Recommended Priorities for NASA'S Gamma Ray Astronomy Program 1999-2013

Report of the Gamma Ray Astronomy Program Working Group June, 1999

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FOREWORD

This document provides a review of the recent discussions of the Gamma-Ray Astronomy Program Working Group (GRAPWG). The GRAPWG is an ad-hoc committee formed by NASA to provide recommendations about the future of gamma-ray astrophysics. More information on the GRAPWG can be found at http://universe.gsfc.nasa.gov/grapwg.html.

This publication updates the original GRAPWG report published in 1997. Based on that input and others, NASA created a Strategic Plan in 1998. In it were two missions of particular interest to high-energy astrophysics and gamma-ray astronomy: The Gamma Ray Large Area Space Telescope (GLAST) and a Hard X-ray Telescope (HXT) on Constellation-X. The charge for the current meetings of the GRAPWG was to look at gamma-ray science opportunities beyond those two major missions and an assumed gamma-ray burst Explorer.

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EXECUTIVE SUMMARY

The time is ripe for new initiatives and missions in gamma-ray astronomy. The results from the current missions, CGRO, RXTE and BeppoSAX, have stimulated tremendous interest in the field and have demonstrated the importance of hard X-ray and gamma-ray observations to our understanding of the universe. Looking ahead to the next decade, further discoveries are expected from these missions and from ESA's INTEGRAL mission (launch in 2001). However, there are currently no future approved missions beyond INTEGRAL to advance the field. With this in mind the GRAPWG made recommendations in 1997 (GRAPWG Report; April 1997) for instruments to fly in the 2000 to 2010 time frame. We are delighted that some of the recommended missions are now part of NASA's Office of Space Science strategic plan. With NASA in the process of updating that plan, we have reassessed and expanded on our recommendations and present this update.

1997 GRAPWG MISSIONS

In the previous GRAPWG report, the top-priority was given to the GLAST high energy gamma-ray mission to follow on the discoveries of the EGRET instrument on CGRO. Other high priority missions were a focusing hard X-ray telescope and a next-generation nuclear line and MeV continuum mission. For Explorer-class missions the top scientific opportunities were found to be for gamma-ray burst observations and hard X-ray surveys. Some of these missions have now been started by NASA: GLAST is in the OSS strategic plan for new start in 2002; the Swift gamma-ray burst MIDEX has been selected for Phase A study with final selection of two missions to fly out of five studies to be made in September 1999. Also, the OSS strategic plan contains the top mission of the X-ray community, Constellation X, which has a focusing hard X-ray telescope (HXT) onboard that achieves some of the objectives identified by the GRAPWG for a focusing hard X-ray mission.

The GRAPWG finds that the scientific case for GLAST, Constellation-X HXT and Swift has grown since 1997. The GRAPWG continues to give its STRONGEST ENDORSEMENT to these mission, which are the backbone of NASA's future program in hard X-ray and gamma-ray astronomy.

1999 SCIENCE PRIORITIES

The GRAPWG identifies the following PRIORITIZED list to be the most compelling science topics that future hard X-ray and gamma-ray missions can address beyond those covered by GLAST, Constellation-X HXT and Swift. These are areas in which hard X-ray and gamma-ray astronomy offers unique capabilities for advancing our understanding of the universe. Each science topic is followed by a list of areas in which key contributions are expected.

The HIGHEST PRIORITY science topic is:

1) Nuclear Astrophysics and Sites of Gamma Ray Line Emission

Gamma-ray astronomy holds the promise of revolutionizing studies of nucleosynthesis in our galaxy and beyond. Through the detection of nuclear lines, sites of nucleosynthesis can be studied and elemental abundances can be measured. In addition, the configuration and dynamics of the emitting gas can be determined. Topics for future missions include:

- Abundance yields of explosive nucleosynthesis
- Mass cut between SN ejecta and core
- Supernova and nova explosion physics and dynamics
- Sites of nucleosynthesis in the Galaxy and universe
- Cosmic nucleosynthesis rate from redshifted SN Ia lines
- Supernova rate in the Galaxy
- Better understanding of SN Ia cosmological distance scale calibration
- Cosmic ray interactions with interstellar gas
- Positron diagnostics of compact objects

Other high priority topics are:

2) Gamma Ray Bursts

Appropriate to their nature, gamma-ray burst studies continue to change quickly and dramatically. The increasing number of counterparts at lower energies when coupled with the impressive BATSE database are leading to a new era in GRB studies. Aside from the intrinsic astrophysics of GRB's, bursts will become an important probe of the early universe. Topics for future missions include:

- Links to star formation
- Evolution and populations of massive stars
- Possible sites of black hole formation
- New GRB populations and mechanisms
- Probes of dusty matter in distant galaxies
- Probes of the intergalactic medium out to high redshift

