.2° in a 4.4°x4.8° field of view. Follow-on missions should have an order of magnitude better sensitivity, and an angular resolution of a few arc minutes to avoid source confusion at this improved sensitivity level. New detector techniques that discriminate against radioactivity background while maintaining high gamma-ray sensitivity will be needed. If the background level can be reduced to $\sim 10^{-3}$ Crab, the desired sensitivity gain could be achieved with a minimum increase in instrument size. Highly segmented detectors and liquid or gas chambers appear to be the most promising methods for this.

Observations that follow up on the NAE will require improved angular resolution while maintaining sensitivity in order to resolve source complexes and identify the fainter sources. An order of magnitude improvement, to ~ 20 arc min while imaging a field of ~ 5° and maintaining the NAE's energy resolution and sensitivity would probably be necessary. Among the presently foreseeable technologies are germanium, or liquid or high pressure noble gas detectors that obtain few mm spatial resolution and are operated with a coded mask placed at least several meters away. Much better resolution, on the order of 1 arc second, could be obtained with a Fourier-transform type mask placed some tens of meters from a detector having < 1 cm position resolution. Studies of the Pinhole/Occulter Facility show that such resolution in the MeV range could be obtained with these methods.

Gamma-Ray Bursts

We assume that the HETE mission will have led to the discovery of the quiescent counterparts of gamma-ray bursts and thus good distance and luminosity estimates, and that the BATSE on the GRO will have determined the nature of the bursts' size-frequency distribution and their spectral-temporal properties on time scales down to $\sim 10^{-3}$ sec. Then the basic nature of bursts will be known and the future work will emphasize the use of the burst radiation and its gamma-ray line features as a probe of the structure of the burst source, its environment, and the physical processes occurring there. If bursts turn out to have detectable transient optical emission, and lines in their soft x-ray emission as well, then these should also be very fruitful areas of study. Further work will require a multiple wavelength band complement of instruments that simultaneously measure (1) the optical emission to an accuracy of 1 arc sec, (2) the UV to optical spectrum with a resolving power of 100 to 1000, (3) the X-ray through medium energy gamma-ray spectrum with a resolving power of 10 for X-rays to 1000 for gamma rays and (4) the high energy gamma-ray flux up to > 1 GeV in order to determine the limits of the emission spectrum. The required time resolution is very speculative, but it is likely to be less than the time scale for intensity variations, which is already known to be as short as 1 msec at 0.1 MeV. This would require rapidly slewing X-ray and UV-optical spectrometers that are steered by an all-sky optical transient monitor, or wide field of view instruemnts with high spatial and spectral resolution. Ground-based systems employing these principles are presently in development.

Foreign Collaboration

We strongly encourage scientific collaborations with missions of opportunity initiated by other nations. We note in this regard the ESA proposal for GRASP, the scientific objectives of which have many common interests with the U. S. program, and the ambitious Soviet plans for GAMMA-1 and SPECTRUM-GAMMA. Data exchanges with other nations are regarded as vital to the continued health of this discipline.