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RECOMMENDED PRIORITIES FOR NASA'S GAMMA RAY ASTRONOMY PROGRAM 1996-2010

(U.S.) NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, DC

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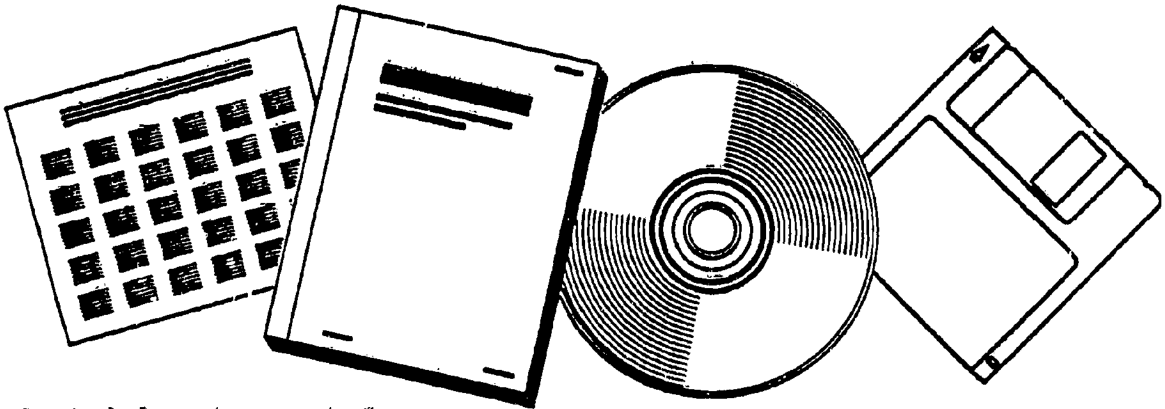

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Report of the Gamma Ray Astronomy Program Working Group
April, 1997

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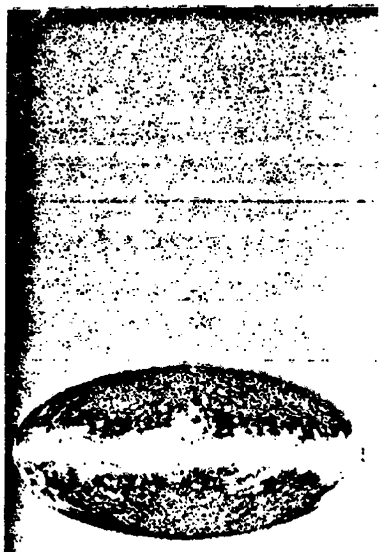
Abstract: It has assessed the state of the field including current missions and approved future missions, the critical scientific problems open today, the promising technologies for the future, the mission priorities for the future, and the needs for data analysis and theory. This report presents a summary of the GRAPWG findings and gives detailed recommendations.



FOREWORD

In 1995, NASA formed the Gamma-Ray Astronomy Program Working Group (GRAPWG) to formulate recommendations for future directions in NASA's gamma-ray astronomy program. The energy range considered in this study extends from hard x-rays (>~ 15 keV) through TeV gamma rays. The mandate of the working group is to recommend a road map to the future for use as an input to the next NASA strategic plan, currently slated for 1997. The working group, whose membership is given below, has met four times over the past 2 years. It has assessed the state of the field including current missions and approved future missions, the critical scientific problems open today, the promising technologies for the future, the mission priorities for the future, and the needs for data analysis and theory.

This report presents a summary of the GRAPWG findings and gives detailed recommendations. The acronyms used in the report are defined in Appendix A.

GAMMA-RAY ASTRONOMY PROGRAM WORKING GROUP MEMBERS:

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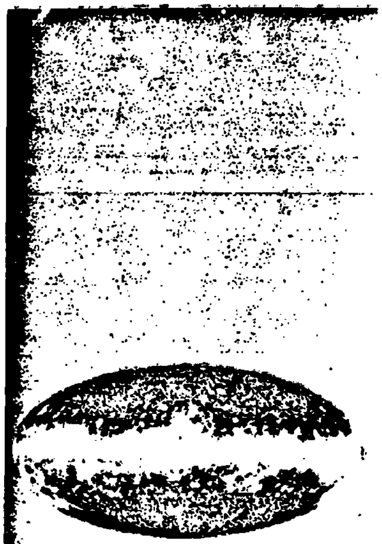

EXECUTIVE SUMMARY

With new results from the Compton Gamma Ray Observatory (CGRO), the Rossi X-ray Timing Explorer (RXTE), and GRANAT, hard X-ray and gamma-ray astronomy are in a period of discovery and vigor unparalleled in their history. The CGRO mission in particular has made fundamental contributions to understanding many classes of galactic and extragalactic objects. The CGRO discoveries of gamma-ray blazars, an isotropic distribution of gamma-ray bursts, bright black hole and neutron star transients, sites of galactic nucleosynthesis, and a large class of unidentified high energy sources have intrigued astronomers and the public alike. These discoveries have prompted a wide range of correlated observations by X-ray satellites and ground-based radio, IR, and optical observatories, adding to our rapidly expanding knowledge of the nature of high-energy emission. We now have the beginnings of a better understanding of the astrophysics of gamma-ray sources, and this in turn has raised fundamental new questions about the origin and evolution of high-energy objects and about the nonthermal astrophysical processes that occur in them.

Looking ahead to the next decade, further discoveries in hard X-ray and gamma-ray astronomy are anticipated with further CGRO and RXTE observations and with the ESA INTEGRAL mission (launch ~2001). However, there are currently no major missions being planned beyond INTEGRAL and none being planned at all by NASA. Of particular concern is the high-energy regime (100 MeV - 100 GeV), where observations will soon come to a virtual halt in the next 2 years as the EGRET instrument on CGRO runs out of spark-chamber gas. Also of concern is the present lack of plans for missions that would 1) significantly improve on the BATSE capabilities to study gamma-ray bursts as well as conduct a full-sky survey and monitor transient source 2) follow-on the first exploration of the MeV band by COMPTEL with much better sensitivity, and 3) continue the important studies of nucleosynthesis begun by balloon instruments, OSSE, and COMPTEL. From a scientific standpoint, there is an urgent need for new observational missions. From a technical standpoint, the timing is excellent since powerful new detector and imaging technologies are in hand that promise major steps in observational capabilities.

With this in mind, the GRAPWG recommends the following program in hard X-ray and gamma-ray astronomy.

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INTERMEDIATE MISSIONS ($75M - $300M)

The HIGHEST PRIORITY recommendation of the GRAPWG is:

- A next-generation 10 Mev to 100 GeV gamma-ray mission such as GLAST. One to two orders of magnitude improvement in sensitivity compared to EGRET are expected resulting in breakthroughs in our understanding of particle acceleration and nonthermal processes in AGN and galactic sources.

The GRAPWG identified two other missions as very high priority for initiation within the next decade. These programs would serve pressing scientific needs and represent areas where prompt support for technology development and mission study promises great gains in the capabilities and efficiency of future missions.

- A focusing hard X-ray telescope. The expected two orders of magnitude improvement in sensitivity compare to RXTE would address questions such as the nature of accretion onto compact objects in galactic sources. A new multilayer mirror technology can extend the focusing range to ~100 keV. The HTXS concept includes a focusing hard X-ray telescope that extends up to 50 keV.
- A next-generation nuclear line and MeV continuum mission. A major step forward compared to INTEGRAL in both sensitivity and energy range would allow detailed studies of sites of nucleosynthesis in the galaxy and of nonthermal sources in the universe. The GRAPWG views this mission as a follow-on to INTEGRAL.

KEY QUESTIONS IN HARD X-RAY AND GAMMA-RAY ASTRONOMY

- What is the origin and nature of gamma-ray bursts?
- What are the physical conditions and processes near accreting black holes and neutron stars?
- How does matter behave in extreme conditions like those in neutron stars, supernova explosions and active galactic nuclei?
- How do astrophysical accretion processes work and what are their instabilities, periodicities and modes?
- What is the nature of the jets emanating from galactic black holes and AGN and how are the particles accelerated?
- What is the origin of the diffuse gamma-ray background?
- What is the nature of the unidentified high energy gamma-ray sources?
- Where are the sites of nucleosynthesis?
- How do supernovae work? What are the progenitors and explosion mechanisms? What has been the rate in the last several hundred years?
- What and where are the sites of cosmic ray acceleration?

MIDEX AND SMEX MISSIONS

Future MIDEX and SMEX missions are crucial for NASA's gamma-ray and hard X-ray astronomy program. The two highest priorities for near-term SMEX and MIDEX missions are (of equal priority):

- A gamma-ray burst localization mission. Such a mission would address the question of the origin of gamma-ray bursts. Missions with coding apertures or an array of small telescopes would fill this need. Searches could also be made for a halo population of burst sources around M31 to test galactic halo models. Example mission concepts are BASIS, ETA, and BLAST.
- A hard X-ray all-sky survey and monitor mission such as EXIST. More than two orders of magnitude improvement over the HEAO-1 survey could be obtained in the 10 - 200 keV range. A significant fraction of the entire sky could be scanned every day for transient sources.

HETE

The loss of HETE is a major setback to the study of gamma-ray bursts. The objectives of that mission are still compelling; rapidly obtained precise positions are invaluable for multiwavelength counterpart searches. The HETE spacecraft can be rebuilt and reflown relatively quickly and inexpensively.

- We endorse this initiative and further recommend that support be provided for the construction of rapidly slewing ground-based telescopes.

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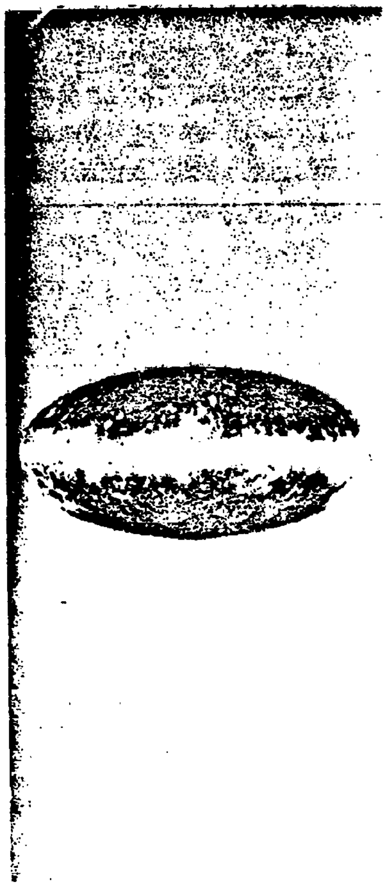
CURRENT AND APPROVED MISSIONS

While future missions are being developed, it is essential to continue scientific discovery with the existing and approved missions in gamma-ray and hard X-ray astronomy.

- CGRO and RXTE are tremendously productive multi-instrument NASA missions that promise to remain scientifically exciting into the future. Adequate MO&DA funding should be made available to continue full operation and scientific utilization of these missions.
- The INTEGRAL will provide substantially better low-energy gamma-ray sensitivity than CGRO with major improvements in spectral and angular resolutions. NASA should continue to provide adequate support for U.S. participation.

OTHER RECOMMENDATIONS

- TECHNOLOGY: The future vitality of hard X-ray and gamma-ray astronomy depends critically on the development of new instrumentation. With opportunities for new technologies opening, there is increasing need for funding of basic technology development. The GRAPWG recommends that the SR&T funding level be increased and/or other funding identified for basic technology development.
- BALLOON PROGRAM: The GRAPWG views NASA's balloon program as highly important for the continuing vitality of our field. We strongly endorse continued support for ballooning and the development of a 100-day balloon capability at midlatitudes.
- DATA ANALYSIS & THEORY: Recent missions have left us with a number of outstanding puzzles. We recommend enhanced support for analysis of the rich trove of space data and for the theoretical work essential to interpretation of gamma-ray observations. At modest cost, this maintains the vitality of the field.
- TeV ASTRONOMY: An important extension to high-energy gamma-ray studies is provided by ground-based observations in the TeV range. The GRAPWG endorses the development of new telescopes with low energy threshold for TeV astronomy.



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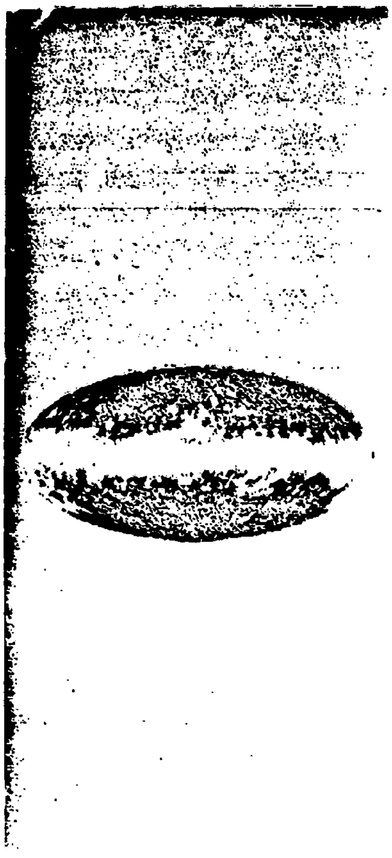

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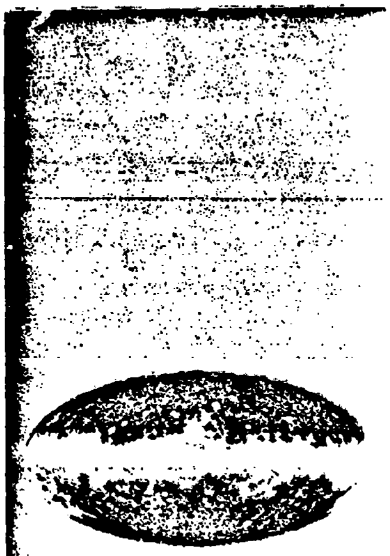

1. THE ROLE OF GAMMA-RAY ASTROPHYSICS

The place of gamma-ray measurements in astrophysics has undergone a fundamental change in the CGRO era. In the field's infancy, advocates focused on the penetrating power of cosmic gamma rays and noted their high-energy production—especially in radionuclide decay as familiar from the early days of nuclear physics. Experimental techniques in the PI-class missions of the 70's and 80's similarly drew heavily from high-energy physics programs. A principal goal was a "discovery" level opening of several decades of the electromagnetic spectrum, adopting familiar high-energy techniques. The objectives focused on identifying radiation processes responsible for the diffuse background emission, separating point sources and localizing transients. These missions led to a census of astrophysical sites where nonthermal gamma-ray processes occur.

CGRO and its predecessors have been very successful in giving an overview of the high-energy sky. Many of the anticipated high-energy processes have been confirmed and gamma-ray emission has proved a robust signature of the most violently active sources in the universe. The CGRO era has moved gamma-ray astronomy to a central role in mainstream astrophysics. We now realize that several of the most important puzzles of modern astrophysics are manifest in the gamma-ray band. The strong guest investigator program of CGRO and contemporary missions and the wide interest in follow-on programs highlight the impact of gamma-ray studies on numerous astrophysical problems. We can best illustrate this impact by summarizing a few key puzzles brought to light by CGRO observations, followed by some new scientific directions inspired by recent results. More complete descriptions can be found in section 2.

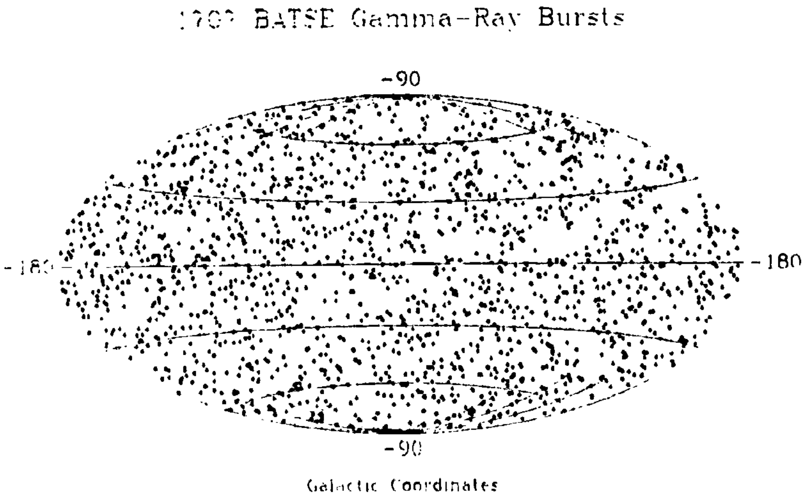

Figure 1.1 - The remarkable isotropy of the gamma-ray burst distribution.

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Before 1991, descriptions of the gamma-ray burst problem acknowledged the wide range of feasible models, but focused with increasing confidence on the view that these bursts arose in a nearby population of galactic neutron stars. In a rather dramatic development, the presentation of the initial BATSE spatial and flux distributions at the 1st Compton Symposium abruptly overturned established thinking and gave strong support to the idea that bursts represent titanic energy releases at cosmological distances. To many, establishing the gamma-ray burst distance scale is a principal problem of high-energy astrophysics. Discoveries during the CGRO mission, such as the great variety of gamma-ray burst time structures and spectral shapes and the existence of multi-GeV photons persisting for over an hour after the onset of the burst event, emphasize that the basic physics of these explosive events remains largely unexplained. Indeed, if burst are truly cosmological, the problem of releasing a supernova's worth of energy in such a highly relativistic form proves a severe challenge to most radiation models. As described in the body of this report, progress on the problem will require a significant improvement in burst sensitivity, particularly at high energies, and careful coordination with other wavebands. Several missions in the post-GRO era present exciting opportunities for advancing our understanding of these enigmatic events.

Another important result of the CGRO mission has been the observation of certain strong, non-thermal emission associated with jet sources. In particular, the detection of over 50 "blazars" by the EGRET experiment, often with large and rapid flux variations and hard photon spectra extending above a GeV, shows that the AGN engine exhibits dramatic effects in this energy range. Two of these AGNs have been detected by ground-based telescopes with energies up to 5 TeV and doubling time variability as short as 15 minutes. These AGN are objects of intense study at lower energies; in particular, many GeV blazars exhibit "superluminal" motions at VLBI scales emphasizing the important connections of ground-based studies with gamma-ray observations. The correlation of outburst events in high angular resolution images with high-energy fluctuations hints at the mechanics and products of the AGN engine.

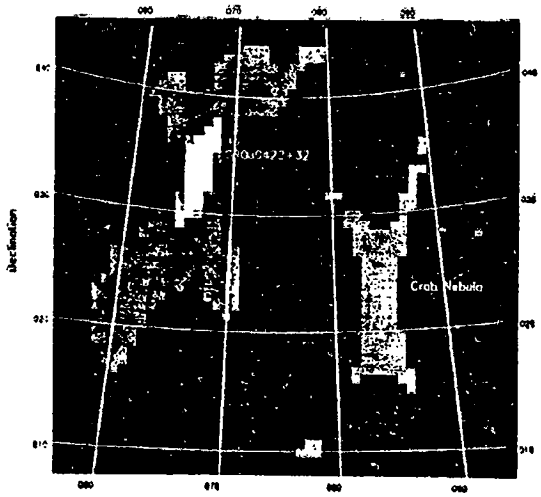


Figure 1.2 - The black hole candidate GRO J0422+32 at peak outburst, outshining the nearby Crab pulsar.

A related series of discoveries stems from the BATSE monitoring of X-ray outbursts along the galactic plane. Several sources show hard spectral tails extending beyond several tens of keV and approaching 1 MeV. Some sources showing strong outburst activity were recently discovered to show evidence of relativistic jet outflows in the radio band. Jet production has been a puzzle for several decades. These new measurements suggest that the hard X-ray/soft gamma-ray emission of accreting sources are spectral fingerprints of such jet activity. The nonthermal observations provide unique information on the particle and radiation fields in these jets. Gamma-ray detections should thus provide key probes of the nuclear activity/jet connection.

When a new wavelength range is opened, the most intriguing results arise when a class of sources not prominent at other energies dominates the sky. At MeV-GeV energies, SAS-2 and COS-B showed that there is a significant population of galactic sources not identified with previously known objects. CGRO with improved sensitivity, energy resolution and background modeling has surveyed this population, detecting over thirty such objects. Since Geminga, the brightest of these sources, has now been identified as a radio-quiet pulsar, it seems likely that many others will be spin-powered pulsars. This provides an important new window on the neutron star population in our galaxy. Equally exciting is the possibility that other classes of gamma-ray stars will be discovered; the detective work of identifying the galactic plane population will be a theme in follow-on work to CGRO.

In the technically challenging nuclear line regime, CGRO has uncovered only the tip of the expected MeV line emission science at sensitivities of a few times 10^{-5} photons $cm^{-2}s^{-1}$, but already some surprising results have appeared. For example, distribution of radioactive ^{26}Al mapped by COMPTEL argues for production dominated by massive star death, although surprising excesses in the Vela region are unexplained. Also, the strong COMPTEL detection of ^{44}Ti from Cas A(Figure 3.1.1) implies substantial synthesis of ^{56}Ni. This makes the low luminosity of this Type II supernova event a mystery. Finally, the COMPTEL discovery of what may be broad cosmic-ray induced MeV emission lines from C and O in Orion suggests that the molecular cloud complex is a hotbed of cosmic ray acceleration. The young stellar objects in Orion are thus depositing enormous amounts of energy into shock waves. While the INTEGRAL will provide a significant improvement in sensitivity, efforts to develop new technology in this area will be needed for the field to reach its full potential.