3) Hard X-ray Emission from Accreting Black Holes and Neutron Stars

Hard X-ray and gamma-ray studies of accreting sources are becoming increasingly critical for full understanding of these objects. Detections of galactic and extragalactic black hole systems at high energies provide a laboratory for studying black holes across a wide range of masses. Topics for future missions include:

- First population study of absorbed Seyfert 2's
- Constraints on blazar spectra and diffuse IR background
- Non-thermal components in galactic transients
- Jets associated with galactic BH's and AGN
- Black hole parameters (spin, mass)
- Accretion physics

4) Medium Energy (500 keV–30 MeV) Emissions

Distinct from nuclear lines, the continuum emission in the medium energy range has been shown to be important for understanding nonthermal emission from objects such as pulsars and AGN and sites of cosmic ray interaction with gas. This relatively unexplored band ties together studies at MeV and GeV energies. Topics for future missions include:

- Search for MeV blazars and spectral studies to understand emission
- Pulsar physics through broad-band spectral studies
- Components of diffuse galactic emission
- Extragalactic diffuse emission in poorly measured MeV band
- Nonthermal components from accretion-driven sources
- Cosmic ray interactions with the ISM

1999 MISSION RECOMMENDATIONS

Figure 1 shows the mission roadmap that the GRAPWG has developed for hard X-ray and gamma-ray astronomy. In addition to the three missions mentioned above, the GRAPWG finds three near-term missions and two long-term concepts to be the most exciting for addressing our top-priority science topics. These are as follows.

Advanced Compton Telescope (ACT)

The HIGHEST PRIORITY major mission recommended by the GRAPWG is ACT, a high-technology MeV line and continuum Compton telescope mission operating in the 500 keV to 30 MeV range. With a factor of 30 improvement in sensitivity compared to CGRO and INTEGRAL, it promises detailed studies of sites of nucleosynthesis in the universe and a deep survey of continuum sources. The optimum configuration of large imaging detector arrays based on either semiconductor or high density rare gases is being studied to enable a mission in this challenging energy band. The mission addresses science areas (1), (2) and (4) in the above list.

Two other high-priority missions are of particular interest in the coming decade for accomplishing our science goals.

High-resolution Spectroscopic Imager (HSI)

A high priority intermediate or enhanced MIDEX class mission recommended by the GRAPWG is HSI, a focusing optics telescope operating in the 10 to 170 keV range. With a factor of 100 improvement in sensitivity compared to RXTE, this mission will answer key questions on the nature of accretion onto neutron stars and black holes and will allow detailed studies of sites of nucleosynthesis in the universe. New multilayer mirror technology will enable the upper energy bound of the mirrors to be as high as 200 keV. The mission addresses science areas (1) and (3).

Energetic X-ray Imaging Survey Telescope (EXIST)

A high priority intermediate or enhanced MIDEX class mission recommended by the GRAPWG is EXIST. Factor 100–1000 improvement in sensitivity compared to the only previous all-sky hard X-ray survey (HEAO-1) will allow discovery of the predicted, but so-far unobserved, class of absorbed Seyfert 2's that are thought to make up at least half of the total inventory of AGN's. A large area array of new-technology solid state detectors, used in conjunction with a wide field-of-view coded aperture, will cover the 5–600 keV region and address science areas (2) and (3) as well as significant portions of (1). The International Space Station is a possible platform for such an instrument.

Complementing these missions will be projects which will extend and improve upon those already in the strategic plan.

Next Generation Gamma-Ray Burst mission (NGGRB)

The GRAPWG believes that gamma-ray bursts will continue to be one of the most important and fascinating areas of astronomical research for tens of years to come. A mission will be needed in the post HETE-II and Swift era to further this field. Emphasis in that time frame may involve observations of nonelectromagnetic radiation such as gravitational waves and neutrinos and will certainly involve multiwavelength electromagnetic instrumentation. To correlate these data with known properties of bursts and to monitor the sky for infrequent special events, it will be essential to have a continuous gamma-ray burst monitor in space. The GRAPWG recommends that such a mission, NGGRB, be identified in NASA's program.

Next Generation High-Energy Gamma-ray mission (NGHEG)

The discoveries of GLAST will produce strong interest in the astronomical community in high energy gamma-ray phenomena and will undoubtedly raise new fundamental questions. The band width of the high energy range is huge, from 30 MeV to 300 GeV, and overlaps with the growing number of very high energy (TeV and PeV) ground-based observatories. The GRAPWG recommends that a mission called NGHEG be identified in NASA's program to follow on GLAST.

GAMMA-RAY BURSTS

The GRAPWG is particularly intrigued by the gamma-ray burst problem and the promise that bursts offer for fundamental studies in astrophysics. There are multifaceted implications that bursts have on many future missions. Below are listed some topics and recommendations on gamma-ray burst astronomy. The GRAPWG recommends that:

- HETE-II should be flown on schedule.
- The Swift GRB MIDEX mission, now in Phase A, should have high priority for flight.
- Support should continue for the Interplanetary Network as an effective means for deriving arcminute GRB locations.
- Support should continue for BATSE and the Gamma-ray burst Coordinate Network (GCN).
- The GRB monitor currently planned for GLAST will greatly enhance its GRB capabilities.
- Synergism between space-borne GeV GRB observations and ground-base TeV observations should be recognized and exploited.
- A global network of small, dedicated GRB robotic telescopes should be developed.
- It is highly desirable to establish a network of coordinated 1–3m telescopes to monitor light-curves and (for the brightest events) spectra over the first few days.

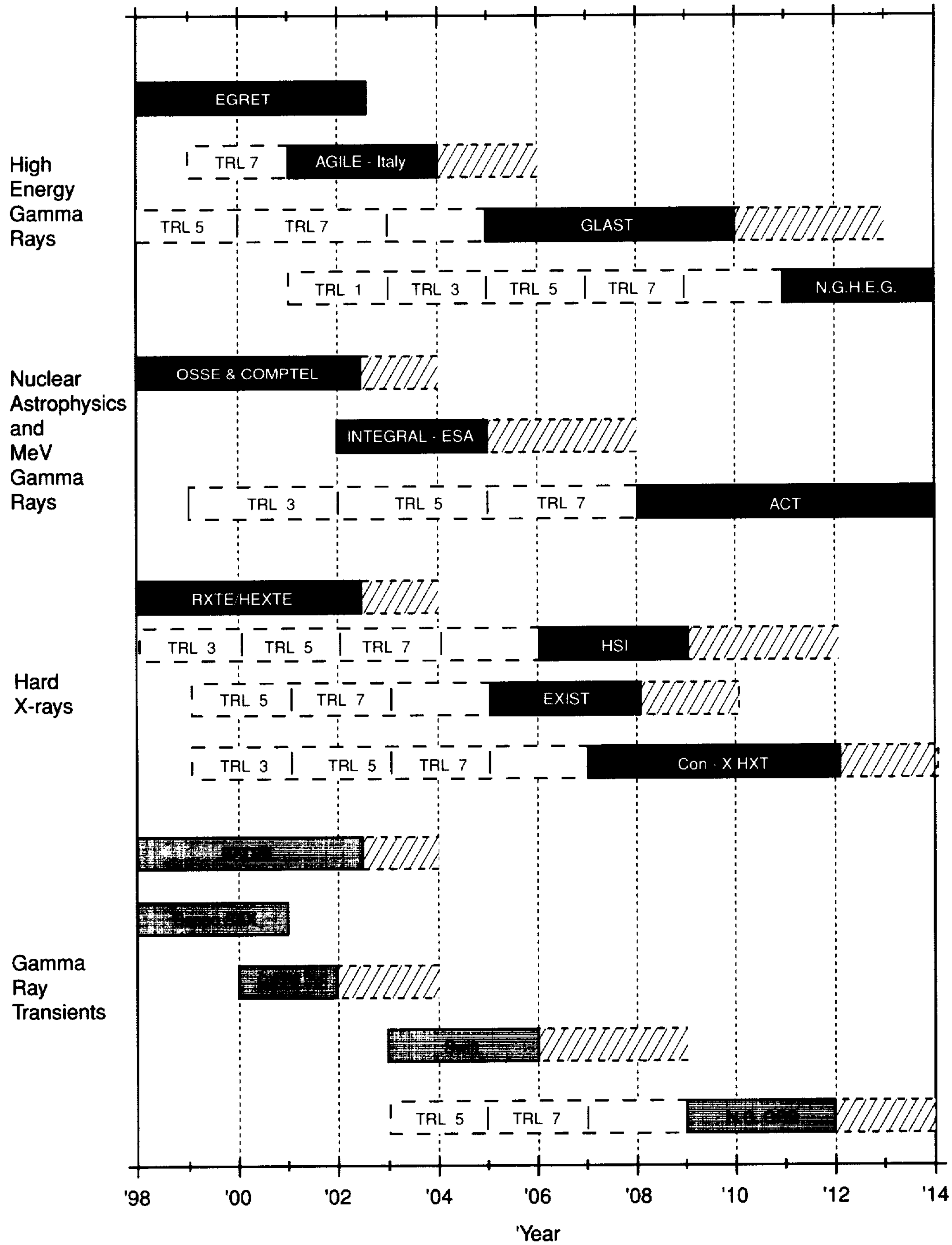
- Time on major ground- and space-based observatories should continue to be provided for GRB follow-up observations.