We should also note some new research directions in gamma-ray astronomy spurred by CGRO observations. The impact on such problems provides a good measure of the power of future missions. One new area is the association of nonthermal spectra with black hole accretion. In addition to the GeV emission and rapid variability of the blazars, the suprathermal hard X-ray/soft gamma tails in some sources are important diagnostics for disk accretion and processes at the disk inner edge. GRANAT, BATSE, and OSSE measurements above 30 keV show such spectral components in Seyfert AGNs. Intriguingly, when similar features appear in galactic X-ray binaries, dynamical studies have shown the sources to be excellent candidates for black hole accretors. Coupled with this, recent work on accretion disk solutions (e.g., advection dominated disks) suggest that disk inner edge conditions are crucial in producing the optically thin regions that generate such nonthermal spectra. Thus, we can hypothesize that the perfectly absorbing boundary of an accreting black hole is central to the formation of optically thin electron population responsible for the hard X-ray mission and possibly to the acceleration of relativistic jets. We see that the gamma-ray regime provides a unique window on this problem. Our understanding of the AGN phenomenon, likely guided by the "Rosetta Stones"—the galactic black hole candidates—should make a dramatic advance with future hard X-ray to GeV gamma-ray measurements.

A second arena where gamma rays draw our attention to the most exotic sources lies in the high-energy emission of gamma-ray bursts. While this emission has been seen in only a handful of events, such emission may be present in most bursts. Conditions needed for the production of this multi-GeV flux, which may dominate the total burst energy, are extreme; we are likely to learn more about burst physics from these radiations than from the more chaotic low-energy emission. This theme of the highest energy providing the sharpest diagnostics is echoed in the study of spin-powered pulsars. While intensively studied in the radio through X-ray bands for over 25 years, the physics of the pulsar magnetosphere is still poorly understood. CGRO has taught us that much of the well-known pulsar emission is a small fraction of the bolometric luminosity: the power spectrum of their spin-down radiation peaks in the GeV range for some pulsars. Pulsar measurements pose some of the most severe challenges in the gamma-ray range, requiring high sensitivity, precise photon timing, and accurate calibration over the entire keV-GeV range and beyond.

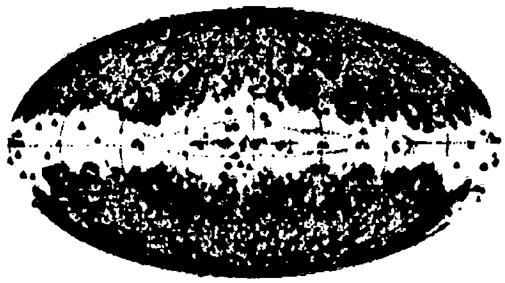
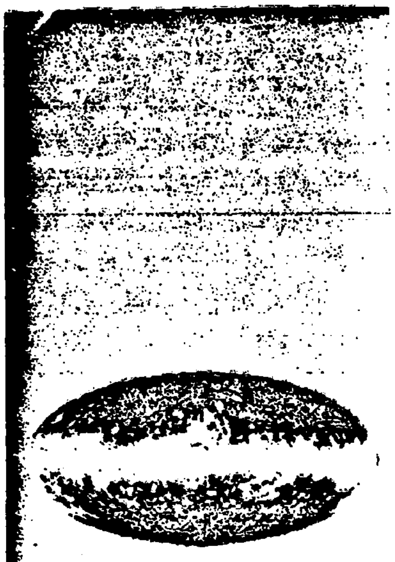


Figure 1.3 - EGRET map of the high energy sky with detected sources marked. Gamma-ray emitting active galaxies and pulsars can be seen above the diffuse glow of the galaxy.

A final example illustrates the ability of new gamma-ray data to address fundamental problems in mainstream astrophysics. The recent detection of several nearby AGNs by ground-based air Cerenkov telescopes with ~300 GeV thresholds illustrates the fact that blazar emission can extend well beyond the present sensitivity limit of space missions. Since this gamma-ray flux is attenuated by the ambient cosmic photon fields, we see that measurements of GeV-TeV spectra may fix the soft IR-optical radiation field at high redshift. This new cosmological tool helps to constrain galaxy formation and environments in the early universe. Conversely, the search for absorption affects in GRBs helps to constrain source distances. However, this promise will only be realized via sensitive surveys at the highest energies, coupled with careful ground-based measurements in the TeV range that we can then correlate with our understanding of the early universe.

The opportunities for future gamma-ray discoveries are manifold, as are the prospects in many other areas of astrophysics. It is therefore important to note the unique observations at gamma-ray energies. Above all, gamma-ray astronomy zeros in on some of the most exotic, violent, and fascinating sources: black holes, neutron stars, and explosive sources of nucleosynthesis and particle acceleration. Also, the field is relatively new. With CGRO, gamma-ray measurements have just reached the sensitivity that attract wide theoretical attention and correlative investigations. The rapid development spurred by this synergy should be encouraged over the next decades. Finally, it is a field where new detector development and adoption of technologies used for related terrestrial applications offer the opportunity for dramatic gains. With directed resources for future development and rapid promotion of new technologies to space payloads, certain areas of gamma-ray astrophysics can expect great leaps in sensitivity. These opportunities will be described in the following sections. Thus, with the potential for dramatic new high-energy phenomena strong and the demonstrated ability to probe some of the most exotic objects in the universe, the opportunities for gamma-ray astronomy over the next decade and a half are exciting.



2. SCIENTIFIC OBJECTIVES

2.1 THE ORIGIN OF THE ELEMENTS

2.1.1 PROMPT EMISSION FROM SUPERNOVAE & NOVAE

Because the sites of explosive nucleosynthesis, novae and supernovae are optically thick to gamma rays, only the delayed gamma-ray line emission from the decay of synthesized radionuclei can be observed. Furthermore, this is possible only for sites that become at least partially transparent on time scales less than the radioactive decay mean lives. The most luminous lines from individual events are the ^{56}Ni and ^{56}Co lines of Type Ia supernovae. Such supernovae are required to make $\sim 0.6\ M_\odot$ of ^{56}Ni during their explosion to provide both the energy to unbind the white dwarf and to power the light curve. The ejecta from these supernovae also have higher velocities than Type II's because the characteristic 10^{51} erg of kinetic energy is distributed within an object about 10 times less massive. The flux at maximum in the prominent lines of ^{56}Co in a typical Type Ia supernova is about 3×10^{-5} (10 Mpc/D)^2 photons cm^{-2} s^{-1} occurring about 50 to 150 days after the explosion. These lines are quite broad, however, with typical velocities of about 5000 km/s. The full width is thus about 30 keV. An enduring goal has been to measure Type Ia supernovae in the Virgo cluster at about 20 Mpc where the event rate is high. To study these supernovae and learn anything save the well-known fact that they made some ^{56}Ni, one needs broad line sensitivities no worse than a few times 10^{-6} photons cm^{-2} s^{-1}. Lacking adequate sensitivity to do this, one must await the occasional nearby event.

Ideally one would like not only to see the lines, but to resolve their velocity structure and get the velocity distribution and mass of ^{56}Ni made in the explosion. This constrains the explosion mechanism (detonation or deflagration) and provides information on mixing of the inner and outer layers of the supernova. Similar information can be obtained by watching the time dependent transparency of the event, but to do this one must begin to measure the flux quite early and continue measuring it for a long time.

SN 1987A was typical of Type II supernovae, though about a factor of 10 brighter at maximum in the gamma-ray lines of ^{56}Co (because it was a blue supergiant instead of a red one). The peak flux at 55 kpc was about 10^{-3} photons cm^{-2} s^{-1}. This means that observations of Type II supernovae will be restricted, for the next decade or so, to improbable occurrences in the local group of galaxies. Type Ib supernovae are also massive stars, but lack hydrogen envelopes. They produce about 5 times less ^{56}Ni than Type Ia, but expand almost as rapidly. Thus their signal is intermediate between Types II and Ia. A mission having broad line sensitivity of a few times 10^{-6} photons cm^{-2} s^{-1} might detect one Type Ib supernova every few years. It is worth mentioning that *any* supernova in our galaxy would be very bright in the decay lines of ^{56}Co and thus CGRO provides a fail-safe against missing the next galactic event.

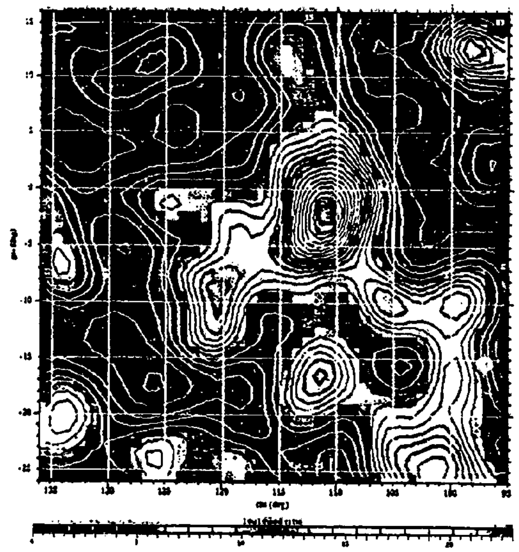


Figure 2.1.1 COMPTEL detection of 1.157 MeV ^{44}Ti line emission from Cas A.

The other isotopes detectable from individual supernovae are ^{44}Ti, ^{57}Co, and ^{60}Co. Models for Type II supernovae predict a ^{44}Ti mass from 0 to $2x10^{-4}$ $M_{\odot}$. Since this isotope comes from the deepest layers ejected in the supernova, its ejection is sensitive to the uncertain explosion mechanism and to the details of the fall back (e.g., whether the supernova makes a black hole). Recently, COMPTEL has reported the detection of the 1.157 MeV line from the ^{44}Ti-^{44}Sc decay from the youngest known galactic supernova remnant, Cas A. The implied yield, 1- $2x10^{-4}$ $M_{\odot}$, is consistent with models, but it remains a mystery why Cas A was not a brighter supernova given that ^{44}Ti ejection implies ^{56}Co ejection. Assuming a comparable ^{44}Ti yield in other Type II supernovae, the planned INTEGRAL mission should discover several other young remnants in our galaxy. However, it should be noted that ^{44}Ti decay also produces comparable fluxes in lines at 67.85 keV and 78.38 keV. It may be that hard X-ray instruments can be built with greater sensitivity. SN 1987A is also expected to have made ~$0.5x10^{-4}$ $M_{\odot}$ of ^{44}Ti (highly uncertain) implying a flux for the next few decades of about $2x10^{-6}$ cm^{-2} s^{-1}.

Gamma-ray lines of ^{57}Co ($T_{1/2}$ = 271.8 d) were detected from SN 1987A by OSSE implying a ratio ^{56}Fe/^{57}Fe of about 1.5 times the solar value, an interesting constraint on both the star's evolution (i.e., the neutron excess in the silicon shell) and galactic chemical evolution. However, the signal of this isotope and ^{60}Co ($T_{1/2}$ = 5.27 y) are such that they are only likely to be detected from fortuitous supernovae in the local group.

The most prominent radioactivity expected to produce gamma-lines from classical novae is ^{22}Na. The synthesis of this species is highly uncertain and is sensitive to the nature of convection during the explosion and whether the nova event occurs on a carbon-oxygen white dwarf or a neon-oxygen white dwarf (the signal is much stronger from the latter).

2.1.2 GALACTIC NUCLEOSYNTHESIS

The 1.809 MeV line from the decay of the very long-lived (mean life $1.07x10^{6}$ years) ^{26}Al was the first nucleosynthetic gamma-ray line to be detected. It shows that nucleosynthesis is an ongoing process in the galaxy. Most recently, images in the 1.809 MeV line have revealed a broad, patchy longitude distribution that is very different from that of the 0.511 MeV line which is strongly peaked at the galactic center. This result demonstrates that the two line emissions have different origins. The observed line fluxes suggest that there is roughly 1 to 2 $M_{\odot}$ of ^{26}Al in the galaxy, which is consistent with that expected from recent estimates of Type II supernova yields and occurrence rates. Although Wolf-Rayet stars have also been suggested as a source, they do not appear to be significant because recent observations of the Vela supernova remnant show an enhancement in the 1.809 MeV line intensity, clearly supporting a supernova origin of the ^{26}Al, while no significant emission was seen from the nearby Wolf-Rayet star γ Vel. The total amount of ^{26}Al observed is consistent with current models of supernovae and galactic chemical evolution.

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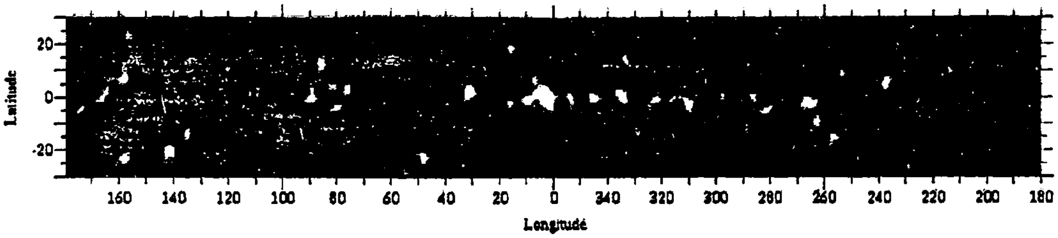


Figure 2.1.2 - Galactic map of the ^{26}Al - 1809 keV line as seen by COMPTEL. A tracer of recent (10^6yr) nucleosynthesis.

In addition to the galactic longitude and latitude distribution of the 1.809 MeV line emission, information on the origin of the ^{26}Al can also be obtained from studies of the shape of the line. Surprisingly large Doppler broadening of the line has recently been observed with a balloon-borne gamma-ray instrument GRIS, implying velocities of about 400 km/sec, much larger than that expected from galactic rotation. This suggests that the emitting ^{26}Al may be in high-velocity grains precipitated from supernova ejecta. Future observations by INTEGRAL should provide a much better understanding of the origin of the radioactive aluminum and of the chemical evolution of the galaxy.

The same models that agree with the observed ^{26}Al signal also predict a strong signal from ^{60}Fe, another long-lived nucleus ($\tau_{1/2} = 1.5 \times 10^6$ y) made in Type II supernovae. The mass of ^{60}Fe predicted is 1.7 ± 0.9 $M_\odot$, implying a signal about 15% as strong as ^{26}Al. This is on the edge of what can be currently detected but should be visible to INTEGRAL.

The diffuse galactic 0.511 MeV line from positron annihilation, which has been extensively observed from the galactic center region, is the most luminous gamma-ray line in the galaxy. The positrons responsible for this emission are most likely from the decay of the radionuclei ^{56}Co, ^{44}Ti and ^{26}Al resulting from various processes of galactic nucleosynthesis.

2.1.3 INTERSTELLAR PROCESSES

The recent discovery of gamma-ray emission lines from the Orion giant molecular cloud complex has revealed exciting new particle acceleration processes in this nearest region of recent star formation. This has very important implications for light element nucleosynthesis. Gamma-ray line emission in the 3 to 7 MeV range was observed from the Orion complex with COMPTEL. The radiation shows emission peaks near 4.4 and 6.1 MeV, consistent with the de-excitation of excited states in ^{12}C and ^{16}O produced by accelerated particle interactions. Moreover, the intensity of these lines is roughly two orders of magnitude greater than that expected from irradiation by low-energy cosmic rays with energy density equal to that of the local galactic cosmic rays. This emission requires that the ambient matter in Orion, both gas and dust, is undergoing bombardment by an unexpectedly intense, locally accelerated, population of energetic particles. The present rate of energy dissipation of the particles in Orion is about 5×10^{38} erg s^{-1}. The most likely source of this energy is the ~80,000-year old supernova which is thought to be responsible for the Orion-Eridanus bubble. If such particle fluxes also exist in other massive star formation regions, their interactions could be the major source of light element (^6Li, Be & B) nucleosynthesis in our galaxy.

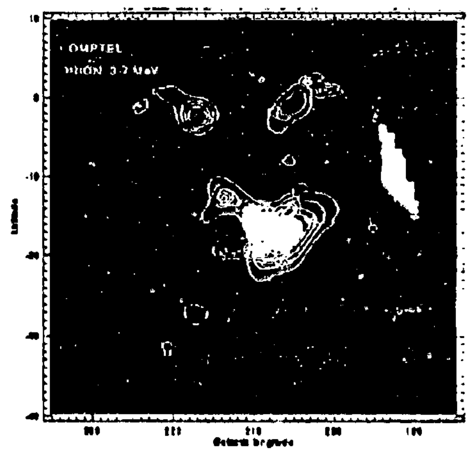


Figure 2.1.3 - ^{12}C & ^{16}O Line emission from Orion star formation region which traces cosmic ray interactions in molecular clouds.

High resolution measurements of the gamma-ray spectrum from the Orion region and a search for such emission lines from other massive star formation regions are essential for a better understanding of these exciting processes.

The galactic diffuse gamma-ray emission is the dominant feature of the high-energy gamma-ray sky. The diffuse emission is produced primarily by cosmic-ray electron and proton interactions with the matter (via Bremsstrahlung and nucleon-nucleon interactions) and photons (via inverse Compton interactions) in the interstellar medium. A high-energy gamma-ray telescope with better angular resolution will permit more detailed searches for cosmic-ray gradients including variations in the electron to proton ratio, cosmic ray contrast between the galactic arm/inter-arm regions, and evidence for regions in which the cosmic-ray spectrum differs from the local observed spectrum. Increased sensitivity coupled with improved angular resolution will also allow the flux from fainter gamma-ray point sources to be more accurately separated from the galactic plane diffuse emission. The gamma-ray emission from molecular clouds arises from the same cosmic-ray interactions with matter which produce the general galactic diffuse emission. Molecular clouds provide a means to study these processes and the galactic cosmic rays in localized regions of the galaxy.

OBJECTIVES:

- Measure gamma-ray line emission from nearby extra galactic supernovae.
- Confirm the COMPTEL results and better define the energy spectrum to better constrain low-energy cosmic-ray abundances of H, He, and Z>8.
- Imaging spectroscopy of Orion with higher angular resolution mapping to localize the low-energy cosmic-ray sources region.
- Search for nuclear de-excitation lines from other regions of the galaxy to determine the extent of low-energy cosmic-ray acceleration and their role in light element production.

REQUIREMENTS:

- Flux sensitivity at least a factor of 10 better than INTEGRAL with comparable energy resolution and angular resolution of <1 degree.

2.2 THE NATURE OF BLACK HOLES & NEUTRON STARS

2.2.1 BLACK HOLE SYSTEMS

Less than a decade ago, the only black holes suspected were in massive binaries such as Cyg X-1. The situation has changed dramatically with the discovery of highly-transient compact binary systems with a low-mass stellar companion and a high-mass compact primary (almost certainly a black hole based on the dynamical mass). The estimated total number of these systems in the galaxy may be hundreds or more, and thus they could be the dominant class of X-ray binaries. Black hole systems with a high-mass companion have persistent hard spectra, often extending out to 200 keV, and low-mass companion transient systems have spectra showing broad line emission at around 200 and 400-500 keV, such as that observed in the flaring of Nova Muscae (GRS 1124-684). Spectra of samples of black holes will allow detailed tests of emission models and comparisons with neutron stars. Further comparisons with spectra of AGNs, believed to contain super-massive black holes, could then be made to determine the self-similarity of accretion flows onto black holes over a wide range of mass scales.

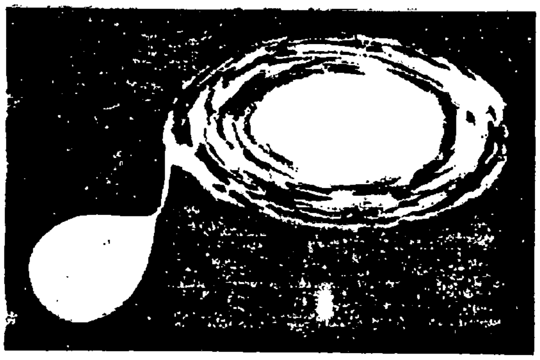


Figure 2.2.1 - Accretion-disk with black hole spectral components. Recent CGRO and RXTE observations have provided important insights into accreting binary systems.

2.2.2 ACCRETING NEUTRON STARS: X-RAY BURSTERS AND PULSARS

In low magnetic field ($B < 10^{8}$-9 G) neutron star systems, the weak field cannot channel the accretion flow onto the neutron star. When in a state of low accretion, these systems appear to exhibit hard X-ray power law components (hard tails) extending out to ~60-100 keV. Spectral measurements to determine the self-similarity of the photon index (typically 2.5-

3) and cutoff energies are of primary interest for understanding the accretion flows onto these systems (versus black holes). Studies of X-ray bursters with BATSE as well as studies of individual systems (e.g., 4U 0614+09 and 4U 1915-05) have suggested common characteristics of the hard spectra from neutron stars and the likely differences between neutron star and black hole hard X-ray spectral components. These suggest many observational follow-up studies for future missions with much higher sensitivity and resolution.

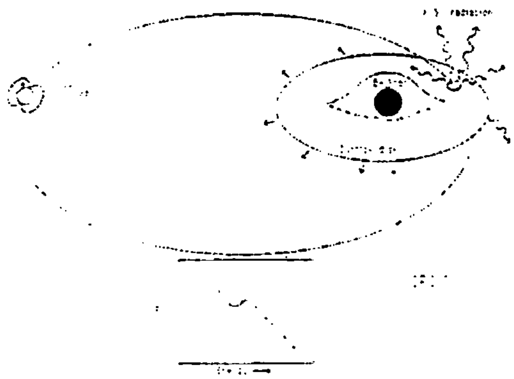


Figure 2.2.2 - Geometry of the A0535+26 & Be binary pulsar. The OSSE detection of a cyclotron line feature provides an important probe of this system.

Accreting high magnetic field neutron stars are observed as X-ray pulsars. The detection and detailed study of cyclotron lines in their hard X-ray spectra are the best and most direct method of determining neutron star magnetic fields. Indirect arguments invoking spin-up or spin-down near the equilibrium spin period often indicate rather high magnetic fields (~10^{14} G in the case of GX1+4). Recent measurements of a cyclotron feature at 110 keV and a possible feature at 55 keV in A0535+26, implying B ~10^{13} G, have strengthened the case for high magnetic fields for some accreting pulsars. High fields are similarly inferred for other Be binaries. Magnetic dipole spin-down remains a possibility although the implied fields approach 10[illegible]G in several cases. Because of the rapid spin-down to the radio pulsar death line, such ultra-high field neutron stars may be best observed in the X-ray regime. Cyclotron line features and high quality continuum spectra of such sources would probe the strongest magnetic fields in nature and should give important evidence of new quantum effects expected near 10^{14}G.

The persistence of such high fields may be related to the accretion history of these objects. If so, relatively low average accretion rates may be important such as seen in the Be systems, implying either transient X-ray sources or low steady luminosities. Accordingly, studying these unique high field sources presents several observational challenges: the sources will be transient or faint and the need to obtain high sensitivity, high resolution spectra covering two cyclotron harmonics requires sensitivity to energies as high as 500 keV-1 MeV. The INTEGRAL should give important results on some brighter systems, but future large area imaging experiments will be needed to probe the physics of ultra high-field accreting neutron stars.

2.2.3 WHITE DWARFS

Since the proton accretion free-fall energy onto a white dwarf is ~200 keV, accreting white dwarfs, or cataclysmic variables (CVs), are natural hard X-ray emitters. The magnetic CVs, or AM-Her and DQ Her systems (strong and moderate magnetic fields, respectively) may have accretion flows closest to free-fall since their disks are nonexistent or marginal (respectively). Much more sensitive hard X-ray observations would allow the first broad comparison with the ROSAT Survey, which has greatly extended (to more than 40) the known sample of AM Her systems. These are "ultra-soft." The higher spectral resolution of future hard X-ray missions would allow (for example) a systematic search for the expected change in hard X-ray cutoff energy vs. mass of the white dwarf (due to changing M/R) as might be observable in "new" ~200 MG AM Her systems.

2.2.4 SPIN-DOWN PULSARS

Isolated pulsars have been known since their discovery to be neutron stars with spin-powered magnetospheric emission. Not long after their radio detection, the Crab and Vela pulsars were found to be pulsing at optical, X-ray and gamma-ray energies. Despite this well established identification, fundamental questions about these objects remain unanswered, including the basic radiation mechanism, the nature of the particle acceleration, the pulsar birthrate, and the relationship to supernova remnants. An examination of a power spectrum of the pulsed emission shows that the peak energy output for pulsars such as Vela lies at several GeV. The solution to the pulsar problem is thus most likely to be extracted from high-energy gamma-ray observations although it is clear that careful ties with other wave bands provides important information from across the spectrum.

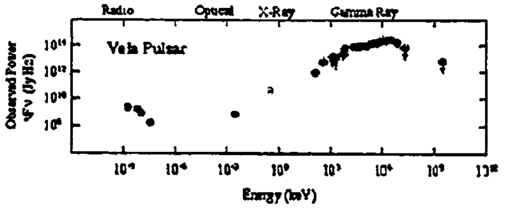


Figure 2.2.3 - νF_{ν} plot of the Vela pulsar showing the peak emission in the gamma-ray range.

With the results from CGRO, the number of gamma-ray pulsars has risen from 2 to at least 7, and several surprises have come to light. The new detections show that pulsars can be remarkably efficient producers of GeV photons, with 10% or more of the energy in the pulsed emissions for 10^5-10^6 year old pulsars. Furthermore, the detection of Geminga as a radio-quiet pulsar shows that radio and high-energy pulsars are overlapping subsets of the neutron star population, but with quite different beam patterns. The gamma-ray observations thus provide a complementary (and apparently more complete) sample of the young pulsar population. Although Geminga remains a sample of one, radio-quiet pulsars are expected to represent a sizable fraction of the unidentified high-energy gamma-ray sources. Thus studying the gamma-ray sample will greatly advance our understanding of the neutron star birthrate (and its relationship to the supernova rate).

The site of the pulsar particle acceleration and the gamma radiation is still under investigation. Theoretical modeling has focused on acceleration at the polar caps and in vacuum regions in the outer magnetosphere. These models have advanced to the point where pulse profiles, luminosities, and spectral variations with pulsar phase can be computed; comparison with CGRO data on the brightest objects (Crab, Vela, and Geminga) have provided significant constraints. What these comparisons make clear is that the GeV emission directly probes the dynamics and geometry of the particle acceleration region where electron/positron energies are inferred to exceed 10 TeV. A unique attraction of pulsar modeling arises from the fact that rotation brings different regions of the acceleration zone into view during the pulse; with sufficient statistics and energy coverage the rich temporal structure in pulsar spectra allow a tomographic analysis of physical conditions in the magnetospheric particle accelerator.

Finding more gamma-ray pulsars, both radio-loud and radio-quiet, will be essential to answering the outstanding questions. A crucial test of pulsar models will be their ability to predict which radio pulsars will be detected as gamma-ray pulsars in the future.

When a source is a known radio pulsar, sensitive pulse searches and measuring high quality phase resolved spectra benefit from very long exposures. Thus the most important attributes of a future high-energy gamma-ray mission are large effective area coupled with large field-of-view. When a source is not identified with a radio pulsar, finding the pulsed emission directly in the gamma-ray data requires a high count rate. In both cases, high angular resolution (< 10') at GeV energies will be very important for isolating sources from the bright galactic background. Further, arcminute positions in the GeV range will enable powerful searches for counterparts with imaging X-ray telescopes and ground instruments. Such counterpart searches offer the best means to trace the origin of the galactic plane sources.

To untangle the physics of the detected pulsars, high quality phase resolved spectra are crucial. Particularly important are extension of the sensitive range above 10 GeV where the pulses merge with unpulsed plerionic emission (and where Compton scattered photons may dominate the pulsed signal) and below 10 MeV where existing observations require a break from the flat GeV spectra and important phase variability is expected in many models.

OBJECTIVES:

- Identify a larger gamma-ray sample of accreting black holes and neutron stars.
- Monitor the sky for transient hard X-ray emission to identify new active accreting black holes and neutron stars.
- Measure temporal and spectral variations of emission from accreting black holes and neutron stars.
- Search for e+-e- anihillation line emission in the flaring 10 keV to 1 MeV spectra of accreting black holes.
- Identify a larger gamma-ray sample of both radio pulsars and radio-quiet pulsars.
- Measure phase-resolved energy spectra for many pulsars over a broad range.

REQUIREMENTS:

- Effective area at least 5 times that of EGRET, for high counting rate; substantially increased FOV for total pulse statistics.
- Moderate spectral resolution from 10 MeV to 100 GeV; excellent calibration at low energies to allow comparison with Compton/Scintillator detectors.
- Source locations one arcmin or better to allow deep X-ray and radio searches for pulsars.
- All-sky monitoring of hard (10-200 keV) X-rays with sensitivity at least two orders of magnitude better than HEAO-1.

2.3 EXTRAGALACTIC ASTROPHYSICS

2.3.1 SEYFERTS

Prior to the launch of the CGRO, only four AGN had been detected significantly at energies above 100 keV; these are NGC 4151, 3C 273, Centaurus A, and MCG 8-11-11. The CGRO instruments clearly separate the high-energy emission of AGN into a gamma-ray blazar class discovered by EGRET and characterized by strong emission above 30 MeV and a Seyfert class seen by OSSE below a few hundred keV with softer spectra which cut off below the EGRET band. The blazar AGN are generally identified with core-dominant radio sources such as flat-spectrum quasars and BL Lac objects.

The distinction between the blazars and Seyfert classes of AGN is thought to be the importance of beamed, relativistic jet emission which presumably dominates in blazars relative to emissions associated with an accretion disk which dominate in Seyfert AGN.

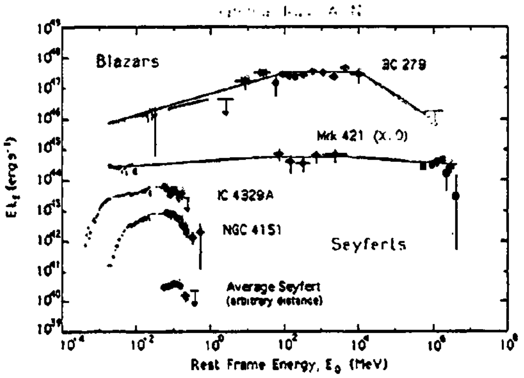


Figure 2.3.1 - νF_ν of gamma-ray detected Seyferts & blazars which form quite distinct classes of gamma-ray AGN.

The X-ray emission of Seyferts can be described by both thermal and nonthermal mechanisms. Key measurements in hard X-rays and gamma rays are needed to resolve the thermal/nonthermal nature of the energy source. In nonthermal scenarios, the creation of pairs through γ-γ -> e^+-e^- interactions significantly alters the emerging high-energy spectrum. Under certain source density-luminosity conditions, broadened pair annihilation features would be observable. In addition, the continuum spectral shape above 100 keV should be different for nonthermal vs. thermal emission mechanisms.

OSSE has detected significant emission above 50 keV from 14 Seyferts. The average spectrum above 50 keV is adequately described by either a power law with energy spectra index α = 2.4 or by a simple exponential with an e-folding energy of 45 keV. Correlated observations with Ginga and/or ROSAT on specific bright sources provides more physical interpretation of the emission. In the case of NGC 4151, the brightest Seyfert detected by OSSE, the spectrum is clearly cutoff. IC 4329A is a more representative Seyfert 1 AGN but is significantly weaker than NGC 4151 in the OSSE band. Combined analysis of IC 4329A data from Ginga, ROSAT, and OSSE require no strong cutoff as in NGC 4151 with the cutoff limit constrained—only to be above 250 keV; consequently both thermal and nonthermal models are acceptable. A simple model of Comptonization in a relativistic, optically-thin, thermal corona above the surface of an accretion disk provides a good description of the observed spectrum.

2.3.2 BLAZARS

One of the major accomplishments of gamma-ray astronomy in recent times has been the detection of high-energy gamma-rays from a class of active galaxies termed "blazars." The observed luminosity of some of these at gamma-ray energies exceeds that at other wavebands by as much as two orders of magnitude; energy considerations demand that the gamma-ray emission be beamed. The gammarays are thought to be produced in jets containing highly relativistic plasma, moving with roughly the same Lorentz factors required to explain the superluminal motions detected in many sources. The timescale of variability of the gamma-ray emission is shorter than at radio frequencies, implying that the gammarays originate in the portion of the jet that lies between the central engine and the radio jet imaged with VLBI. Very little is known about this portion of the jet. Yet it is precisely the region where the most important physics occurs: the formation of the jet, the acceleration of the energetic particles, the collimation of the flow into a narrow cone, and the acceleration of the flow to Lorentz factors up to 20 and possibly as high as 100.

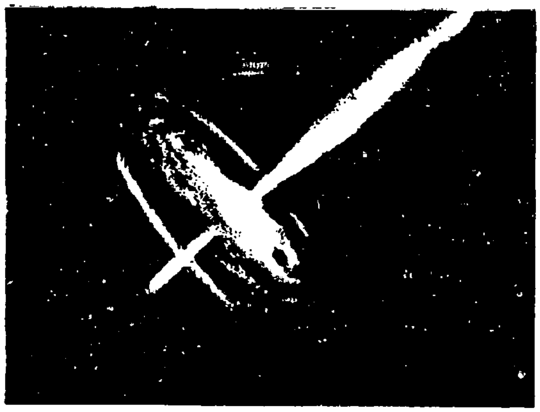


Figure 2.3.2- Illustration of a blazar jet which dominates the emission from gamma-ray blazars.

In some cases, the gamma rays are detected during periods of enhanced activity at other wavelengths. In a few well-monitored objects, there is a close association between flares seen at millimeter to optical wavelengths and high gamma-ray states (e.g., PKS 0528+134 and 3C-279) and between UV to X-ray and very high-energy gamma-ray emission (e.g., Mkn 421). The particle injection/acceleration process, which appears to fluctuate rapidly, can only be studied directly by observing the GeV-TeV gamma rays.

With an improvement in sensitivity of a factor of 10 in a GeV space telescope (a combination of larger effective area and better angular resolution), the number of blazars visible to a future instrument should increase by a factor of at least 30, from the present 50 to several thousand, which would (if there are not basic differences) encompass all the known blazars. A similar improvement in sensitivity in ground-based observatories will permit the detection of weaker nearby blazars as well as long-and short-term monitoring programs.

Simultaneous multiwaveband monitoring will result in exciting inferences regarding relativistic jets and energetic particle acceleration in blazars. The ability to follow flares smaller than those which can be detected with EGRET, and to obtain better time resolution will lead to the derivation of the geometry and physical characteristics of the inner jet by observing time delays at different frequencies as the flare propagates along the jet.

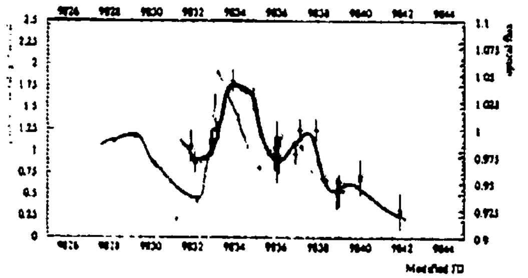


Figure 2.3.3 - One example of AGN flare / multiwavelength time variability. Correlating gamma-ray emission with lower energies provides important diagnostics into emission mechanisms.

Of particular importance will be the measurement of the energy spectra of gamma-ray blazars as a function of redshift, since the ability of high-energy gamma rays to traverse large cosmic distances is limited only by photon-photon pair production off ambient photons. For the closest blazars this cutoff will occur at energies above 4 TeV but for the most distant objects will occur above 30 GeV. To complete this study, observations with high sensitivity will be required from both space-and ground-based gamma-ray telescopes. Observations of the high-energy cutoff to the gamma-ray emission from blazars will therefore allow an inference of the ambient photon field and may define the epoch of galaxy formation.

2.3.3 CLUSTERS

The detection of hard X-ray emission from inverse Compton scattering of 2.7 K background photons from high-energy intracluster electrons would provide a very direct way of investigating intergalactic magnetic fields. The presence of electrons is inferred from the observation of cluster radio halos. The Coma cluster is the best known example, but others include A2255, A2256, A2319, and A1367.

The origin of the magnetic fields in galaxy clusters is not understood, nor is the mechanism by which the electrons are accelerated. Since we cannot be confident of equipartition, the magnetic field cannot be estimated from the radio observations alone. Observation of the inverse Compton X-rays together with the radio observations would provide a much more direct method of establishing the magnetic fields, but requires X-ray observations above about 20 keV to avoid confusion from thermal emission. An estimated flux sensitivity of ~3 x 10^{-6} photons cm^{-2} s^{-1} keV^{-1} in the ~20-60 keV range is needed to make the crucial measurement. While HEXTE will attempt this, imaging instruments are needed to avoid confusion with cluster AGNs. High spectral resolution in the hard X-ray band is also needed for a clean separation of the thermal cluster gas component. Focusing hard X-ray telescopes, with high resolution detectors, are particularly well suited to this important problem.

2.3.4 THE DIFFUSE GAMMA-RAY BACKGROUND

Data on the cosmic diffuse gamma-ray background has been obtained by over 20 balloon- and satellite-borne instruments over the past 30 years, but only recently have good spectral measurements been made. Many questions remain unanswered though, such as the spectral shape in the MeV region, the presence or absence of nucleosynthetic lines, the angular distribution, and the origin of the radiation.

The low-energy portion of the cosmic diffuse spectrum (10 keV to 60 keV) is characterized by a bremsstrahlung spectral form that can be approximated by a power-law segment of energy index ~0.4. The energy spectrum transitions to a power law of index ~1.6 above 60 keV. At an MeV, there is still uncertainty as to the shape. Prior to 1995, the spectrum was thought to have a hump at ~2 MeV as detected by instruments on balloons, HEAO-1, and Apollo 16/17.

However, recent measurements by the COMPTEL instrument on Compton in the 0.8 - 30 MeV range, and a careful reanalysis of data obtained with SMM, have not detected the hump. Above several MeV the spectrum has an energy index of ~1.0 as seen by recent measurements by EGRET.

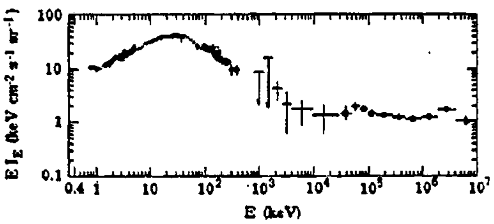


Figure 2.3.4 - The diffuse background from soft X-rays to high-energy gamma-rays.

Various theoretical attempts have been made to model the source of the diffuse background as unresolved AGN. It is generally possible to fit the spectrum with dominant contributions from absorbed Seyfert 2's between 10 and 400 keV and blazars between 3 MeV and 10 GeV. There may be an excess emission at ~1 MeV above the AGN models, although the data quality is not good in this range. The origin of such an excess could be gamma-ray line and continuum emission from unresolved Type 1a supernovae.

OBJECTIVES:

- Detection of an expanded sample of Seyferts and blazars at much higher S/N than with CGRO OSSE.
- Coordinated observations of Seyferts and blazars with good sensitivity into the MeV band.

REQUIREMENTS:

- Flux sensitivity at high energies at least a factor of 10 better than EGRET with comparable angular resolution.
- Hard X-ray telescope.

2.4 THE PUZZLE OF THE UNIDENTIFIED HIGH-ENERGY GAMMA-RAY SOURCES

Only 45% of the gamma-ray sources detected by EGRET have been identified with sources known at longer wavelengths. The nature of the remaining sources is an important question. The distribution of these unidentified sources suggests a largely galactic population; however, there are some at high galactic latitudes. Many of the high-latitude unidentified sources show spectral and time variations similar to those of the identified gamma-ray emitting blazars. It is reasonable to anticipate that those sources are similar to the previously identified blazars. Verifying this depends on reducing the position uncertainties substantially, because many of the error boxes for the unidentified sources contain no bright flat-spectrum radio sources. If dimmer radio sources, which have much higher sky density, are the sites of the gamma-ray production, better gamma-ray source locations are needed to avoid confusion.

The unidentified sources near the galactic plane are more problematic. The only galactic high-energy gamma-ray sources identified with certainty are six pulsars. Although some of the unidentified sources are likely to be radio-quiet pulsars like Geminga, some also show substantial time variations (unlike the detected gamma-pulsars). The potential identification of a new class would be a most exciting discovery.

The mechanism which accelerates cosmic-ray protons to high energies (thought to be shock acceleration due to supernovae) could be verified from the energy spectra of gamma rays from supernova remnants. The supernova remnant cosmic-ray spectrum is expected to have a spectral index in the range 2.0 to 2.4, which differs from the 2.7 spectral index of the local cosmic rays because of propagation effects. There is strong statistical evidence that some of the EGRET unidentified sources in the galactic plane are supernova remnants. Unfortunately, the identifications are somewhat ambiguous, and improved angular resolution is needed to confirm them.

OBJECTIVES:

- Determine the locations of many of the unidentified sources with sufficient accuracy for identification with objects known at other wavelengths.
- Measure time variability, if any, on scales of one day or less.
- Measure the energy spectra of unidentified sources over a broader energy range.

REQUIREMENTS:

- Source location accuracy better than one arcmin. The smallest possible error boxes are important.
- Increased sensitivity (factor of 10 greater than EGRET) to detect more photons and monitor time variability of sources.

2.5 THE GAMMA-RAY BURST ENIGMA

Despite 20 years of effort, astronomers have yet to explain cosmic gamma-ray bursts. This phenomenon is currently the subject of about one publication/day in the astronomical literature, about the same as the observed event rate. Bursts occur at random locations, and for about 20 s can be the brightest objects in the gamma-ray sky before fading into multiwavelength obscurity. Their isotropy and inhomogeneity have been well documented by BATSE. Strictly from a model-independent point of view, the global properties of bursts (i.e., their sky distribution and their number-intensity relation) do not allow the distance scale to be deduced: bursts could be in the neighborhood of the solar system or at cosmological distances. Model-dependent arguments, however, rule out many nearby origins, such as the Oort cloud, or the galactic disk alone, while allowing mixed two-population models (e.g., disk + halo), some purely galactic halo models, or a cosmological origin.