OTHER RECOMMENDATIONS

Gamma-ray astrophysics is a broad enterprise covering many efforts. The GRAPWG recommends that the following items receive special consideration:

- Technology Development: Many exciting new technologies are arising in gamma-ray astronomy, including multilayer mirrors, Laue lenses (Bragg concentrators), complex coded masks, solid-state pixel and strip detectors, rare gas and liquid detectors, and VLSI electronics. These form the backbone and future of our field. The GRAPWG strongly recommends a vigorous program of technology development for hard X-ray and gamma-ray astronomy.
- TeV Astronomy: Aside from their independent successes, ground-based observatories will provide an important complement to future high energy gamma-ray missions such as GLAST. The GRAPWG endorses the continued development of TeV telescopes with low energy thresholds.
- Balloon Program: The ultra-long duration balloon (ULDB) program offers great potential for both instrument development and significant science in gamma-ray astronomy. The GRAPWG recommends strong NASA support for LDB's and ULDB's.
- International Space Station: The GRAPWG views the ISS as an opportunity for hard X-ray and gamma-ray research. It is particularly well suited for wide-field instruments and long-term monitors.
- Optical Telescope Support: Many areas of gamma-ray astronomy research, particularly gamma-ray bursts and AGN studies, benefit from a multiwavelength approach. In particular, optical telescopes can provide important monitoring capabilities which are difficult to achieve at other wavelengths. The development of a network of optical telescopes capable of near-continuous observation of gamma-ray transients is supported by the GRAPWG.
- Data Analysis and Theory: Making the most of the rich databases expected from future missions is an important concern of the GRAPWG. Adequate support for data analysis and theory is a cost effective way of maximizing the return from current and future experiments.

Gamma Ray Astronomy Roadmap



CHAPTER 1

The Role of Gamma-Ray Astrophysics

The place of gamma-ray measurements in astrophysics underwent a fundamental change in the Compton Gamma-Ray Observatory (CGRO) era. In the field's infancy, attention focused on the penetrating power of cosmic gamma rays and their production in familiar processes, especially radionuclide decay. Experimental techniques in the PI-class missions of the 70's and 80's drew heavily from high-energy physics programs of the previous decades. A principal goal was a "discovery" level opening of the MeV-GeV electromagnetic spectrum, adopting established high-energy techniques. Missions focused on identifying the source of 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 providing this 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. Moreover, the CGRO era has moved gamma-ray astronomy to a central role in mainstream astrophysics. Several of the most puzzling phenomena of modern astrophysics figure prominently in the gamma-ray band. The strong guest investigator program of CGRO and the wide participation in follow-on programs at other wavelengths underlines the impact of gamma-ray studies on a range of astrophysical problems. We can best illustrate this impact by summarizing a few key problems brought to light by CGRO observations and a few new scientific directions inspired by such results. More complete descriptions can be found in chapter 2.

Gamma-Ray Bursts

Before 1991, descriptions of the gamma-ray burst problem acknowledged the wide range of feasible models, but focused with increasing confidence on models producing bursts from a nearby population of galactic neutron stars. In a dramatic development, the presentation of the initial BATSE spatial and flux distributions at the 1st Compton Symposium abruptly overturned established think-

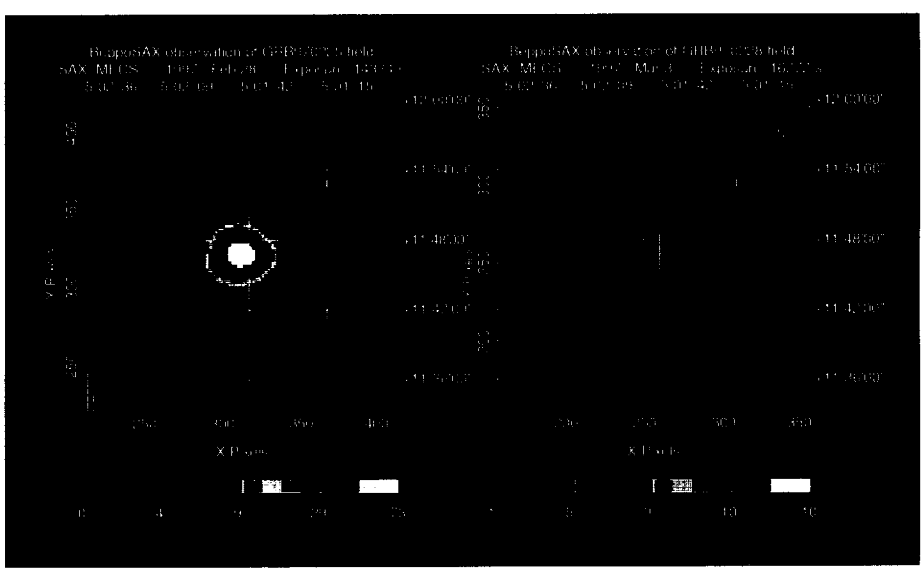


Figure 1.1. This BeppoSax observation of GRB 970228 detected the first ever fading X-ray source in a GRB error box.

ing and gave strong support to the idea that bursts represent titanic energy releases at cosmological distances. This paradigm was confirmed with the detection of X-ray, optical and radio counterparts in 1997/1998 and the measurement of several cosmological redshifts (see Table 2.1). One should remember, though, that these results only intensify the burst puzzle from a physicist's perspective — how is a supernova's worth of energy released in a highly relativistic form and how does this process give rise to the great variety of gamma-ray burst time structures and spectral shapes? 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.