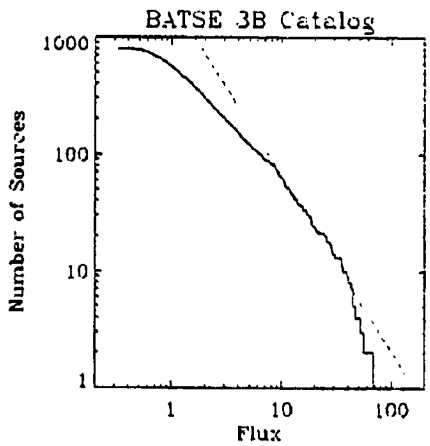


Figure 2.5.1 - logN/logS for BATSE detected gamma-ray bursts showing the lack of dim sources indicating that the edge of the burst distribution is being sampled.

Each distance scale has different possible gamma-ray burst progenitors. Colliding comets have been discussed in the context of Oort cloud models, accreting neutron stars in disk models, high velocity neutron stars in the halo model, and neutron star-neutron star mergers in cosmological scenarios. If bursts are truly at cosmological distances, they would be generated in the most energetic explosions in the universe. The strongest lines of evidence in favor of a galactic neutron star origin were i) rapid time variability; ii) the observations of absorption and emission lines in the spectra of bursts, interpreted as cyclotron resonance scattering and e+/e- annihilation; and iii) the evolution of burst continuum spectra to and from a blackbody shape, consistent with a ratio of emitting region size to source distance of 1 km/1 kpc.

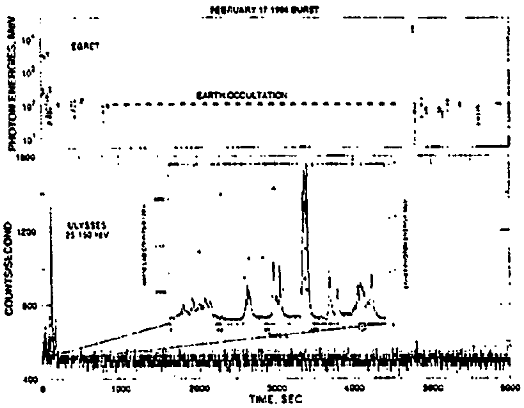


Figure 2.5.2 - 17 Feb 1994 burst with EGRET high-energy photons

The most important question to be answered about bursts is their distance scale. There are many different ways of addressing this question: detection of a counterpart; confirmation of cyclotron absorption or positron-electron emission features; confirmation of a repeating classical GRB source; confirmation of a redshift-luminosity relation, or time dilation; detection of a radio signal dispersed in time, associated with a GRB; detection of a gravitationally lensed burst; detection of a coincident neutrino burst; detection of a coincident burst of gravitational radiation; detection of TeV emission from a burst; study of low-energy (≤ 1 keV) photoelectric absorption in the spectra of bursts; detection of a soft X-ray scattering halo around a GRB source; detection of absorption edges in the low-energy spectra of bursts; detection of an excess of bursts from a nearby galaxy or cluster of galaxies; detection of an excess of bursts from a nearby star (e.g., Oort cloud origin); detection of afterglows due to interactions of gamma radiation with the medium surrounding the source.

For each of these, it is important to consider not only what a positive result would tell us, but also, how a negative result would constrain the available phase space. For example, not all progenitors are expected to have readily detectable counterparts. Counterparts may be characterized by i) the timescale after the burst, i.e., flaring, fading, and quiescent counterparts, and ii) the energy range (e.g., X-ray, UV, optical, IR, and radio). In the resulting matrix of possibilities, fading and quiescent counterparts are expected for most distance scales. Recently, one compelling example of associated transient X-ray and optical sources has emerged—but information is sketchy and many more examples are needed. But even the non-detection of quiescent counterparts has interesting consequences. For example, the lack of bright galaxies in numerous error boxes down to limiting magnitudes mR < 19.5 implies that if these burst sources are in galaxies at cosmological distances, then they must be at distances >1 Gpc (in which case their intrinsic energies exceed 10^{52} erg, the canonical value for merging neutron stars) or they must be associated with subluminous galaxies. But this negative result does not hold for all error boxes, and does not prove that burst sources are not cosmological. Arcsecond-size error boxes will be needed to perform the definitive test.

BATSE, the most sensitive instrument flown to date, has not detected an excess of bursts from Andromeda. Such an excess might be expected if bursts originated in an extended galactic halo. But it can be shown that this result only constrains certain "dark matter" halo models, leaving open the possibility of, for example, exponential halos, which could never be detected by BATSE in the direction of Andromeda. Again, this negative result does not demonstrate conclusively that burst sources are not in the galactic halo. More sensitive experiments are required for this technique.

It is entirely possible that the answer to the distance scale question will not come from a study of the conventional gamma-ray properties of bursts. For example, the detection of TeV emission from a burst would argue strongly against a cosmological origin, because TeV photons should be attenuated by intergalactic IR radiation. Another distance indicator might be the low-energy (sub-keV) spectra of bursts. If the photoelectric absorption of this portion of the spectrum, due to the column density between the source and the observer, could be detected, it could distinguish between various models.

In summary, there does not appear to be any "Michelson-Morley" experiment where cosmic gamma-ray bursts are concerned, that is, an experiment for which a negative result would answer the distance question. In view of this, it is important to attack the problem from several aspects, either with single experiments which are capable of returning different kinds of information, or with multiple experiments with different objectives.

The soft gamma repeaters (SGRs) are repeating sources of low-energy (<100 keV) bursts, which appear to be associated with young ($<10^4$ y) neutron stars. Three are known. A fourth repeating source, the "bursting pulsar" shares some of the characteristics of SGRs, but is in a binary system, whereas the SGRs appear to be lone neutron stars. Thus while accretion seems to power the bursting pulsar, the bursting mechanisms for the SGRs are still unknown. These objects may be new manifestations of neutron stars, and their continued study will shed light not only on their physics, but may also hold clues to the physics of GRB sources.

OBJECTIVES:

- Identify gamma-ray positions to arcsec precision for deep searches for quiescent counterparts or host galaxies and to test for repetition.
- Measure the time dependence of burst spectra with high energy resolution and sensitivity to confirm or refute the existence of absorption features.

REQUIREMENTS:

- High spectral resolution for absorption feature search.
- Arcsec source locations to allow prompt, deep optical, X-ray and radio counterpart searches.

2.6 SOLAR GAMMA RAYS: EXCEPTIONAL PHOTONS FROM AN UNEXCEPTIONAL STAR

Gamma-ray lines from solar flares were first observed in 1972 with the NaI scintillator on OSO-7. It was not until 1980, however, that routine observations of gamma-ray lines and continuum became possible with the much more sensitive Solar Maximum Mission (SMM). Most recently, gamma-ray observations have been carried out with the CGRO instruments COMPTEL, EGRET and OSSE, as well as with the PHEBUS instrument on GRANAT.

Two previously accepted solar flare paradigms were drastically modified by the gamma ray work. Prior to the SMM observations, based on timing arguments, it was thought that in the impulsive phase of flares only electrons are accelerated; ion acceleration was believed to be a delayed, second phase, phenomenon. This paradigm has been overturned by the SMM data which showed very prompt and impulsive gamma-ray emission, often in temporal coincidence with the hard X-ray time profiles. Another accepted paradigm of solar flare research has been that a large fraction of the released flare energy resides in nonthermal electrons of tens of keV, with the energy content in accelerated ions constituting only a small fraction of this energy. This result depended on the manner in which the ion spectrum was extrapolated from around 10 MeV/nucleon, where the bulk of the gamma-ray production takes place, to lower energies. Recent work on abundances, based on SMM data, and the requirement to account for the very strong observed ^{20}Ne gamma-ray line whose production threshold is near 1 MeV/nucleon, implies an extrapolation of the ion spectrum as an unbroken power law down to that energy. This yields an ion energy content comparable to the energy content in the low-energy electrons, placing ion and electron acceleration on an equal footing: both components are impulsively accelerated and contain approximately equal amounts of energy.

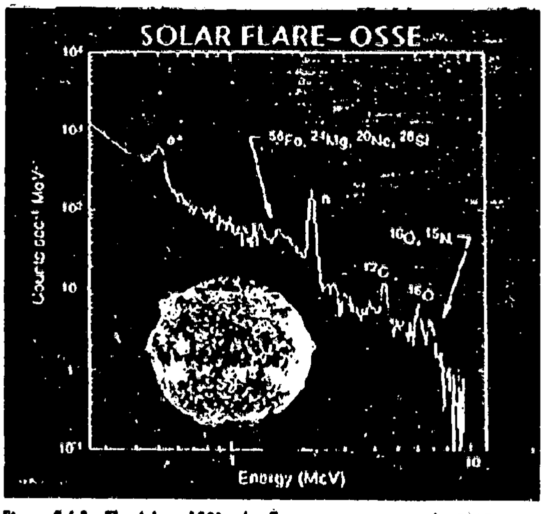


Figure 2.6.1 - The 4 June 1991 solar flare spectrum as seen by OSSE

Further gamma-ray work has provided important information on abundances of both the ambient medium and the accelerated particles.

Concerning the ambient medium, the analysis of gamma-ray lines has shown that in the gamma ray production region the abundances of elements with low first ionization potential (FIP) are enhanced relative to those of elements of high FIP. This FIP bias has been discovered previously using accelerated particle data and atomic spectroscopy. The nuclear spectroscopy is telling us that the bias sets in quite deep in the solar atmosphere, probably already in the chromosphere where the bulk of the gamma rays are produced. This result, which was not known prior to the gamma-ray work, has important implication on the dynamics of the solar atmosphere. Another interesting result concerns the photospheric ^{3}He abundance. Studies of the time dependence of the 2.223 MeV neutron capture gamma-ray line emission, suggest that the $^{3}He/H$ ratio in the solar photosphere is lower than that previously estimated suggesting that there is no significant mixing into the photosphere of ^{3}He made in the solar interior.

Concerning the accelerated particles, the gamma-ray work has shown that these particles exhibit large abundance enhancements for the heavy ions, particularly Fe. This has important implications for the particle acceleration mechanism, strongly suggesting that the acceleration is due to resonant particle interactions with plasma turbulence.

The rising portion of solar cycle 22 (1988-1993) was observed until 1989 with SMM. The maximum of this cycle, however, was only studied with non-dedicated instruments: Phebus/ GRANAT; GAMMA-1; CGRO. Nevertheless, these instruments found exceptionally interesting results, for example, the observation of pion decay emission and nuclear line emission lasting for hours. This indicates that in post-flare conditions it is possible to either trap or accelerate over extended time periods ions of energies as high as several GeV. While long lasting flare emissions have been known previously, this was the first instance that such time extended emission could be associated with GeV ions. These observations were only possible because of the very good sensitivities of the new instruments, in particular CGRO.

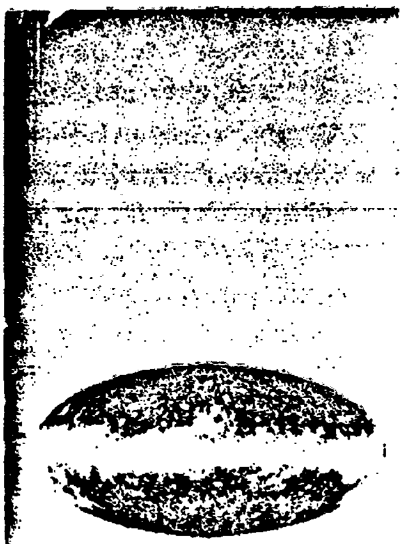
There are no approved future high-energy solar missions. Solar flare gamma-ray observations with detectors of much higher sensitivity and better energy resolution than those of the previously employed instruments should allow important new investigations. For example, much more detailed abundance studies will be possible, including the determination of accelerated particle abundance as a function of time with good time resolution, leading to the most direct tracing of the acceleration process. These studies will include observations of the gamma-ray signatures of ^{3}He, due to the reactions $^{4}He(^{3}He,p)^{6}Li^{*3.56}$ MeV and $^{16}O(^{3}He,p)^{18}F^{*0.937,1.04,1.08}$ MeV. The abundance of ^{3}He, which in the solar atmosphere is only a few times 10^{-4} relative to ^{4}He, routinely becomes comparable to that of ^{4}He in the accelerated particles from impulsive flares, most likely due to gyroresonant interactions of the particles with plasma waves. In addition, observations of the Sun with a high sensitivity gamma-ray detector will allow some entirely new types of investigations. For example, it will be possible to observe the relatively long lived radioactivity (e.g., ^{56}Co) produced by accelerated particle interactions in flares, thereby allowing the study of the dynamics of the atmosphere. Finally, the flare observations could be used as a local laboratory for the testing of the various proposed models of the galactic sources of gamma-ray line emission.

OBJECTIVES:

- Abundance measurements of both the ambient medium and the accelerated particle spectrum for a larger number of solar flares.
- High-energy (> 10 MeV) measurements on a larger number of flares to compare on a flare-by-flare basis with hard X-ray and nuclear-line fluxes.
- Large duty cycle of solar observations since correlated data from ground-based observatories are critical for proper interpretation. What distinguishes high-efficiency gamma-ray flares?
- Identification of gamma-ray production regions.

REQUIREMENTS:

- Extended spectral coverage (~ 100 keV - 100 MeV)
- Imaging at hard X-ray/gamma-ray energies (~ few arcsecond)
- Good sensitivity with large dynamic range.
- Good spectral resolution with "diagonal" energy response.



3. CURRENT PROGRAM

3.1 COMPTON GAMMA RAY OBSERVATORY

The Compton Gamma Ray Observatory (CGRO) was launched in April 1991 with a broad range of science objectives including the understanding of gamma-ray bursts, studies of black holes and neutron stars, the search for sites of nucleosynthesis, probing the galaxy through the interaction of cosmic rays with the interstellar medium, and studying the nature of active galaxies in gamma rays. While significant insight has already emerged in these areas, unanticipated discoveries have challenged our understanding of the conditions and energy-generating mechanisms for many astronomical sources, as indicated in sections 1 and 2.

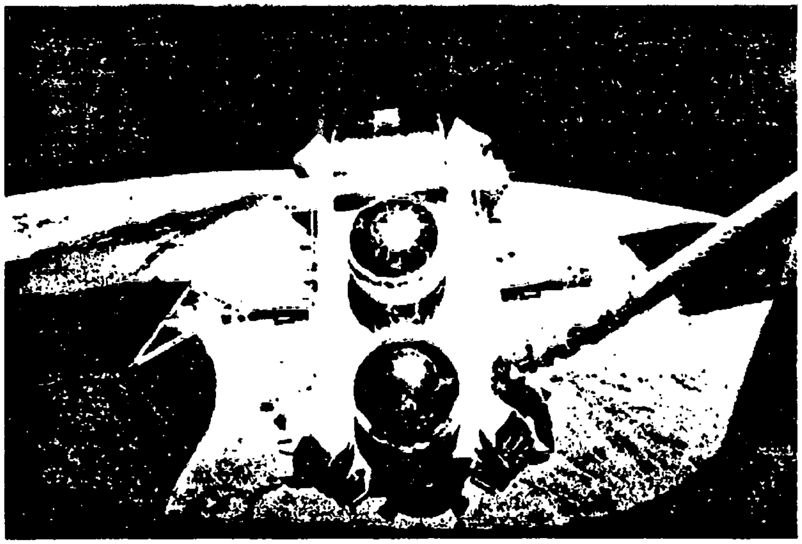


Figure 3.1 - The Compton Gamma Ray Observatory during it's deployment.

CGRO continues to operate flawlessly and none of the instruments, except EGRET, has life-limiting consumables. Over 700 scientists from 23 countries have participated in the CGRO Guest Investigator program. One additional orbit reboost is expected to provide an operational capability for the Observatory well into the next century. EGRET has a limited supply of spark chamber gas which is being conserved through carefully selected observations and operating modes. Through this conservation program, EGRET expects to support a few limited science observations and targets of opportunity over the next five years.

The science contributions which are anticipated from future CGRO observations are:

- Solving the GRB mystery. Counterparts may be identified using the near real-time BATSE and COMPTEL notification system and the BACODINE-triggered ground observer network.
- Continued all-sky monitoring for transients, X-ray pulsars, and sources of e+e- annihilation radiation.
- Nucleosynthesis in Type Ia supernova. OSSE and COMPTEL have the

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sensitivity to study gamma-ray lines from such supernovae to nearly 10 Mpc.

- Continued galactic plane observations with OSSE and COMPTEL to improve the sensitivity to diffuse line emissions such as ^{60}Fe and ^{44}Ti.
- High energy emission during the next solar maximum. CGRO may well provide the only opportunity to observe the Sun in gamma rays during the entire next solar maximum.
- Continued multiwavelength observations of AGNs.
- Testing nucleosynthesis models for novae; ^{22}Na emission from novae within 1-2 kpc may be detectable.

3.2 INTEGRAL

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) is an ESA mission due for launch in 2001 that is dedicated to fine spectroscopy ($E/\Delta E = 500$) and imaging (12 arcmin FWHM) in the 15 keV to 10 MeV energy range. The two main instruments on board are a spectrometer with high-spectral-resolution germanium detectors and an imager that employs high-spatial-resolution arrays of cadmium telluride and cesium iodide detectors. Optical and X-ray monitors complete the scientific payload. The spectrometer has a field-of-view of 16 degrees (fully coded), an angular resolution of 2 degrees FWHM and a sensitivity to narrow spectral lines of $\sim 4\times10^{-6}$ ph cm^{-2} s^{-1} in a 10^6 s observation. The imager has a field-of-view of 9 degrees fully coded, an area of $\sim$3000 cm^2 and a continuum sensitivity of 4×10^{-7} ph cm^{-2} s^{-1} keV^{-1} ($\sim$1 mCrab) at 100 keV.

The key scientific objectives of the INTEGRAL include (1) the study of explosive nucleosynthesis in SN I out to $\sim$15 Mpc through the detection and measurement of ^{56}Co lines; (2) a survey of galactic supernovae from the past 300 years through detection and mapping of ^{44}Ti line emission; (3) a determination of the sites of nucleosynthesis in the galaxy over the past million years through the mapping of the ^{26}Al line emission; (4) a broad-band (5 keV - 10 MeV) study of AGNs and the spectral characteristics of different classes such as Sy 1, Sy 2, and blazars; (5) a study of the galactic center region and galactic plane to determine the positions, spectra and nature of the compact objects; (6) a sensitive, multi year survey of the galactic plane for study of galactic transient sources such as X-ray novae and Be transient pulsars.

The INTEGRAL is being developed primarily by ESA and the European member countries, but will include Russia (USA launch proton rocket) and the United States (tracking instrumentation). A science data center is located at the Geneva Observatory in Switzerland. The observing program will be divided between a core program ($\sim$30% of the time) that will be largely devoted to galactic plane scans and a general program that will have observations chosen from an open competition of proposals submitted by the members of the community at large.

3.3 COMPLEMENTARY X-RAY MISSIONS

Two recently launched X-ray missions have instruments observing in the hard X-ray band which provide complementary observations to those of CGRO in addressing the key science objectives identified in sections 1 and 2.

The Rossi X-ray Timing Explorer (RXTE) was launched by NASA in December 1995, as a mission to study the temporal and spectral variability of X-ray emission from a broad range of astronomical objects. A complement of three scientific instruments observing in the 2 - 250 keV energy band is addressing important questions concerning the structure and dynamics of compact X-ray sources such as accreting neutron stars, white dwarfs and black holes in our galaxy as well as the massive black holes thought to be present in the nuclei of distant active galaxies.

Important features of RXTE are its capabilities for creating high resolution time series for temporal investigations, the incorporation of the All-Sky Monitor that views approximately 70% of the sky per orbit for the detection of new transient sources, and its ability to re-orient quickly (within 7 - 24 hours) for detailed study of new transients. RXTE has expected orbital lifetime of 4-5 years.

The primary objective of the Italian-Dutch X-ray mission BeppoSAX is the broad band spectral characterization of galactic and extragalactic X-ray sources. Launched in April 1996, it carries a complement of four co-aligned narrow field-of-view instruments observing in the 0.1 - 300 keV energy band and two wide-field cameras for the detection of new transient sources in the 2 - 30 keV range. The SAX detectors have relatively large area, good energy resolution and approximately 1 arcmin imaging at low energies. The wide-field cameras provide milliCrab sensitivity for transient detection and monitoring. The BeppoSAX mission has a ρ

minimum lifetime of 2 years with a possible extension to 4 years of operation.

3.4 GAMMA-RAY BURST INSTRUMENTS

BATSE continues to operate, detecting approximately one burst per day and providing burst locations with several degree accuracy. At present, the only means of obtaining the arcminute-size GRB error boxes required for deep counterpart searches is triangulation with a network of widely separated detectors. The currently operating 3rd Interplanetary Network (IPN) consists of one distant spacecraft, Ulysses, and a cluster of near-Earth experiments, but primarily BATSE. The Russian Mars 96 would have completed the network, had it been launched successfully. Its failure means that the IPN will not be complete until 2001 at the earliest. Both BATSE and IPN burst locations are distributed rapidly to a wide community using the BATSE Coordinates Distribution Network (BACODINE). Follow-up searches for optical counterparts are carried out by several dedicated telescopes built to respond quickly and automatically to BACODINE triggers. A world-wide network of optical and radio observatories with sensitive telescopes also conducts counterpart searches based on both BATSE and COMPTEL burst locations relayed through New Mexico State University. Although these searches are not as prompt, they are much deeper. Soon HETE, the High Energy Transient Experiment, may be resurrected. The HETE X-ray camera can detect about 25 bursts per year and localize them to arcminute accuracy. Very small error boxes such as these, and indeed, much smaller ones, are required to perform the deepest possible counterpart searches without source confusion.

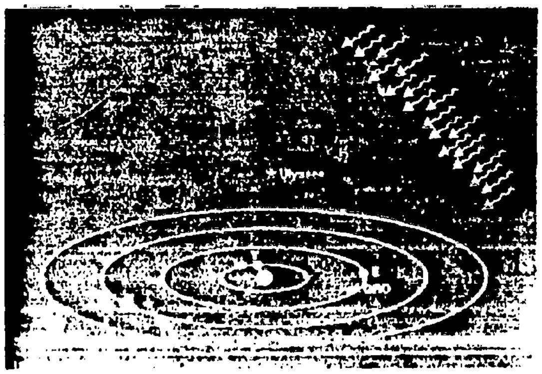


Figure 3.4 - Ulysses/CGRO (IPN Ne[illegible]rk) in relation to the solar system

CATSAT (Cooperative Astrophysical and Technology Satellite) is a small, inexpensive mission that will fly under the Student Explorer Demonstration Initiative program. It will measure the sub-keV emission of bursts to detect photoelectric absorption features, that could reveal the galactic or extragalactic nature of the sources, and the multi-keV spectra for cyclotron resonance features. In addition, an Earth albedo polarimeter will measure the X-ray polarization of bursts and thick scintillators will measure the MeV spectrum. CATSAT will be launched in early 1998 for a nominal, but extendible, one year mission. Depending on the triggering logic it will detect between 50 and 100 bursts per year.

The controversy over whether gamma-ray burst spectra contain line components may be resolved by the Transient Gamma-Ray Spectrometer (TGRS) aboard NASA's Wind spacecraft. TGRS consists of a passively cooled Ge spectrometer covering the 20-8000 keV energy range with resolution 2.7 keV at 500 keV. If lines indeed exist as previously reported, they should be detected in strong bursts by this instrument.

Table 3.1 - GRB Instruments and their capabilities

Mission	Degree Size Error Box	Arcmin Size Error Box	10" Size Error Box	Energy Spectra for Line Searches	Optical Counterpart Counterpart	Polarization	Low-Energy Absorption
BATSE	350/Year			100/Year			
3rd IPN	50/Year	50/Year	1/Year .				
GROSCE					10/Year mV=8		
GTOTE					18/Year mV=12		
ETA					10/Year mV=10		
TGRS				25/Year			
HETE		25/Year	25/Year	25/Year			
CATSAT	100/Year			30/Year		6/Year	12/Year

3.5 TEV TELESCOPES

At energies above 100 GeV, observations are conducted with ground-based gamma-ray telescopes. By observing the Cherenkov light from air showers produced by gamma-rays interacting in the upper atmosphere, it is possible to detect discrete sources of gamma-rays with great sensitivity. The detectors are simple, inexpensive and well-understood.

There are now at least five well-established TeV gamma-ray sources (three of them pulsar/plerions and two of them AGNs). The technique is also sensitive for time-variation (burst and pulsar) searches. In the past decade ground-based gamma-ray astronomy has become a viable discipline and an important complement to observations from orbiting gamma-ray telescopes.

The Atmospheric Cherenkov Imaging Technique (ACIT) is the most effective method of detecting sources of gamma rays with energy > 200 GeV. It was developed at the Smithsonian's Whipple Observatory by a collaboration of U.S., Irish, and British institutions. The ACIT has now been adopted by most of the ground-based gamma-ray observatories overseas. The Whipple telescope is a 10m optical reflector (figure 3.5) with a 109 pixel camera. Recently, a second reflector and camera have come on-line to provide a stereo imaging system. The flux sensitivity (5 sigma level) at an energy threshold of 300 GeV is 8×10^{-12} photons-cm^{2}-s^{1} for an exposure time of 50 hours.

There are more than ten "second-generation" ground-based gamma-ray observatories in operation or under construction. There is one collaboration active in the United States and there are major groups in Germany, France, the U.K., the former U.S.S.R., India, Japan, South Africa, and Australia. In addition, the MILAGRO instrument is coming on-line. It is an underwater Cherenkov telescope that has the distinct feature of a large field-of-view in the TeV range. Ground-based telescopes improve continuously in small increments; there is no technical barrier to further increases in both flux sensitivity and reduced energy threshold. In principle, a telescope can be built with an energy threshold as low as 10 GeV.

Figure 3.5 - The Whipple Observatory 10m detector. Ground-based gamma-ray telescopes are an important complement to satellites operating at lower energies.

3.6 LONG-DURATION BALLOON PROGRAM FOR HIGH-ENERGY ASTROPHYSICS

Since the 1960's numerous U.S. and foreign X-ray and gamma-ray astronomy groups have conducted balloon-borne astronomy experiments to study celestial sources as well as to verify satellite instrument concepts. The latter use of balloons, has been particularly important in the proof-of-concept for the CGRO instruments. Balloon instruments have also produced many scientific results. For example, the pulsating X-ray binary source GX 1+4 and the 511 keV annihilation line, both in the galactic center region, were discovered on balloon flights conducted in the Southern Hemisphere. Experiments such as these helped pave the way for current satellite missions like ROSAT and CGRO. With a reduced number of satellite opportunities and the emphasis on reducing the size and cost of these missions, reliance on a strong balloon program becomes even more important. For example, gamma-ray instruments tend to be relatively heavy to attain a high efficiency to image weak sources. Consequently, unless the satellite version of the experiment can be conducted on a MIDEX or smaller mission, some vital X-ray or gamma-ray observations may never be conducted from satellites because of the mass constraint. There are numerous astrophysics experiments that can be inexpensively and quickly carried out on heavy lift balloons. Experience with operations in the Southern Hemisphere with long-duration balloon flights of two- to four-week duration clearly demonstrates the capabilities of the balloon platform for long flights. High-energy astrophysics would benefit greatly from further development of Southern Hemisphere long duration flight balloon operations and extension of this capability to the Northern Hemisphere.

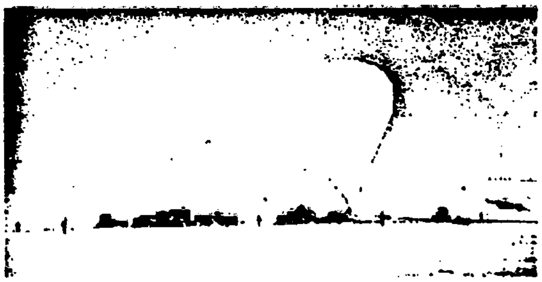


Figure 3.6 - Launch of the UC Berkeley Ge spectrometer array in Antarctica. This flight lasted ~10 days. Mount Erebus is visible in the background.

The following specific points should be considered in assessing the value of long duration ballooning to high-energy astrophysics.

- The balloon program is responsive to user needs because it is efficient, low in cost, and is an excellent training ground for young scientists and engineers that are needed for the long-term future of gamma-ray astronomy.
- The suborbital balloon program may be the only way to perform some important astrophysics experiments in the next 20 years (see comments above).
- Free-flying spacecraft are the preferred platform for gamma-ray astronomy if there is no weight or cost restriction. However, because of the restrictions, the balloon program will be needed to verify instrument concepts in the near-space environment and to perform some new frontier science.
- For the foreseeable future there are no alternatives to the balloon program.

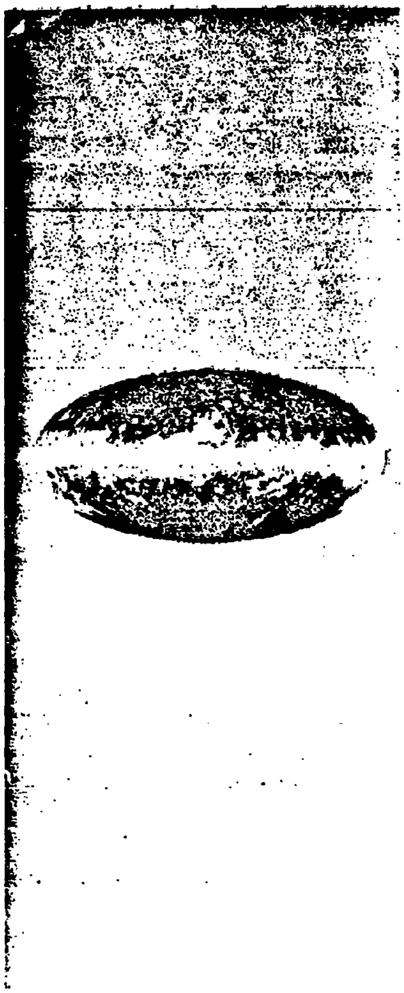
3.7 THEORY

As the sensitivity and resolution of NASA's astronomy missions improve, so too must the realism of the theory used to interpret the results and give them meaning. Progress in theory accompanies the progress in experiment. One cannot lead the other for long. Theory is both interpretive and predictive. On the one hand, for data that are relatively well understood, theory builds models to extract the greatest amount of information possible from them. From these models emerge new predictions that can be tested and improved until the phenomenon can be satisfactorily understood. On the other hand, measurements may uncover surprises that generate great controversy and, if properly understood, offer potential for scientific advancement. It is such phenomena that pose the greatest challenge to theory and require it the most. Many examples of each category could be given. We present just two: nucleosynthesis gamma-ray lines and gamma-ray bursts.

It is widely accepted that the elements heavier than helium are made in stars with supernovae playing a major role. It is also well documented by measurement and understood in theory that the short time scales and high temperatures of supernovae lead to the creation of short and intermediate lived radioactive isotopes. The species ^{26}Al, ^{44}Ti, ^{56}Co, and ^{57}Co have been detected and studied. The role of theory is to obtain quantitative agreement between physical models and the line measurements in terms of flux, line shapes, and angular distributions. This then leads to constraints on models of stellar evolution and supernovae and a better understanding of their nature; improved accuracy in our models for galactic chemical evolution; and a better depiction of massive star formation in our galaxy. Based upon these improved models, theory makes predictions that can be confirmed by subsequent measurements, e.g., a detectable signal from ^{60}Fe.

Gamma-ray bursts represent science of a different sort. Although the puzzle has made good headlines for a decade or two, ultimately the goal of science is understanding. Here the theorist is much less constrained, but also highly challenged by an unexpected and poorly understood phenomenon. Quick, qualitative speculations are useful for a time, but ultimately progress requires that speculation be backed up by detailed physical analysis and simulations. Frequently these simulations lead to the death of the model, but that too is progress. Eventually a model, or set of models, will be found that explains what is observed and makes predictions that can be confirmed. Meanwhile theory guides observations in defining the sensitivity of future missions required to see bursts from the halo from Andromeda, for example, or whether X-ray absorption lines should be visible in the spectra of cosmological gamma-ray bursts. Three dimensional general relativistic calculations of neutron star merger can show whether or not relativistic beams can emerge. Calculations of planetesimal accretion on neutron stars in the halo reveal that tidal disruption will likely prevent the intact arrival of an object at the neutron star. Some models predict a large number of hard X-ray bursts for every gamma-ray burst; others predict that enduring hard GeV emission should be a common characteristic, etc. All these predictions can and must be refined and eventually tested.

New observations will drive theory as they always do. It is important however that NASA continue to provide support to theory particularly during these times of constrained budgets. For a comparatively modest investment, NASA ensures the existence of a cadre of trained specialists interested in making the most of the valuable data. Without the activities of these people, the value of the data is greatly diminished.



4. FUTURE MISSIONS

We present here the components of a program which address the scientific goals discussed in section 2. The program requires a broad range of missions from suborbital balloon flights to intermediate class missions, in addition to an active SR&T support base for technology development. While significant advance over the capabilities of current missions, CGRO and INTEGRAL, requires intermediate class missions, key contributions to the understanding of gamma ray bursts and surveying the hard X-ray sky can be achieved in the context of the MIDEX program.

4.1 INTERMEDIATE CLASS

4.1.1 HIGH-ENERGY

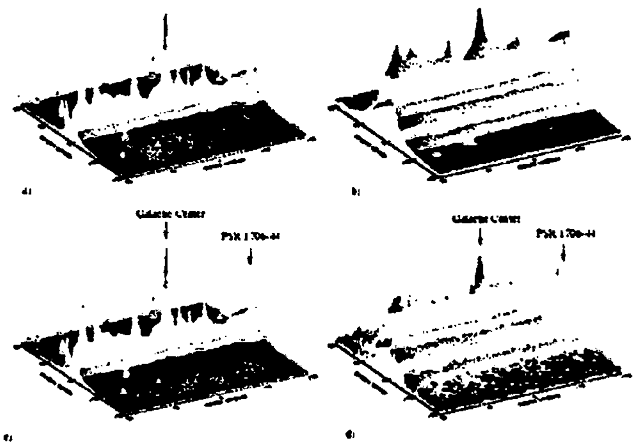


Figure 4.1 - Simulation of the galactic plane as it would be seen by the proposed GLAST instrument.

EGRET has provided important discoveries of gamma-ray emission from a diverse population of astrophysical sources. However, our understanding of the gamma-ray emission mechanisms operating in these sources is limited by current instrumental capabilities. A future high-energy gamma-ray mission should provide an imaging, wide field-of-view telescope that covers the energy range from approximately 10 MeV to more than 100 GeV. In this energy range, gamma-rays are identified by recording the characteristic track signature of the electron-positron pair that results from pair conversion in the presence of a nucleus. The telescope consists of interleaved thin converters (metal foils) and position sensitive charged particle detectors followed by a calorimeter for energy measurement. Finally, the telescope requires a very efficient anticoincidence system for rejecting the much higher flux of background particles and an on-board trigger and data acquisition system. Modern particle tracking detectors (silicon microstrip detectors for example), sophisticated on-board processing, and higher telemetry rates will allow the required major advance in observational capability over EGRET within the constraints of an intermediate class astrophysics mission. One proposal for such a mission, selected for study as a NASA New Mission Concept in Astrophysics, is the Gamma-ray Large Area Space Telescope (GLAST) shown in fig. 4.2.

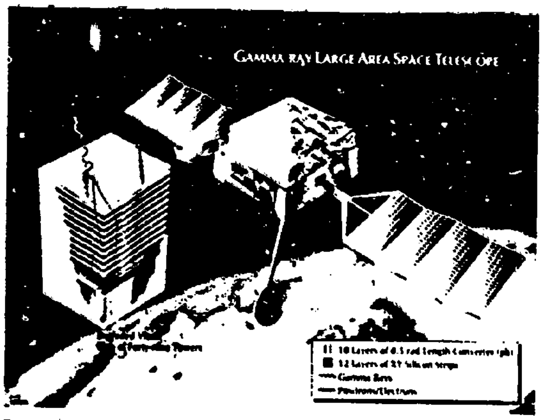


Figure 4.2 - Artist's concept of the GLAST instrument and spacecraft

For the baseline mission parameters given in Table 4.1, a nearly two-order-of-magnitude improvement in flux sensitivity and a factor of 10 improvement in point source location capability will be obtained. Determination of the spectra of the sources over a broad energy range will also be possible. A wide field-of-view telescope will allow the detection of many more transient sources such as AGN flares and high-energy gamma-ray bursts.

TABLE 4.1. Characteristics of a High-Energy Gamma-Ray Mission Using an Imaging Pair Conversion Telescope

Energy Range	10 MeV - 100 GeV
Energy Resolution	10%
Effective Area	8,000 cm^2 (above 100 MeV)
Single Photon Angular Resolution (68% containment angle)	< 2.5 deg x (100 MeV/E) (10 MeV - 3 GeV) < 0.10 deg (E > 10 GeV)
Field-of-View	> 1.5 sr
Point Source Sensitivity	2×10^{-9} ph cm^{-2} s^{-1}
Source Location Determination	30 arcsec - 5 arcmin
Mass	3,000 kg
Power	600 W
Telemetry	100 kbps
Mission life	> 2 years
Orbit	low inclination
Spacecraft pointing	10 arcsec knowledge < 2 deg accuracy
Operating modes	all-sky survey mode, pointed observation mode, any direction at any time

The principal scientific objectives for the mission include:

- Active galactic Nuclei: determine the mechanisms of AGN jet formation, particle acceleration, and radiation by studying gamma-ray emission from all known blazars (and possibly other AGN classes) and correlating these observations with those at other wavelengths.
- **Unidentified Gamma-ray Sources**: determine the type of object(s) and the mechanisms for gamma-ray emission from the unidentified gamma-ray sources by measuring precise positions of these sources.
- **Isotropic Background Radiation**: determine if the high-energy background is resolvable into point sources or if there is a true diffuse component, by a deep survey of high-latitude fields.
- **Gamma-Ray Bursts**: provide constraints on physical mechanisms for gamma-ray bursts by detecting high-energy radiation from 50 - 150 bursts per year and studying the GeV : keV-MeV emission ratio as a function of time; image burst positions to a few arcminutes or better, allowing deep "real-time" multiwavelength observations.

- **Endpoints of Stellar Evolution (Supernovae, Neutron Stars, and Black Holes)**: provide direct evidence of proton cosmic-ray acceleration in supernova remnants by gamma-ray mapping and energy spectral measurements; distinguish between models for high-energy gamma-ray emission from pulsars by measuring detailed phase-resolved spectra. Determine whether or not galactic superluminal jet sources emit significant high-energy gamma radiation.
- **Molecular Clouds, Normal Galaxies and Clusters**: probe the cosmic-ray distribution in dense molecular clouds and in nearby galaxies (LMC, SMC, M31) by gamma-ray mapping and measuring the spectra of diffuse emission from these objects; search for extended emission from possible cold dark matter clouds in the galaxy and from galaxy clusters as a signature of unusual concentrations of unseen gas or cosmic rays.

4.1.2 HARD X-RAY FOCUSING

Dramatic increases in flux sensitivity have always yielded major progress in astrophysics. For the traditional X-ray band (≥ 0.1 to 10 keV), this came in the late 1970's and early 1980's with the flight of the first focusing X-ray telescopes, Einstein and EXOSAT. The upcoming launches of AXAF, XMM, and ASTRO-E will extend this field further, thus bringing soft X-ray astronomy to maturity. The situation is far less satisfying at higher energies. In particular, the decade in energy from 10 to 100 keV has barely been probed. Current experiments in this energy range (e.g., the HEXTE instrument on XTE) are more than two orders of magnitude less sensitive than even the early focusing X-ray telescopes.

Compelling motivation for extending observational capabilities in the hard X-ray band (10 - 100 keV) is provided both by the existence of sources whose energy output peaks in this range, and by astrophysical processes which are uniquely observable there. The separation of thermal and nonthermal processes becomes distinct above 10's of keV and the diagnostics provided by observing these nonthermal processes are astrophysically important, and often are unique and fundamental. Unfortunately, in the hard X-ray band, the internal detector background count rates dominate the source fluxes by several orders of magnitude for most sources. Focusing — or concentration of the signal onto a small region of the detector — is the only approach to achieving detection thresholds comparable to what has been obtained at lower energies.

The use of focusing optics for hard X-ray experiments has been limited by the fact that the maximum incidence, or graze angle, allowed for significant X-ray reflection decreases approximately linearly with X-ray energy, making it difficult to obtain substantial effective area for telescopes of moderate focal length. The recent development of graded multilayer coatings, which are capable of substantially increasing the graze angles of traditional focusing optics over a broad energy band, allow for the design of a mission which would greatly extend the flux sensitivity of grazing incidence telescopes to ≥ 100 keV. A mission incorporating such focusing optics with graded multilayer coatings is a priority of the gamma-ray astrophysics program. This mission would incorporate an array of Wolter type I or conical approximation telescopes coated with graded multilayers capable of reflecting hard X-rays in the 10 to ~ 100 keV band. Table 4.2 lists typical instrument parameters for such a mission. The typical flux sensitivity achievable at 50 keV is approximately two and a half orders of magnitude lower than that achieved by HEXTE.

TABLE 4.2. Characteristics of a Hard X-ray Focusing Mission

Field-of-View	5 arcmin
Source Location	30 arcsec
Point Source Sensitivity (60 keV)	20 microCrab in 10^5 sec
Mass	2500 kg
Power	300 W
Telemetry	20 kbps/sec (ave)
Mission life	5 yr
Orbit	low inclination
Spacecraft Pointing	5 arcsec

The most important science objectives for a hard X-ray focusing mission include:

- **Active Galactic Nuclei.** A principal goal of this mission will be sensitive studies of AGN, obtaining for the first time high-quality hard X-ray/soft gamma-ray spectra for a significant number of quasars and Seyfert galaxies.

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Observations in the energy band from 10 - 100 keV provide a measure of the intrinsic luminosity of the central source and address many basic questions, including the relationship among the various classes of AGN, in particular Seyfert Is, IIs, and quasars (QSOs).