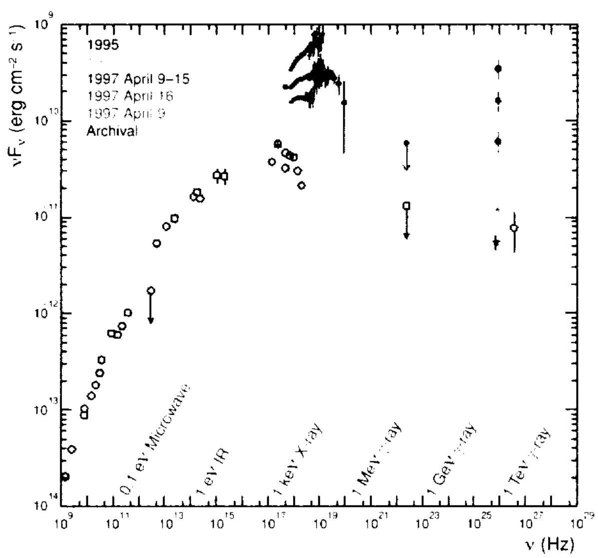


Figure 1.2. Gamma-ray observations such as those shown here for MRK 501 have become an integral part of multiwavelength monitoring of AGN.

Accreting Black Holes

Another important result of the CGRO mission has been the observation of strong, non-thermal emission associated with jet sources. A spectacular example is the detection of nearly 100 "blazars" by the EGRET experiment, often with rapid flux variations and hard photon spectra extending above a GeV. Several 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 underscoring the important connections of ground-based studies with gamma-ray observations. Related discoveries have resulted from BATSE monitoring of X-ray outbursts along the galactic plane. Several sources show hard spectral tails extending to roughly an MeV. Some sources showing strong outburst activity, such as GRS 1915+105 and GRO J1655-40, were recently discovered to show evidence of relativistic jet outflows in the radio band. These observations suggest that non-thermal emission, starting in the hard X-ray/soft gamma-ray and extending to TeV energies, is closely connected with the formation of relativistic jets. Study of the high energy emissions, especially in correlation with multiwavelength variability, promise to provide important new insights into the physics of the 'central engines', the accreting black holes believed to be the core of AGN and these transient Galactic X-ray sources. Hard X-ray observations have now shown the excess of obscured AGN and may provide the most direct way to inventory the stellar black hole content (in X-ray transients) in the Galaxy.

Unidentified Sources

When a new wavelength range is opened, it is most exciting 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 population of Galactic sources not identified with previously known objects. CGRO, with improved sensitivity, energy resolution and background modeling has surveyed this population. Of the 169 objects detected, 79 are located within 10 degrees of the galactic plane. Since Geminga, the brightest of these sources, is now 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.

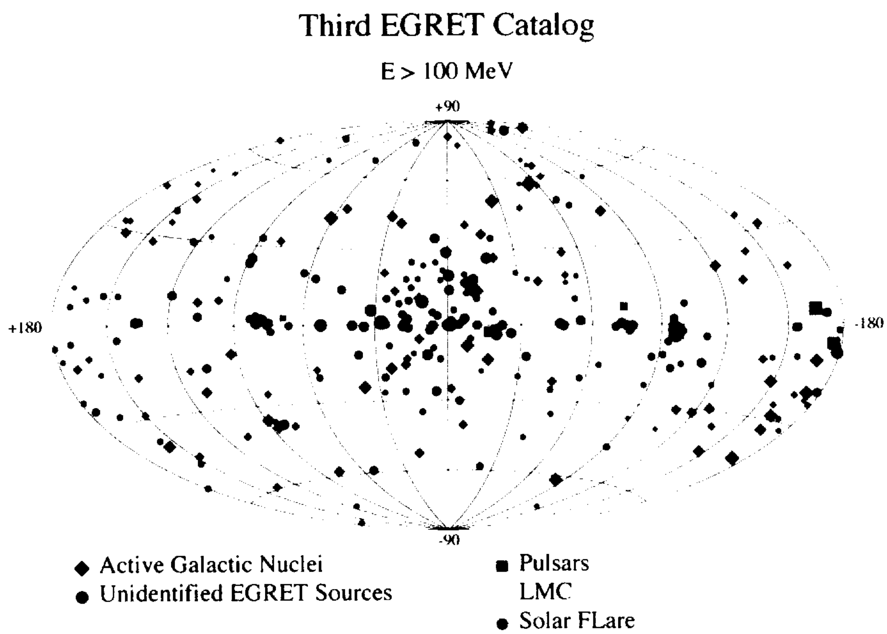


Figure 1.3. Sources from the 3rd EGRET catalog. One of the most obvious features continues to be the large number (169) of unidentified sources.