- **Population Studies in the Local Group.** Studying the compact objects, such as weakly magnetic ($B \leq 10^9$ G) neutron stars in low-mass binaries, and black hole candidates with both high-and low-mass companions outside of our own galaxy at hard X-ray energies is an important goal possible only with a focusing instrument.
- **Measurement of the Intracluster Magnetic Field in Clusters of Galaxies.** As described in Section 2.3.2, hard X-ray observations can provide a direct measurement of the magnetic field strength in galaxy clusters.
- **Nucleosynthesis and Dynamics in Type II Supernovae.** The high sensitivity and imaging capability of a hard X-ray focusing telescope make it ideally suited for mapping the at 68 and 78 keV emission from ^{44}Ti in young supernova remnants (see 3.2.1).
- **Investigation of Shock Acceleration in Young Supernova Remnants.** In addition to the soft thermal X-radiation produced in the shocked ejecta, young supernova remnants like Cas A exhibit hard X-ray "tails" extending out to ~50 keV.

Although future X-ray missions such as HTXS plan to extend the excellent sensitivity of focusing instruments up to ~40 keV for point sources, many of the objectives described above require that the energy sensitivity extend to ~100 keV, and that the field of vision be maximized for study of diffuse emission and nearby galaxies. Neither of these capabilities is a priority for HTXS.

4.1.3 NUCLEAR ASTROPHYSICS/MEDIUM ENERGY

The realm of nuclear astrophysics and medium energy gamma rays probes some of the most energetic phenomena in astronomy - the endpoints of stellar evolution in supernovae, neutron stars, and black holes. Measurements in this band can address fundamental questions in astronomy such as star formation, supernova physics, galactic structure, and chemical evolution. The observational challenges of nuclear line astrophysics have been addressed by several missions in the past, beginning with the High Energy Astrophysics Observatory (HEAO) series in the 1970's through the current Compton Gamma Ray Observatory. These missions, along with balloon flight experiments have provided several notable achievements: 1) maps of galactic diffuse ^{26}Al and 0.511 MeV emission with a few degree resolution, 2) study of ^{56}Co and ^{57}Co lines from the Type II supernova, SN1987A, and interesting limits on ^{56}Co from Type Ia SN, 3) detection of cosmic ray induced lines including ^{12}C and ^{16}O emission from the Orion region, and 4) detection of ^{44}Ti from Cas A. Some of these detections are of low statistical significance; better sensitivity is needed to provide diagnostics into the phenomena involved.

The planned INTEGRAL mission, which is to be launched in 2001, is expected to provide a significant improvement over existing capabilities by having 2 degree imaging resolution, 2 keV spectral resolution, and a sensitivity to narrow lines of 5×10^{-6} photons cm^{-2} s^{-1} for a 10^6 s observation of a line of 5 keV width. This is approximately a factor of 10 improvement over OSSE or COMPTEL. At this level, one can begin to make detailed maps of ^{26}Al showing regions of recent star formation and supernovae improvement. A meaningful search for lines from ^{60}Fe, and detailed study of both the diffuse and central galactic pair annihilation lines become feasible. However, INTEGRAL's sensitivity to diffuse or broadened line emission is degraded. Studying the physics of supernova explosions will, lacking great serendipity, be restricted to Type Ia. Type II and Ib occuring in the Local Group. A Type Ia in Virgo (20 Mpc) would have a flux at peak of about 8×10^{-6} photons cm^{-2} s^{-1}. However the lines are broad, about 30 - 40 keV FWHM, so the sensitivity of INTEGRAL is reduced to just detecting the typical event in a 10^6 s observation. Investigating the physics of SN Ia in Virgo will require greater sensitivity.

Development of a nuclear astrophysics mission which applies new technology to improve sensitivity and to address the deficiencies in the current and planned instruments is a priority of gamma-ray astronomy. The goal of this development would be an intermediate mission new start in 2005. The characteristics of such a mission are summarized in Table 4.3. A large field-of-view with good imaging capability is required to provide sensitivity to diffuse emission from the Milky Way as well as to support a high-sensitivity sky survey. An example of a mission concept with these capabilities is a Compton telescope, similar to COMPTEL on CGRO, but using spatially sensitive Germanium detectors. The priority objectives of this mission include:

- **Type Ia Supernovae in the Virgo Cluster.** With the indicated sensitivity, the mission would detect 2 - 4 Type Ia SN per year from the Virgo cluster at a level of significance considerably better than INTEGRAL. This would permit class studies of ^{56}Ni production and emission line profiles. These measurements provide the best diagnostic of Type Ia structure and burning which have implications for galactic chemical evolution as well as supernova physics.
- **Diffuse Galactic Nucleosynthesis.** This mission should map the galaxy with good angular resolution in line emissions from ^{26}Al, ^{60}Fe, ^{44}Ti, ^{12}C, ^{16}O, ^{56}Fe and positron annihilation and positronium continuum. These maps will reflect the nucleosynthetic contributions of supernovae, novae and massive stars, discover sites of galactic supernovae, and map interactions of low-energy cosmic rays in the ISM and molecular clouds. The 100-fold improvement in sensitivity and angular resolution over COMPTEL should permit localization of young individual star clusters by the core collapse supernovae remnants they contain.
- **Galactic Positron Emission.** A large component of the observed galactic 0.511 MeV radiation is likely attributable to galactic Type Ia SN. Thus Ia SNRs could be detected by their residual 0.511 positron annihilation radiation associated with ^{56}Co production. Diagnostics of the physical properties can be provided by the line profiles and positronium fraction.
- **Galactic Novae.** Detection of nuclear emission lines from novae would provide critical tests of the models of novae as thermonuclear runaways on white dwarfs. CNO-rich novae should be detectable in ^{7}Be and ^{22}Na to a distance of 1 kpc and positron annihilation radiation will be detected from all novae within 3 kpc during the first hours of the outburst.

Table 4.3. Characteristics of a Nuclear Astrophysics/ Medium Energy Mission using a High Resolution Compton Telescope

Energy Range	200 keV - 20 MeV
Energy Resolution	2 - 5 keV (below 4 MeV)
Detector Area	~10,000 cm^2
Field-of-View	~10°
Point Source Localization	~5 arcmin
Line Sensitivity	~2x10^{-7} cm^{-2} s^{-1} (1 MeV, Narrow Lines) ~1x10^{-6} (SN Ia lines, broadened)
Continuum Sensitivity	~1x10^{-5} cm^{-2} s^{-1} MeV^{-1} (0.5 MeV)
Mass	3500 Kg
Power	2500 W
Telemetry	3 Mbps
Mission life	> 2 years
Orbit	low inclination
Spacecraft Pointing	30 arcsec stability 10 arcsec knowledge
Operating Modes	pointed observation mode, any direction, any time

4.2 MIDEX & SMEX

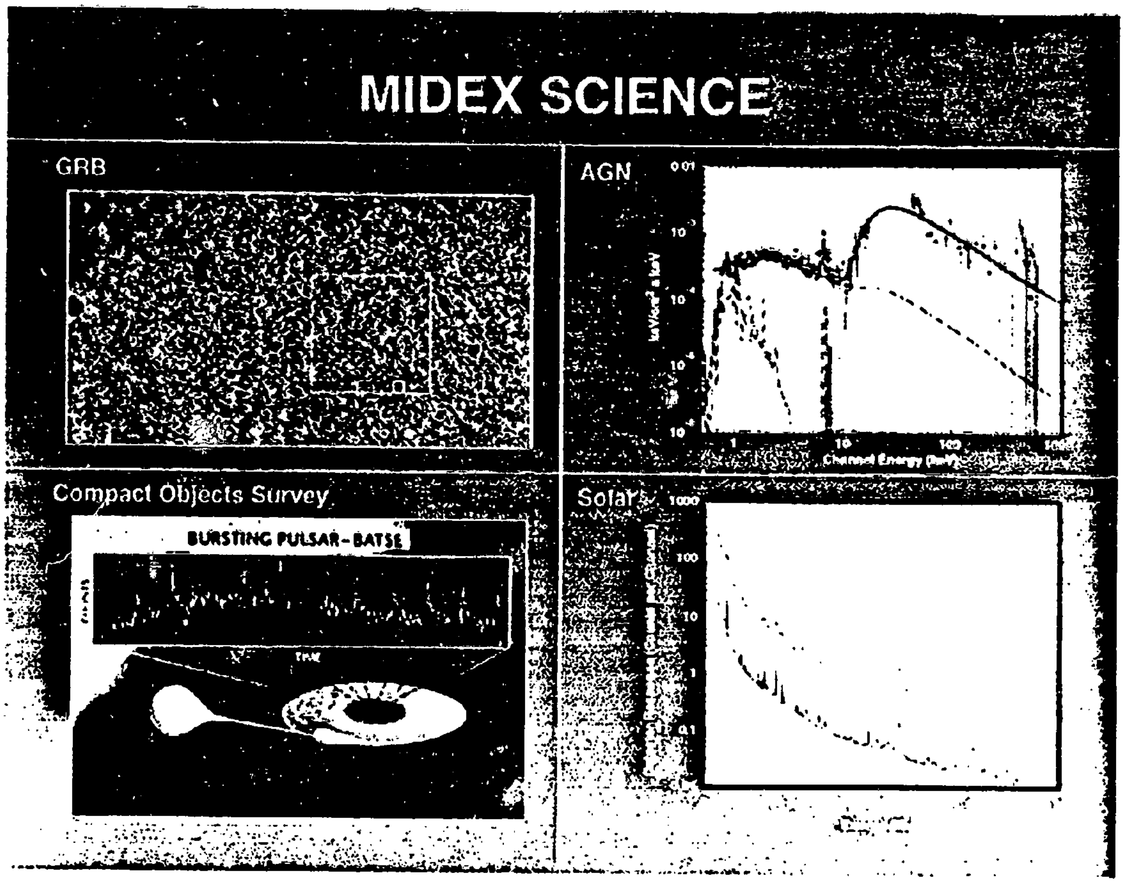

Figure 4.3 - The wide variety of science is addressable through the MIDEX program.

4.2.1 HARD X-RAY SURVEY

The hard X-ray sky, broadly defined as 10 keV to 600 keV, is relatively poorly explored and yet rich in promise. This is the energy range where numerous sources and source mechanisms are either already known (at 10 keV) or strongly suggested. It is the energy domain where fundamental transitions from primarily thermal to primarily nonthermal sources and phenomena are expected. Here we briefly outline the case for a broad-band sky survey mission to be followed by a focusing mission (section 4.1.2) for detailed study of individual sources over a more limited energy range.

Only one truly all-sky survey has been conducted in the hard X-ray band: the pioneering HEAO-A4 survey which yielded a catalogue of some 80 sources down to flux levels of typically 50 mCrab in the 13-180 keV band. Meanwhile, the soft X-ray sky has now been explored fully to flux levels a factor of ~10^3 times fainter with ROSAT but only up to energies of 2.5 keV. The need is therefore great for a hard X-ray survey mission above 10 keV that could achieve a sensitivity increase of a factor of 100 or more to close the gap. Such a mission must be imaging to avoid the source confusion limits that plagued both HEAO-A4 and follow-on hard X-ray/soft gamma-ray collimated detectors such as OSSE on CGRO, particularly in the galactic plane. The imaging resolution needed for such a future high sensitivity survey should be at least ~15 arcmin.

An all-sky survey mission for hard X-ray imaging will not only locate and study a vastly increased hard X-ray source population (e.g., hundreds of X-ray binaries and over a thousand AGN), but will provide unprecedented sensitivity and temporal

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coverage for time variability studies. The high energy universe is highly variable, and a future mission that not only pushes the hard X-ray boundary but the temporal limits and allows coverage of compact objects from milliseconds to months is essential. Finally, the same survey mission at hard X-ray energies must allow at least moderately high spectral resolution. This is needed for study of the variety of thermal and nonthermal emission mechanisms in a wide range of sources. It is also needed for the relatively isolated spectral line features expected: cyclotron lines in highly magnetic neutron stars in accretion powered binaries, possible 511 keV (positron annihilation) or 478 keV (^{7}Li) lines in black hole binaries, or nuclear decay lines (e.g., ^{44}Ti lines at 68 and 78 keV) in young supernova remnants.

All of these needs are described in section 2 above and could be met with a wide field-of-view coded aperture imaging survey mission operating over a broad energy band (10-600 keV) and achieving large total exposure times on any given source by virtue of its large field-of-view. Missions such as EXIST, BASIS, and BLAST which would accomplish these goals are under study as part of New Mission Concepts or MIDEX programs.

4.2.2 GAMMA-RAY BURSTS

Twenty years of intensive effort have passed with no concrete identification of a quiescent counterpart to a gamma-ray burst. Rather than solving the puzzle, BATSE on CGRO has eliminated the previously favored model of galactic disk neutron stars. The current highest priority in understanding GRBs is obtaining the distance scale for the population of sources. However, once that is done, additional study will be required to determine the physical nature of the sources.

Many approaches to the determination of the distance scale have been proposed, including (see section 2.3): 1) identification of counterparts in other wavebands 2) detection of an extended halo distribution in the nearby Andromeda Galaxy, 3) search for lines and photoelectric absorption in the spectra of gamma-ray bursts in the X-ray, and 4) search for TeV emission from bursters. Of the four, results from the first two would be less ambiguous. The search for counterparts requires few arcsec error boxes for burst directions and/or rapid notification of burst occurrence to ground observers. GRB positions accurate to 5 arcsec are required to identify spiral and dwarf galaxies detected to redshift z ~ 1. Detection of the anisotropy in the angular distribution of GRBs caused by a putative extended halo around Andromeda requires an instrument approximately 10 times more sensitive than BATSE.

A number of GRB missions have been proposed and studied. As New Mission Concepts, ETA, BASIS, and EXIST are being studied, and, as MIDEX Missions, BLAST and EXIST, are contenders. Of these concepts, BLAST, BASIS, and ETA provide arcsec burst positions - ETA by burst arrival timing with an array of satellites, BLAST and BASIS by accurate positioning of the incident flux. They all provide capabilities to measure, to varying degrees, a possible anisotropy in the direction of Andromeda. With the exception of ETA, all provide hard X-ray survey capabilities to address the objectives outlined in section 4.2.1. The characteristics of a GRB mission which addresses both accurate positions and the Andromeda anisotropy measurement are summarized in Table 4.4. Interplanetary networks of gamma-ray burst detectors are a means of providing many small error boxes, in principle down to several arcsecond size. The miniature, low-cost instruments required for planetary missions are fully developed, and require only to be included in future missions.

TABLE 4.4. Characteristics of Gamma-Ray Burst Mission

Energy Range	5 - 300 keV
Energy Resolution	10%
Detector Area	≥ 10,000 cm^2
Field-of-View	1 sr (0.5 sr for Andromeda)
Point source localization	~2 arcsec
Burst Sensitivity	~0.03 photons cm^{-2} s^{-1} (x10 BATSE)
Sky survey Sens.	~1 mCrab in 10^5 seconds
Mass	1500 Kg
Power	500 W
Telemetry	25 kbps
Mission life	2 years
Orbit	500 km, low inclination
Spacecraft Pointing	few arcmin accuracy stability 1 arcmin/orbit, < 1 arcsec/sec
Operating Modes	inertial, 3-axes any direction, any time

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4.2.3 SOLAR

As discussed in section 4.1.3, the Sun is capable of producing large measurable gamma-ray fluxes at Earth with even moderate solar flares. One might think that this obviates the need for sensitive instruments in investigating solar phenomena. This is not so. Given that the Sun is resolvable at most wavelengths we know much of the basic physics of solar flares. This increases the demands on the hard X-ray and gamma-ray measurements as more and better data are necessary to properly use the information obtained at other wavelengths. Of utmost importance is the ability to image gamma-ray emitting features on the solar disk. This would reveal the extent of the energetic particle population as it evolves through the course of the flare. Also of considerable importance are high-energy resolution measurements. These measurements provide information about the composition of the solar atmosphere that is being bombarded with energetic protons. Conceivably, there may inhomogeneities in the composition of the lower corona and good spectral data coupled with imaging data could reveal this. Expanding the size and dimensionality of the data space in this manner means that solar gamma-ray instruments will not be small. The ideal instrument should be large, able to handle a large dynamic range of intensities, and have good spectral resolution as well as being a gamma-ray camera. These are serious and demanding requirements of an instrument or a suite of instruments even given the strong solar signal. However, some aspect of these problems could be addressed with instruments on mid-sized and small spacecraft. For example, an instrument that images up to about 300 keV with standard scintillator energy resolution would be of value in tracking the distribution of energetic electrons in the solar atmosphere. Another good instrument would be one along the lines of the Gamma Ray Spectrometer on SMM, but with Ge-type resolution. One final possibility is to design an instrument to attack a specific problem such as the polarization of the electron bremsstrahlung radiation. Any of these missions would be scientifically interesting.

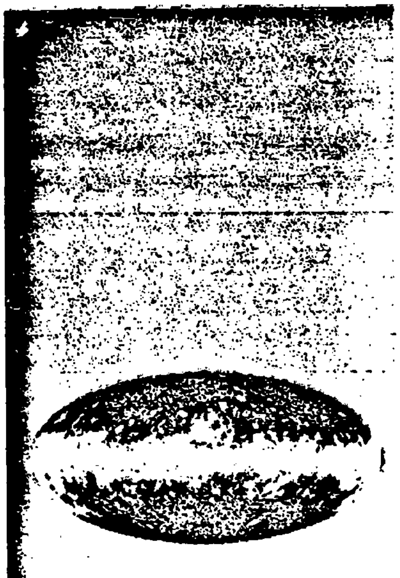
Some general gamma-ray spectral monitoring is necessary for proper interpretation of hard X-ray image data, polarization measurements and high-energy measurements. A useful and productive set of instruments could be flown on a small to mid-sized platform.

4.3 SUBORBITAL PROGRAM

The future of gamma-ray astronomy will continue to depend in a major way on the balloon program for the development of new instruments and techniques. The role of the sub-orbital program has been particularly important for gamma-ray missions, with all the instruments on CGRO (for example) having balloon programs. The role of the balloon program in gamma-ray science has not been as widely appreciated. Important scientific advances include the discovery of galactic 511 line emission, ^{56}Co line emission from SN1987A, the hard X-ray imaging study and identification of several galactic bulge sources, and the mapping and study of both the diffuse 511 keV and ^{26}Al 1.8 MeV emission.

With the newly revived, and highly promising, development of superpressure balloon technology, the long-sought goal of long-duration balloon flights of large payloads appears to be finally within reach. The development of 100-day balloon flights with 3000 lb payloads will provide a significant opportunity for new gamma-ray missions and science.

The GRAPWG strongly encourages that the current push to develop the 100-day long-duration balloon capability receive the technical, engineering and science payload development support needed to capitalize on this new mission opportunity. To ensure the timely success of this effort, action is needed on several fronts: incorporation of upgraded and currently available electronics (e.g., power and telemetry systems) and mechanical (e.g., gondola shock isolation and controlled parachute systems) engineering into the balloon program; attention to innovative data recovery and payload control systems (e.g., using worldwide cellular phones); and attention to establishing and maintaining international overflight agreements.



5. TECHNOLOGIES

The breadth of gamma rays in the electromagnetic spectrum — a range of more than 10^9 in photon energy — demands a wide variety of technologies. Advances in relevant technologies span the full range of opportunities for gamma-ray instruments, giving a high potential for major improvements in many aspects of the field.

Section 5.1 describes the imaging techniques needed in the different parts of the gamma-ray spectrum. Section 5.2 illustrates how technologies are currently being developed to take advantage of the full range of gamma-ray possibilities.

5.1 IMAGING TECHNIQUES

The physics of gamma-ray detection is the ultimate driver for all gamma-ray telescopes. In the keV energy range, gamma rays interact primarily through the photoelectric effect; in the MeV range, primarily through Compton scattering; and at energies above a few tens of MeV, almost exclusively by electron-positron pair production. Only at the lowest gamma-ray energies is any form of reflection possible. Most gamma-ray telescopes require substantial detector areas.

Table 5.1 Comparison of gamma-ray imaging techniques

Imaging Technique	Energy Range	Characteristics
Multi-layer mirrors	below 100 keV	high resolution, narrow field-of-view
coded-aperture mask	below 10 MeV	good resolution, wide field-of-view
Compton telescope	~1 MeV - ~ 100 MeV	good resolution, wide field-of-view
Pair telescope	above 10 MeV	good resolution, wide field-of-view
Atmospheric Cerenkov	above 100 GeV	good resolution, narrow field-of-view

5.1.1 MULTILAYER MIRRORS

The familiar technical challenge to extending traditional grazing incidence optics into the hard X-ray band ($E \geq 10$keV) is the decrease with energy in incident angle (referred to as graze angle) for which significant reflectivity can be achieved. For a Wolter or conical approximation mirror geometry, the graze angle, γ, on a given mirror shell is related to the focal ratio by $\gamma = 1/4 \times (r/f)$, where r is the shell radius and f is the focal length. Coating the reflective surfaces with multilayer structures, which operate on the principal of Bragg reflection, can substantially increase the maximum graze angle for which significant reflectivity is achieved over a relatively broad energy range, while maintaining realistic focal ratios. Other concentrating techniques and mirror geometries such as polycapillary optics and Kirkpatrick-Baez telescopes can also be extended into the hard X-ray band; however, given the current state of technology and the desire for good imaging performance, systems based on Wolter-I or conical optics are the most attractive.