Nucleosynthesis

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}A1 mapped by COMPTEL (see Figure 2.2) 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 Vela (Figure 2.1) implies substantial synthesis of ^{56}Ni. This makes the low luminosity of this Type II supernova event a mystery. 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.

New Directions

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 non-thermal spectra. Thus, we can hypothesize that the perfectly absorbing boundary of an accreting black hole is central to the formation of an optically thin electron population responsible for the hard X-ray mission and possibly to the acceleration of relativistic jets. Thus the gamma-ray regime provides a unique window on this problem. A second arena where gamma rays draw our attention to the most exotic sources lies in the mult-GeV emission of gamma-ray bursts. CGRO sensitivity limited detection of this emission to a handful of the brightest bursts, but it may be a common feature of the burst process. Conditions required for the production of this multi-GeV flux, which in some cases may dominate the total burst energy, are extreme. We may 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 the familiar radio pulsar emission is a small fraction of the bolometric photon luminosity: the power spectrum of their photon emission peaks in the GeV range for many young pulsars. A final example illustrates the ability of new gamma-ray data to address fundamental problems in mainstream astrophysics. The detection of several nearby AGNs by ground-based air Cerenkov telescopes with ~300 GeV thresholds shows 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, measurements of absorption of the GeV-TeV spectrum may be used to 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.

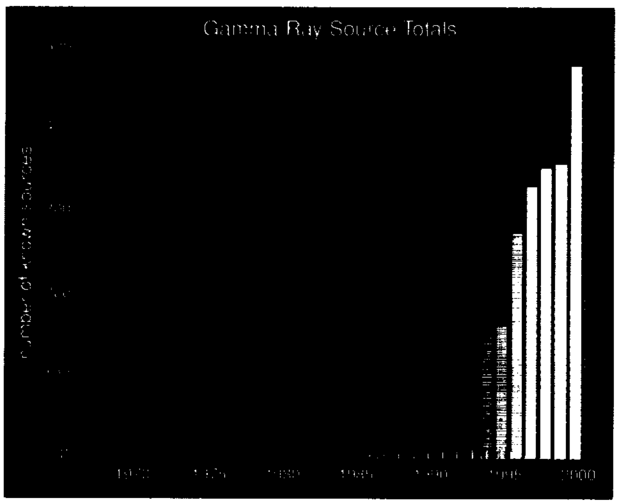


Figure 1.4. The number of known gamma-ray point sources (detected at energies above 50 keV) during the 30-year history of gamma-ray astronomy through early 1999.

While there are great opportunities for future gamma-ray discoveries, the prospects in many other areas of astrophysics are strong as well. It is therefore important to highlight the unique potential of gamma-ray observations. 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 novel technology greatly advancing our observational capabilites, gamma-ray astronomy will continue to provide new physics insight by probing the most exotic objects in the universe. The opportunities for this field over the next decade and a half are particularly exciting.

CHAPTER 2

Scientific Objectives

The legacy of the past and current generation of gamma-ray missions is a diverse and compelling picture of the high-energy universe. From Solar physics to the endpoints of stellar evolution, from the diffuse glow of the Milky Way to the extragalactic diffuse emission, gamma-ray observations continue to make fundamental contributions. This chapter describes the status and direction of gamma-ray research for all of these topics.

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 comparable to 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 ~0.6 M_0 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} ergs 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 4 times less ^{56}Ni than Type Ia, but expand almost as rapidly. Thus their signal is intermediate between Types II and Ia, about 5×10^{-6} (10 Mpc/D)^2 photons cm^{-2} s^{-1} and the lines are a little narrower. Thus a mission having broad line sensitivity of a few times 10^{-6} photons cm^{-2} s^{-1} might detect an extragalactic Type Ib supernova during a mission lifetime of several years. 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.

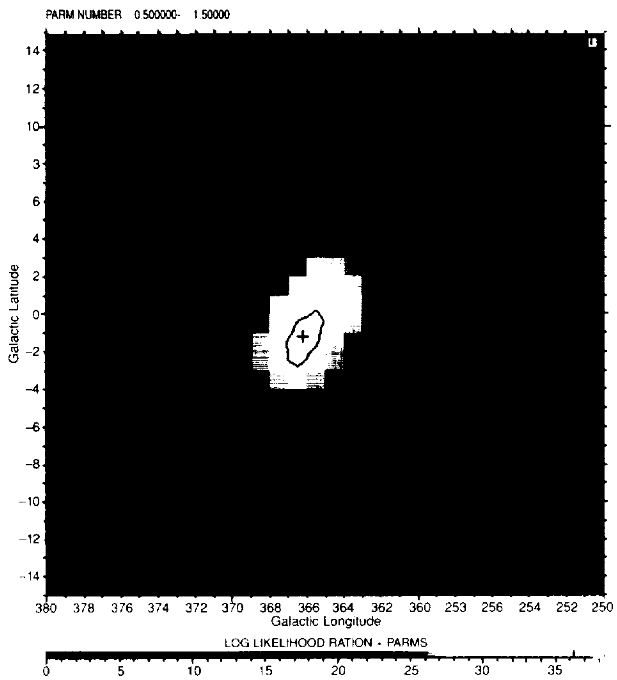


Figure 2.1. COMPTEL detection of 1.157 MeV ^{44}Ti line emission from Vela.

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 2×10^{-4} M_O. 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), which makes detection of this isotope very interesting. COMPTEL has reported the detection of the 1.157 MeV line from the ^{44}Ti–^{44}Sc decay from the Galactic supernova remnants, Cas A and Vela (Figure 2.1). For Cas A, using current estimates of the distance and a new half-life determination for ^{44}Ti, the implied yield is about 2×10^{-4} M_O, 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 ~0.5×10^{-4} M_O of ^{44}Ti (highly uncertain) implying a flux for the next few decades of about 2×10^{-6} cm^{-2} s^{-1}. A deep galactic plane survey for obscured SNR using the hard x-ray (68, 78 keV) lines from ^{44}Ti will provide important new constraints on the SNR rate in the Galaxy with its implications for both galactic nucleosysthesis and the pulsar birthrate problem.

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-ray 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

Among the several windows we have on star formation, evolution, and death, and the associated generation of the elements, gamma-ray spectroscopy provides unique information. Nature provides us with radioactive tracers of current nucleosynthesis across the entire Galaxy. This gives insight into the global star formation rate and the mass spectrum of stars, especially at the massive end. As we can see the production of specific isotopes, we are in effect looking right into the zones of stars where they are produced.

The prototype isotope for these studies is ^{26}Al (mean lifetime 1.1 My.) We see a million-year snapshot of core-collapse supernovae (and their massive star progenitors; how much each produces will be clear only with better observations) across the Milky Way. It traces the thin disk with apparent enhancements in nearby regions of increased activity, possibly the Galaxy's spiral arms. A handful of individual objects are close enough that we can already begin to assess their nucleosynthesis yields directly. The Large Magellanic Cloud might be detectable to a mission having narrow line sensitivity better than 10^{-6} cm^{-2} s^{-1} in a field of view that encompassed the LMC. At 10^{-7} cm^{-2} s^{-1} one might even begin to see ^{60}Fe in the LMC and ^{26}Al in the SMC.

From some of the same regions where ^{26}Al is produced, and probably different sites as well, we also expect observable quantities of ^{60}Fe (mean lifetime 2.2 My). This will not only clarify core-collapse supernova nucleosynthesis but also possibly teach us how the nuclear flame begins in thermonuclear explosions of white dwarfs.

Another bright line, at 511 keV from electron-positron annihilation, also appears to trace disk nucleosynthesis of at least a few isotopes, including ^{26}Al, ^{44}Ti, and ^{56}Ni. It is additionally very bright from the Galaxy's central region, roughly tracing the nuclear bulge. How much of this is from radioactive decay or compact objects such as pulsars and black hole binaries, especially those with jets, will be determined only with more and better data.

The potential of these types of observations remains unrealized mainly because of the limited sensitivity and spatial resolution of current instruments. With much improved sensitivity and good spatial resolution, some of these "diffuse" emissions would resolve into individual massive stars, supernova remnants, star clusters, and associations. We would gain unprecedented understanding of each, seeing perhaps the variation of nucleosynthesis yields, explosion dynamics, and the efficiency of massive star formation, as well as their mean values. We could hope to see relic emission of past starburst episodes at the Galactic center. The detection of point sources of positron annihilation radiation would clue us in to the contributions of those sources to the diffuse emission as well as to the nature of their central engines.

Some of these objectives will be addressed by the forthcoming INTEGRAL spectrometer SPI, but not most. Its coded-mask technique is optimized for point sources, so its sensitivity to extended sources degrades rapidly with source extent. It will study well the brightest concentrations of ^{26}Al emission and probe the physics of the central Galaxy's positron annihilation medium with its good energy resolution, but it will be hard pressed to detect ^{60}Fe unless its distribution has sharp peaks.