The requirements for the multilayer materials are that the K-shell absorption edges not lie in the energy range of interest, and that the two

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materials employed be chemically compatible for forming stable thin films. In the hard X-ray band, this is satisfied by several material combinations that have been used to fabricate X-ray multilayers with the appropriate dimensions. The most promising combinations for operation above ~5 keV include W/Si (W K-edge at 69.5 keV), Ni/C (both edges below 10 keV, and therefore effective up to ~100 keV), and Pt/C (Pt K-edge at 78.4 keV). Technical limits restrict the operational energy band to below ~ 120 keV.

The graze angles for multilayer hard X-ray telescopes are still smaller than those typically employed at low energies. Therefore thin, lightweight, highly-nested mirror substrates are required. Development of such optics is also critical for future missions operating in the soft X-ray band (the spectroscopy telescopes on HTXS, for example), and these efforts are directly applicable to future hard X-ray focusing missions.

5.1.2 CODED APERTURE IMAGING

Although multilayer coatings and small graze angles allow imaging up to perhaps 100 keV (see above), this is restricted to narrow fields-of-view (typically less than 10 arcmin). Although Bragg reflection can be incorporated into Laue lenses at still higher energies (e.g., up to several MeV), these focusing techniques are restricted to narrow energy bands (typically less than 1-2% of the incident energy). Therefore alternative concepts must be used to achieve the important advantages that imaging, with moderate to wide fields-of-view, can provide: simultaneous measurements of source(s) and background without the need to chop on and off source; measurements of source locations with resolution typically much higher than in non-imaging (e.g., collimated) detectors; and resolving source structure for true imaging of extended sources. All of these can be achieved by using coded aperture imaging, whereby images are constructed from shadows of a coded aperture mask cast on a position-sensitive detector located at focal length, below the mask. Coded aperture imaging is particularly well suited for the hard X-ray/soft gamma-ray band (10 keV - 1 MeV) since it depends on source photons being either absorbed (photoelectric) or scattered (Compton) if they strike a closed cell of the coded mask. However the images become increasingly blurred, with consequent loss of sensitivity, as Compton scattering dominates and the coded mask becomes (eventually) optically thin; thus it is not optimum for energies above ~1 MeV.

For a coded mask of open and closed holes with usual open fraction 0.5, images are derived simply by correlating the detected pattern of source counts on the detector with the (known) pattern of the mask. This may be understood simply as measuring the x- and y- shift of the detected shadow on the detector and thus the angular position (in the orthogonal angles giving rise to x- and y- offsets) of the source relative to the optical axis of the telescope.

The technique has now been well developed and a variety of successful imaging telescopes have been flown from balloons and in space. The premier space mission to date has been the French/Russian SIGMA telescope which imaged selected regions of the sky (primarily the galactic center region) down to sensitivities of (typically) 30-50 mCrab in the 35-150 keV band. Future missions are now planned (INTEGRAL) or proposed (e.g., EXIST, BASIS, BLAST) which will be based on coded aperture imaging. The proposed missions are all survey missions and thus require very large fields-of-view for maximum exposure time, temporal coverage and sensitivity. These requirements effectively point to coded aperture imaging as the imaging technique of choice. The technique requires position sensitive detectors of large area and high spatial resolution. New CZT detectors (cf. section 5.2.1) are particularly promising since they provide fixed pixels (which can be very small) and yet high-energy resolution.

5.1.3 COMPTON SCATTER TELESCOPES

Compton telescopes have been used since the early 1970's for making astronomical observations and measurements above about 1 MeV. The first orbiting Compton telescope is COMPTEL on the CGRO and it has performed the first all-sky survey at MeV energies with a resolution of about one degree. The principle behind the instrument is that photons scatter in a low-Z material in a forward detector. The scattered photon is then detected by a second, or rearward detector, typically made of a high-Z material to fully absorb the remaining energy. By requiring that the photon scatter twice, three advantages become apparent. The first is that the telescope has a natural directionality. If the time-of-flight is measured between

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the triggered detectors, then only photons traveling in the proper direction (forward or backward) need be accepted for further analysis. The second advantage is that although the efficiency of the instrument is low (two scatters are required and one pays the price in effective area), it efficiently rejects background events. These background events can arise in single element detectors through activation. Finally, by measuring the energy deposits in the two detectors one not only has a measure of the total incident photon energy but also a measure of the Compton scatter angle that can later be used to create an image.

Present day Compton telescopes only employ the technologies that allow them to measure the location of the photon interactions, the energies of the interactions and the time-of-flight. These data are not sufficient to assign a unique incoming direction to the incident photon. One also needs the direction of the scattered electron in the forward detector. This is not easily accomplished. MeV electrons scatter efficiently and unless the material in the forward detector is tenuous and of low-Z composition, the direction information of the electron is quickly lost. The problem of tracking the scattered electrons is now being attacked with solid-state silicon or liquid Argon particle detectors. If silicon detectors are used as the forward detector and the detectors are kept thin the electrons do not scatter much. This then allows one to greatly constrain the incident photon direction, thereby improving its imaging properties and also its signal-to-noise ratio. An angular resolution of a few arc minutes is attainable with technology currently under development. The next major step in Compton telescope design will come in the form of an electron-tracking forward detector and the high density electronics necessary to support the large number of data channels.

5.1.4 PAIR PRODUCTION TELESCOPES

The observation of high-energy gamma-rays is done indirectly, by detecting the electron and positron produced when the gamma-ray undergoes pair production in the presence of a nucleus. A high-energy gamma-ray telescope consists of high-Z pair-production material (metal foils) interleaved with position sensitive charged particle detectors. The direction and energy of the incident gamma-ray is reconstructed from the direction and energy of the electron and positron. Thus, a gamma-ray telescope is, in effect, a track imaging charged particle detector and calorimeter. An anticoincidence is needed to screen the track imaging detector from the charged particle cosmic rays which outnumber the gamma rays by a factor of approximately 10^4.

Since the electron and positron emanate from a common vertex, giving the inverted V signature of the gamma-ray conversion to an electron/positron pair, the two-track resolution of the track imaging detector is important for both event recognition and subsequent direction determination. The instruments which define high-energy gamma-ray astronomy — SAS-2, COS-B, and EGRET — all used this same basic design. The great advance possible in this area comes from the application of recent developments in particle tracking detectors (see below), along with improvements in on-board processing and telemetry bandwidth.

5.1.5 ATMOSPHERIC CERENKOV TELESCOPES

At sufficiently high gamma-ray energies, typically above 100 GeV, the Earth's atmosphere itself can be used as part of a gamma-ray telescope. As these high-energy photons collide with the upper atmosphere, they convert to electron-positron pairs just as 100 MeV photons do, but these particles are sufficiently energetic to produce a cascade of secondary particles traveling fast enough through the air to produce a flash of Cerenkov radiation. This radiation is then detected by large-area optical collectors on the ground. The Whipple Observatory, HEGRA, and CANGAROO telescopes are all active now, and new telescopes (e.g., CELESTE, MILAGRO, VERITAS) are either under construction or proposed.

5.2 DETECTOR TECHNOLOGIES

A number of detector technologies are used for gamma-ray imaging and spectroscopy. Many aspects of such detectors are well established, such as plastic scintillators and photomultiplier tubes. What makes dramatic progress obtainable in this field is new and developing technologies which influence all types of gamma-ray imaging. Several general areas stand out as key new technologies.

5.2.1 STRIP AND PIXEL DETECTORS

5.2.1.1 CdZnTe

CdZnTe detectors are at the threshold of becoming a widely used tool in gamma-ray astronomy.

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The basic properties that make them interesting are: 1) large enough band gap energy (1.6 eV) to permit room temperature operation; 2) high density (~6 g cm^{-2}) for good stopping power; 3) high atomic numbers (48 for Cd, 52 for Te) for photoelectric absorption up to high energies (For example, CdZnTe has a photoelectric attenuation coefficient that is more than 10 times the Compton scattering coefficient up to 110 keV compared to 60 keV for Ge and 25 keV for Si.); 4) low bias voltages of typically 200 volts compared with thousands of volts for Ge; 5) ease of electrode segmentation for fine imaging; 6) low susceptibility to contamination problems so that the detectors can be easily fabricated and handled; 7) availability of large crystals so that multi detector arrays can be fabricated at low cost; and 8) increased resistivity with introduction of Zn to improve performance over CdTe.

The high density and particularly high atomic number of CdZnTe combine to give several important characteristics. The domination of photoelectric attenuation means that CdZnTe has single-site absorptions (good for imaging) throughout the low-energy gamma-ray band. Also, the large attenuation coefficient for photoelectric absorption means that CdZnTe detectors can be very thin and still efficient at stopping gamma rays.

The typical size of a CdZnTe detector is 1 cm^2 in area by 2 mm thickness, with the thickness limited by hole trapping effects. Recently, however, it has been shown that detectors with segmented electrodes can achieve reasonable spectroscopy using only the electron signal due to the "near-field" effect, thus enabling thicker detectors. The small sizes of CdZnTe detectors means that large-area detection planes will require arrays with hundreds or thousands of individual detectors. In order to keep the electronics power level within reasonable levels for spaceflight applications, VLSI front-end amplifiers are typically used. Power levels of a few mWatts per detector are then achievable.

The ability to finely segment the contacts of CdZnTe detectors, combined with their high photoelectric attenuation coefficient, means that they are ideal for high-resolution imagers. Detectors with strip contacts and with pixel contacts have been fabricated with pitches of 100 μm or less. Applications of such finely segmented detectors include wide-field coded mask instruments with better than arcminute (in some cases approaching arcsecond) angular resolutions and high-sensitivity focusing hard X-ray telescopes with arcminute resolutions.

Examples of instruments that incorporate CdZnTe or CdZn detectors are: the INTEGRAL imager; the BASIS, and EXIST, mission concepts; and several recently-proposed balloon instruments.

5.2.1.2 GERMANIUM

Germanium remains the only solid state detector capable of high resolution spectroscopy in the nuclear energy band. This is the reason it has been used in satellite (HEAO C-1 and INTEGRAL) and balloon missions (Bell/Sandia, Lockheed/MSFC, GRIS, Hexagone) requiring the best resolution. However, detector geometries other than the current large volume co-axial detector are needed to develop instruments with imaging capabilities and sensitivities beyond INTEGRAL. Two geometries which are being investigated are the Ge planar strip detector and the Ge "finger" detector. Both of these concepts produce pixelated detectors with appropriate position resolution for applications in coded-aperture or Compton telescope imaging systems. Ge detectors with 2-mm spatial resolution have been demonstrated in the laboratory. A Ge Compton telescope using such pixelated detectors could achieve sensitivities 10 - 50 times better than INTEGRAL and have good sensitivity to both diffuse and broadened line emissions. This is because the good energy resolution of Ge also reduces the background by improving the angular resolution in Compton telescopes so that the sensitivity improves proportionally with resolution, not as the square root of resolution.

5.2.1.3 SILICON STRIPS

Silicon microstrip detectors have been developed at accelerators and are now readily available from several commercial manufacturers. These devices are, in effect, big integrated circuits fabricated on Si. The spatial resolution is determined by the width of the semiconductor strips fabricated on the Si. Resolution of 50 μm is easily attainable by modern photolithography. Because the Si microstrips are fabricated on thin layers of silicon, they have very good two track resolution, typically 3 times the strip pitch. Si microstrip detectors are available, currently, in 6 cm x 6 cm size. Si strip detectors are applicable to both Compton and pair telescopes.

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5.2.1.4 GAS MICROSTRIPS

Gas microstrip detectors represent a new technology which has been the subject of intensive investigations at accelerators and for X-ray telescopes. The gas microstrip detector is a cross between the silicon microstrip and drift chamber detectors. The drift chamber anode cathode wires are replaced by thin metal traces photo-etched on an insulating substrate at a pitch of about 200 μm. The field shaping wire grids of the drift chamber are replaced with a single plane electrode separated from the anode/cathode plane by 2-4 mm. These detectors have potentially large areas, limited by the photolithographic or direct etching fabrication equipment and not by the size of the substrate. They are, however, gas detectors which require a clean gas vessel and gas supply. The principal gamma-ray application of gas microstrips would be a pair telescope.

5.2.1.5 LIQUID XENON

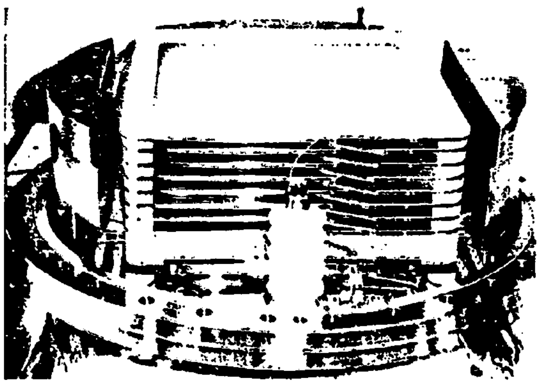

Figure 5.2 - A prototype of a liquid xenon detector.

Liquid xenon, with its high density (3 g cm^{-3}) and high atomic number (54) is a very good detector material for gamma rays. Liquid Xe detectors can be realized in a variety of configurations, using either its good ionization (64,000 electrons/MeV) or scintillation (similar yield as NaI, < 5 ns time response) properties, or both. In a liquid Xe Time Projection Chamber (LXeTPC), both the ionization electrons and the scintillation light signals are detected to infer the energy deposit (resolution of ~6% at 1 MeV) and the three-dimensional spatial coordinates (resolution < 1 mm) of each gamma-ray interaction. Events with multiple-site interactions are unambiguously recognized and the original gamma-ray direction reconstructed from kinematics, resulting in high detection efficiency for true source events. The characteristics of a LXeTPC for gamma-ray imaging and spectroscopy have been demonstrated with a prototype of 400 cm^2 active area and 8 cm thickness. A double-scatter Compton telescope based on a coincidence of two liquid TPCs is being studied. With a Liquid Ar TPC as the low Z converter and Compton electron tracker, at a fixed distance from a LXeTPC as calorimeter and imager, a substantial improvement in sensitivity and angular resolution over COMPTEL in the 1-10 MeV range could be achieved. Moreover, such a configuration, with TPCs of ten times the area of the existing prototype, appears feasible within a MIDEX mission cost and weight constraints.

5.2.2 VLSI/ASIC

A characteristic common to many of the current and future technologies for gamma-ray detector systems is the large number of channels with relatively small signal outputs. Most such applications will, therefore, rely on Application Specific Integrated Circuits (ASICs) and Very Large Scale Integration (VLSI) techniques in order to keep the power consumption to a modest level for spaceflight. Although the specific circuits are tailored for individual applications, general approaches to designing and building such electronics can be improved. Any technology developments that allow faster or cheaper production of these electronics will directly benefit a broad range of gamma-ray telescope designs.

5.3 COMPUTATIONAL CAPABILITIES

The information explosion that will come with the next generation of satellite gamma-ray experiments will put severe demands on the current computing capabilities both on-board and ground-based. Increased data rates, even without better resolution, will demand computational upgrades. Increased angular resolution will force better image analysis, better time resolution will drive deeper pulsar and quasi-periodic searches and more sophisticated spectral techniques will require more complicated analysis routines. Fortunately, this is a field which can be expected to rapidly improve with time so that it is only necessary to ensure that state-of-the-art computer facilities are available for gamma-ray data analysis.

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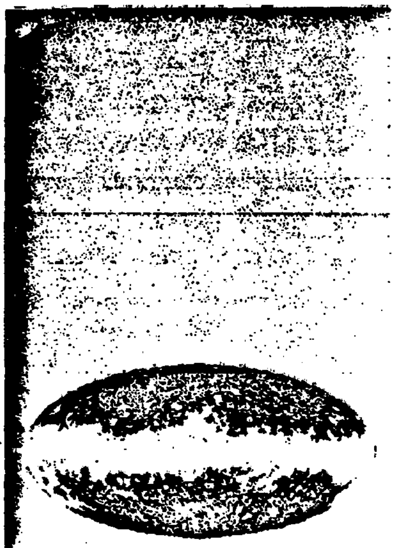


6. SUPPORTING PROGRAMS

6.1 DATA ANALYSIS

Over the years NASA has supported the analysis of archival data from past and existing missions. This research opportunity has served to extract important science from data sets that have had only limited initial analyses. Given the great cost of developing and launching spacecraft-based instruments, this is a cost effective method of doing science—on a par with keeping existing missions operating. This avenue takes on new importance in this age of declining resources. Further, with the modern multiwavelength approach to understanding high-energy sources, continued observation and discovery at other wavelengths makes correlative studies of archival space data an essential astrophysics tool. Finally, new numerical and statistical techniques are continually developed; examination of archival data provides new discoveries and improved guidelines for new observations and new missions. These scientific rationales argue for a vigorous and adequately funded program of long-term archival data analysis.

Strong arguments for continued archival research also stem from the need to preserve human capital. The focused effort of the 1980's and early 1990's to develop the CGRO mission has resulted in a strong scientific community and important connections with other wavelengths. Because major mission opportunities like CGRO are rare, it is essential to support continued data analysis to maintain a stable intellectual infrastructure in the upcoming period when few new missions are anticipated. Young scientists developing future mission hardware need contact with gamma-ray data to balance their training while researchers in other fields will maintain active connections with high energy problems through the study of the the wealth of data produced by CGRO and other recent missions. Such efforts position the community for an effective use of the major new missions planned for the next decade.

6.2 THEORY

Gamma-ray observations probe exotic physics from remarkable, energetic sources. However, the nonthermal nature of the emission, the modest photon statistics and the need to connect the high-energy radiations with lower energy observations makes progress in the field particularly dependent on adequate theoretical support. In turn the puzzles posed by high-energy observations have spurred a ferment of theoretical activity, as exemplified by the continuing stream of papers on gamma-ray burst models. As discussed earlier, many CGRO observations remain unexplained. Late in the CGRO era, support for theoretical work on high-energy problems is becoming very limited. The NASA theory program plays an important role, but experiences extreme pressure from other disciplines. Because new understanding spurred by CGRO and other recent missions offers hope of important advances in our understanding of compact objects and other high-energy sources, expanded support of theoretical work in this area can provide important progress in the post-CGRO era. It will also be important to continue to refine theoretical predictions, looking forward to the sensitive observational tests of future missions.

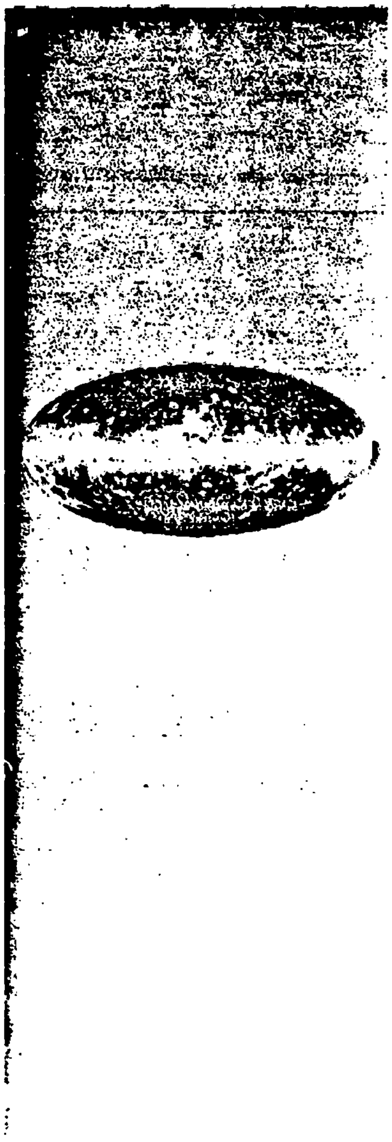
6.3 GROUND BASED

Many ground-based "third-generation" atmospheric Cherenkov systems are now under consideration which will have sensitivity in the 10 - 100 GeV energy range. The energy threshold varies inversely as the product of the square root of the total mirror area, the light collection efficiency and the quantum efficiency of the detectors. Hence if a threshold of 200 GeV can be achieved with a 10m aperture reflector, then a threshold of 20 GeV is feasible with a reflector with an effective aperture of 100m. In practice an array of detectors offers better background rejection and more economical construction than a single reflector. One such approach is VERITAS (Very Energetic Radiation Imaging Telescope Array System); this is a logical development of the imaging atmospheric Cherenkov concept and consists of an array of nine telescopes of 10m aperture each closely based on the proven design of the Whipple 10m optical reflector. This array would easily reach a threshold of 50 GeV with conventional photomultipliers; with advanced technology detectors it could be as low as 30 GeV. Its flux sensitivity for discrete sources would be very competitive with planned high-energy gamma-ray space missions i.e., 2×10^{-12} photons cm^{-2} s^{-1} at 100 GeV. It would also have excellent spectral resolution.

Figure 6.1 - This artist's conception of the proposed VERITAS Instrument is one example of the future direction of ground-based gamma-ray astronomy.

The VERITAS approach is not unique among atmospheric Cherenkov observatories proposed as a next generation system although it is probably the most conservative and predictable. Other approaches include a large, steerable, single dish (17 m aperture) with a high resolution camera, the Solar Array approach whereby existing arrays of heliostats (built as solar energy collectors) are utilized as large area light collectors with a central detector, and the Arecibo concept in which a single fixed optical dish is located at very high mountain altitude and imaged unto an array of some 10,000 photomultipliers. Mention should also be made of large water Cherenkov systems e.g., MILAGRO which are most useful as burst monitors and for all-sky surveys.

Developments in space-and ground-based detector technology have an obvious impact on one another; ground-based detectors will rely on space missions for selection of suitable sources and for all-sky monitoring of source activity. In return, ground-based observation can supply improved spatial localization, high-energy spectrum measurements and high count statistics to probe short-time variability. It is clearly advantageous in the planning of future missions/telescopes that the development of the overlapping techniques proceed in parallel. Ground-based observatories will continue to operate after the demise of EGRET and will thus provide continuity in the field; they can be continually upgraded to achieve maximum sensitivity at the launch of an EGRET successor.



7. EDUCATION AND PUBLIC OUTREACH

Since its inception, one of NASA's mandates is to disseminate the results of its programs to the general public. Because of people's inherent interest in astronomy and spaceflight, NASA has been particularly successful in this outreach endeavor. Programs in gamma-ray astronomy are making a significant contribution to NASA's goals of education and to raising the level of public understanding and appreciation of science and technology. As our knowledge of the high-energy sky increases, so does our ability to communicate the promise and excitement of gamma-ray astronomy. The mystery of gamma-ray bursts, direct measurement of ongoing galactic nucleosynthesis, and observations of exotic objects such as black holes are examples of fields to which gamma-ray astronomy contributes.

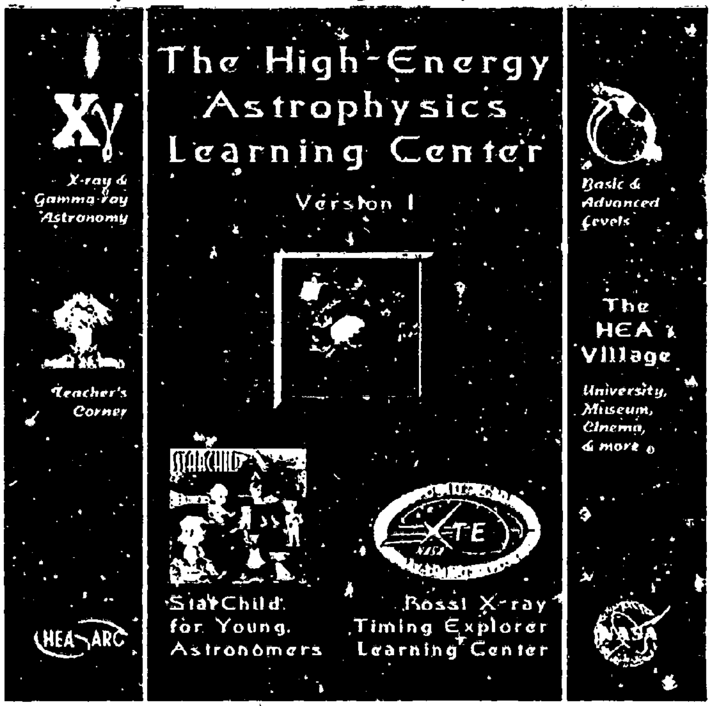


Figure 7.1 - This cover image of a CD version of the high-energy Astrophysics Learning Center represents on of the many outreach efforts which are making gamma-ray astronomy results accessible to the general public.

Public information flourishes as a result of the many discoveries and new mysteries that have accompanied the growth of gamma-ray astrophysics in the last five years. This includes public talks by leading scientists at museums and planetariums around the country and front page articles in newspapers and magazines. More concerted efforts at public outreach activities in the CGRO era alone include posters and brochures put together by the CGRO Science Support Center and other organizations as well as numerous World Wide Web pages created by groups and individuals on specialized topics. A well-received exhibition at the Smithsonian Air and Space Museum is another example. Continuing this legacy of public

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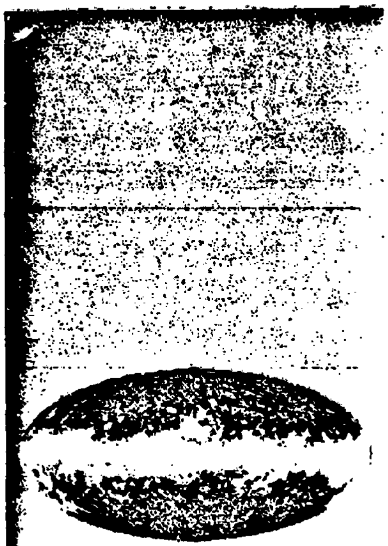
outreach should be an important component of the gamma-ray astronomy programs in the future.

Gamma-ray astronomy has touched education in a number of ways. Special grants to use the success of CGRO for educational purposes under the IDEAS program, from elementary to high schools, to college undergraduate and graduate education have also been highly successful. In addition, efforts such as the HEASARC's Learning Center page are beginning to present gamma-ray astronomy resources to younger students using the Internet. We encourage the use of add-on grants for educational purposes as an effective way to help active researchers contribute to science education.



8. RECOMMENDED PROGRAM

8.1 FUTURE MISSIONS

The recommendations of the GRAPWG are divided into the following categories: future intermediate-class missions ($75M to $300M), future MIDEX and SMEX missions ($70M and $35M respectively), current missions, supporting programs, and new technologies.

8.1.1 INTERMEDIATE MISSIONS

Although several important science objectives can be met with small missions in hard X-ray and gamma-ray astronomy (see below), major progress on a broad front depends on intermediate-class missions. The HIGHEST PRIORITY recommendation of the GRAPWG is:

- A **next-generation high-energy gamma-ray mission.** Such a 10 MeV to 100 GeV mission would follow on the successes of EGRET and address the questions of the nature of jets and AGN, the origin of the diffuse high-energy gamma-ray background, the origin of cosmic rays, the high-energy emission from gamma-ray bursts, the nature of the unidentified high-energy sources. For a mission like the GLAST concept, point-source sensitivity improvements could be one to two orders of magnitude compared to EGRET. New pair tracking technology would be used to give arcminute angular resolution over a field-of-view of 1 steradian or larger. Timely approval of such a mission is imperative to provide the unique and important observations that can be made in this energy range.

The GRAPWG identified two other missions as very high-priority for initiation within the next decade. These programs would serve pressing scientific needs and represent areas where prompt support for technology development and mission study promises great gains in the capabilities and efficiency of these substantial future missions.

- **Focusing hard X-ray mission.** Such a mission would address the questions of the nature of jets and AGN, the sites of recent galactic supernovae (through ^{44}Ti line observations), the origin of cosmic rays, the nature of neutron stars, black hole systems and the accretion process. MicroCrab (3×10^{-9} photons cm^{-2} s^{-1} keV^{-1} at 50 keV) sensitivities in the 10 - 100 keV range could be obtained. This is more than two orders of magnitude more sensitive than RXTE. Arcminute imaging would be possible over small (~10 arcmin) fields-of-view.
- **Next-generation nuclear line and MeV continuum mission.** Such a mission would address the questions of the sites of nucleosynthesis, the supernova rate in the galaxy, the nature of supernova explosions, the origin of cosmic rays, the origin of the diffuse background, the nature of jets and AGN, and how the accretion process works. A large array of position sensitive detectors, possibly configured as a Compton telescope, could give an order of magnitude better detection sensitivity for gamma-ray lines than that expected from INTEGRAL and two orders of magnitude better continuum sensitivity at 10 MeV than COMPTEL. The GRAPWG views this mission as a follow-on to INTEGRAL.

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8.1.2 MIDEX AND SMEX MISSIONS

The GRAPWG strongly supports the current MIDEX and SMEX programs. Frequent flight opportunities are crucial for our field and the open peer review process should allow the best missions to be selected. There are several critical hard X-ray and gamma-ray measurements that can be accomplished within the weight and cost envelopes of these programs. The two highest priorities for near-term MIDEX and SMEX missions are (of equal priority):

- **Gamma-ray burst localization mission.** Such a mission would address the question of the origin of gamma-ray bursts. A large array of position sensitive CdZnTe or scintillation detectors combined with a wide-field coded mask or Fourier transform aperture could position bursts to arcsecond accuracy to allow deep unconfused searches for counterparts at other wavelengths. Another possibility for this measurement is an array of small-satellites spread around the Earth's orbit to accurately triangulate burst arrival times. Searches could also be made for a halo population of burst sources around M31 to test galactic halo models. Such missions would likely lead to a breakthrough in the understanding of gamma-ray bursts. Examples of NASA mission concepts for gamma-ray bursts are BASIS and ETA, as well as the MIDEX concept BLAST.
- **Hard X-ray all-sky survey and monitor mission.** Such a mission would address the questions of the nature and evolution of AGN, the origin of the diffuse background, the sites of recent galactic supernovae (through 44Ti line observations), and the nature of neutron stars, black hole systems, and the accretion process. For a mission concept like EXIST, a large array of position sensitive CdZnTe detectors combined with a wide-field coded mask aperture would give an all-sky survey at the 100 microCrab sensitivity level in the 10 - 200 keV range. This surpasses the HEAO 1 survey by more than two orders of magnitude. A significant fraction of the entire sky would be scanned every day for detection and arcminute positioning of transient sources.

8.1.3 HETE

The loss of HETE is a major setback to the study of cosmic gamma-ray bursts. The objectives of that mission are still compelling: rapidly obtained precise positions would be extremely valuable for multiwavelength counterpart searches. The HETE spacecraft can be rebuilt and reflown relatively quickly and inexpensively. Therefore we endorse this initiative, and further recommend that additional support be provided for the construction of about ten small rapidly slewing ground-based telescopes to assure the maximum possible return on this investment.

8.2 CURRENT AND APPROVED MISSIONS

While future missions are being developed, it is essential to continue scientific discovery with the existing and approved missions in gamma-ray and hard X-ray astronomy.

- CGRO and RXTE. CGRO and RXTE are tremendously productive multi-instrument NASA missions that promise to remain scientifically exciting for a long time into the future (5-10 years). The GRAPWG recommends that adequate MO&DA funding be made available to continue operations, data production and scientific investigations with these missions. The current biennial Senior Review peer evaluation of the missions is good and should be continued. The GRAPWG is concerned that the overall MO&DA budget beyond FY97 for astrophysics missions is not nearly adequate to realize the scientific potential of the existing missions.
- INTEGRAL. The INTEGRAL is an ESA-led mission with U.S. and Russian participation. It is scheduled for launch in 2001 and will operate in the 15 keV to 10 MeV range. The combined capability of its two main instruments will offer an order of magnitude better sensitivity than CGRO with significantly improved spectral and angular resolutions. This is the next major observatory for gamma-ray astronomy following CGRO. The GRAPWG recommends that NASA continue support for U.S. participation in the mission.
- The inclusion of small, inexpensive gamma-ray burst detectors aboard approved and future planetary missions is encouraged to provide an interplanetary network for burst localization. The GRAPWG recommends adequate MOEDA support to take advantage of fine localizations. A major step towards

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solving the gamma-ray burst mystery would be achieved by the identification of a counterpart at other wavelengths.

8.3 SUPPORTING PROGRAMS

8.3.1 TECHNOLOGY DEVELOPMENT AND BALLOON PROGRAM

The future vitality of hard X-ray and gamma-ray astronomy depends critically on the development of new instrumentation with significantly enhanced capabilities over current hardware. The key steps in this process are: 1) basic detector, aperture and electronics technology development; 2) instrument building; 3) laboratory and accelerator testing; and 4) balloon-flight performance verification. All of these activities are currently funded under the NASA high energy astrophysics Supporting Research and Technology (SR&T) program. The growing over subscription to the SR&T program indicates that the available funding is falling below the community's needs. The GRAPWG recommends that the SR&T funding level be increased and/or other funding be found, such as through the Advanced Technology (ATD) program.

The GRAPWG views NASA's balloon program as highly successful and essential for the continuing vitality of our field. The importance of the program is increasing as faster space flight opportunities like SMEX and MIDEX require fully proven technology. The program also continues to be an avenue for scientific research. Enhancements to the program, like long-duration capability, are encouraged.

8.3.2 DATA ANALYSIS AND THEORY

The current revolution in our understanding of the high-energy sky is the result of detailed data analysis and theoretical study of the data from the new missions. Much of the recent progress in understanding energetic continuum sources has resulted from a careful comparison of data from many missions, with support from ground-based studies. The GRAPWG recommends support for such correlative studies in the MO&DA and Astrophysics Data Programs. Because multiwavelength investigations often require years to assemble the key data, the Long-Term Space Astrophysics Research Program has particular relevance to high-energy investigations. Further, in view of the many outstanding puzzles in the gamma-ray regime, vigorous fundamental study of exotic high-energy sources remains essential. The Astrophysics Theory Program provides the primary support for these investigations.

8.3.3 TEV ASTRONOMY

An important extension to high energy gamma-ray studies is provided by ground-based observations in the TeV range. The current energy threshold of ~0.1 TeV could be lowered into the 10's of GeV range for critical overlap with a future high energy space mission if new proposed telescopes are funded. An example of the science possible with such broad band coverage is the study of the intergalactic infrared radiation density via measurements of cut offs in AGN spectra due to photon-photon (gamma-IR) pair production. The GRAPWG strongly endorses the development of new telescopes for TeV astronomy.

Investment in the operation and improvement of ground-based (atmospheric Cherenkov) gamma-ray observatories by the appropriate funding agencies (U.S. Department of Energy, National Science Foundation, Smithsonian Institution) should proceed with the aim of having a third-generation telescope in operation by the launch date of the High-Energy Intermediate Mission (see section 8.1.1).

8.4 NEW TECHNOLOGIES

New detector and imaging technologies promise to revolutionize the field of hard X-ray and gamma-ray astronomy. They offer significant improvements in performance over existing hardware while being lower in cost. Some of these are mature developments that are near flight readiness while others are showing promise in the lab but still need significant development. A vigorous program of research and development is essential to bring these technologies to fruition. The technologies needed to support the recommended new missions include the following:

- Detectors for tracking electrons and positrons in pair telescopes. Examples are strip detectors, gas microstrips, and scintillation fibers. These offer better position resolution than spark chambers and have much longer lifetimes.
- Mirrors with multilayer coatings that extend focusing optics into the 10-100 keV range. Alternating layers of low- and high-atomic number coatings on X-ray mirrors can

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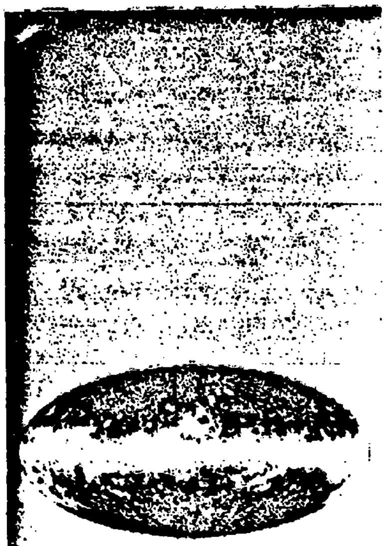
focus photons up to ~100 keV. With image concentration onto a position sensitive detector, the detector and sky background for a point source of interest can be negligible, allowing much deeper observations than the current background-limited instruments.

- **Liquid and high-pressure-gas detectors for keV through MeV astronomy.** The high density and atomic number of Xe offers good stopping power. Large volume liquid time projection chambers with finely segmented electrodes for high spatial resolution are feasible. They combine high detection efficiency with good energy resolution and three-dimensional imaging.
- **Cadmium zinc telluride detectors for hard X-ray astronomy.** The high density and atomic number of CdZnTe give good stopping power, and the large band gap allows room temperature operation. Large-area arrays can be easily and inexpensively implemented. Fine segmentation of the electrodes can give high spatial resolution.
- **Germanium detectors with finely segmented electrodes.** These detectors must be cryogenically cooled, but offer the best energy resolution of existing mature technologies and now can also have high spatial resolution.
- **Very Large Scale Integration (VLSI) of custom low-power analog circuits.** These devices enable detector systems utilizing millions of signal channels. Such systems are components of several of the recommended new missions.



Appendix 1: ACRONYM LIST

BASIS - Burst Arc Second Imaging and Spectroscopy. Selected concept study for gamma-ray bursts. MIDEX/SMEX class.

BATSE - Burst and Transient Source Experiment on CGRO. Gamma-ray burst instrument and all-sky monitor. Energy range is 0.02-1 MeV.

BeppoSAX - launched in April 1996 and named in honor of Giuseppe Occhiallini, Satellite per Astronomia X, is a broad-band, X-ray mission featuring 4 instruments covering the energy range from 0.1-200 keV.

BLAST - Burst Locations with an Arc Second Telescope. MIDEX proposal.

CANGAROO - Collaboration between Australia and Nippon for a Gamma-Ray Observatory in the Outback. Features a pair of currently operating southern hemisphere air Cherenkov detectors.

CATSAT - Cooperative Astrophysics and Technology SATellite. A gamma-ray burst experiment utilizing several instruments and intended to measure among other things, the soft x-ray spectrum in order to address the GRB burst distance scale. A project of the Student Explorer Demonstration Initiative program.

CELESTE - CErenkov Low Energy Sampling & Timing Experiment. A proposed air Cherenkov instrument which would operate in the 20-300 GeV range.

COMPTEL - Imaging Compton Telescope on CGRO. Wide-field (~1 sr) imaging instrument. Energy range: 1 - 30 MeV.

CGRO - Compton Gamma Ray Observatory. NASA Great Observatory for 15 keV to 30 GeV astronomy. Four instruments onboard are BATSE, OSSE, COMPTEL, and EGRET. Launched in 1991.

EGRET - Energetic Gamma Ray Experiment Telescope on CGRO. Wide-field (~0.6 sr) imaging instrument. Energy range: 0.02 - 30 GeV.

ESA - European Space Agency. An organization of 14 member states which promotes space research and technology.

ETA - Energetic Transient Array. Selected concept study for gamma-ray bursts. MIDEX/SMEX class.

EXIST - Energetic X-ray Imaging Survey Telescope. Selected concept study for a MIDEX class hard X-ray all-sky survey.

GLAST - Gamma-ray Large Area Space Telescope. Selected concept study for high-energy gamma-ray astronomy from 10 MeV - 100 GeV. Intermediate class.

GRANAT - Russian mission with French gamma-ray instrument (SIGMA). SIGMA images with ~10 arcmin resolution in 0.04-1.3 MeV range.

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GRAPWG - Gamma Ray Astronomy Program Working Group. NASA committee.

GRIS - Gamma-Ray Imaging Spectrometer. A high-energy Ge spectroscopy experiment. Flown on 9 balloon flights since 1988.

HEGRA - High Energy Gamma Ray Astronomy. A collaboration of mainly German institutions, operating an eventual array of 5 individual telescopes with two currently in place.

HETE - High-Energy Transient Experiment. NASA small mission designed for multiwavelength studies of gamma-ray bursts. Initial launch failed December 1996, possible reflight in 1999.

HEXTE - High-Energy X-ray Timing Experiment. The high energy 15-250 keV instrument onboard RXTE.

HTXS - High Throughput X-ray Spectroscopy. Mission concept for high-resolution X-ray spectroscopy and hard X-ray (5 - 50 keV) imaging. Incorporates the NGXO, LAXSM, and HXT concepts. Intermediate Class.

INTEGRAL - International Gamma Ray Astrophysics Laboratory. ESA observatory designed for fine spectroscopy ($E/\Delta E = 500$) and accurate imaging (~10 arcmin) in the 15 keV to 10 MeV range. Two main instruments onboard: spectrometer which employs high-spectral-resolution Ge detectors and imager which employs high-spatial-resolution CdTe and CsI detector. Launch scheduled for 2001.

MIDEX - Medium Explorer. NASA program for $70M missions (not including launch). Weight limit is ~1300 kg.

MO&DA - Mission Operations and Data Analysis. NASA program for funding operations and data analysis for flight missions.

OSSE - Oriented Scintillation Spectroscopy Experiment on CGRO. Spectrometer with 4 x 11 deg. field-of-view. Energy range is 0.05-10 MeV.

RXTE - Rossi X-ray Timing Explorer. NASA explorer mission for X-ray timing. Two instruments cover 2-200 keV with narrow (~1°) fields-of-view. One instrument is an all-sky monitor in 2-10 keV band. Launched in 1995.

SMEX - Small Explorer. NASA program for $35M missions (not including launcher). Weight limit is ~500 kg.

SMM - Solar Maximum Mission. Launched in February 1980 and operating till 1989, SMM made hard X-ray and gamma-ray observations of the Sun and other astrophysical sources.

SR&T - Science Research and Technology. The NASA program which handles proposals for technology development.

TGRS - Transient Gamma-Ray Spectrometer. A sensitive Ge spectrometer launched in 1994 aboard the WIND spacecraft.

VERITAS - Very Energetic Radiation Imaging Telescope Array System. A proposed array of 10m optical reflections as a next-generation Air Cerenkov telescope.