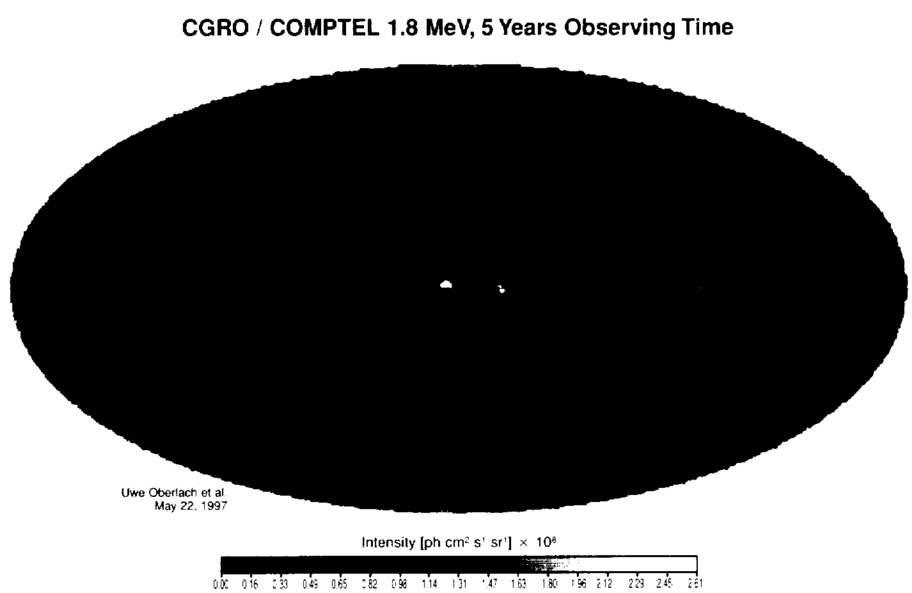


Figure 2.2. The intensity of ^{26}Al emission as observed with COMPTEL shows interesting structure along the galactic plane.

2.1.3 Interstellar Processes

The detection of nuclear de-excitation lines, such as those at 4.44 and 6.13 MeV from excited states in ^{12}C and ^{16}O, produced by accelerated particle interactions with interstellar gas and dust can provide the first direct measure of the intensity of low energy cosmic rays in the Galaxy. Such particles with energies < 100 Mev/nucleon could make a significant contribution to the galactic nucleosynthesis of the light elements, Li, Be and B, but these low energy particles can not be detected in the inner solar system because they are excluded by the solar wind. Thus a search for nuclear de-excitation lines both from the diffuse interstellar gas and from star formation regions around giant molecular clouds can provide unique information on the intensity, spectrum and spatial distribution of cosmic rays at low energy, and offer clues to their origin and acceleration. The reported discovery by

COMPTEL of such gamma-ray emission lines from the Orion giant molecular cloud complex has turned out to be only an artifact of the data analysis. However, the announcement reawakened awareness of the importance of such measurements and demonstrated the need for new observations with much more sensitive detectors than those planned for the near future.

The galactic diffuse gamma-ray continuum emission is the dominant feature of the high-energy (> 10 MeV) gamma-ray sky. This 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.

Nucleosynthesis Objectives:

- Measure gamma-ray line emission from nearby extra-galactic supernovae.
- Search for nuclear de-excitation lines from both the diffuse interstellar medium and from star formation regions in the galaxy to determine the intensity, extent and origin of low energy cosmic rays and their role in light element production.

Nucleosynthesis Requirements:

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

2.2 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 extending out to beyond 100–200 keV, with transient broad and redshifted 511 keV line emission reported for at least one system (Nova Muscae 91). 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. These similarities are of growing interest as galactic black hole candidates exhibit relativistic outflows of radio emitting matter. Sources such as GRO J1655–40 and GRS 1915+105 which have been detected at energies as high as 800 keV provide a local laboratory for black hole studies.

2.2.2 Accreting Neutron Stars: X-Ray Bursters and Pulsars

In low magnetic field ($B < 10^8$–10^9 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 usually only ~60–100 keV. Spectral measurements to determine the self-similarity of the photon index (typically 2.5–3.0) and cutoff energies are of primary interest for understanding the accretion flows onto these systems (versus black holes).

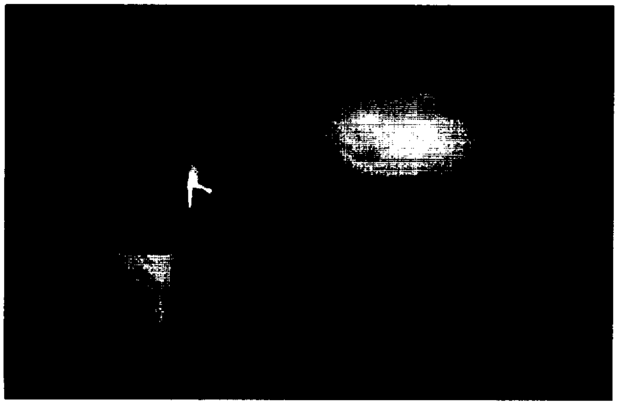


Figure 2.3. Recent CGRO and RXTE observations have provided important insights into accreting binary systems.

Studies of X-ray bursters with BATSE, RXTE and BeppoSAX 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 differences (primarily hard x-ray luminosity) 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 2.4. An artist's view of a magnetar. The superstrong magnetic fields of these objects provide a unique laboratory.

Accreting neutron stars with high magnetic fields 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 ($\sim 10^{14}$ G in the case of GX 1+4). Recent measurements of a cyclotron feature at 110 keV and a possible feature at 55 keV in A 0535+26, implying B $\sim 10^{13}$ 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^{14} 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.

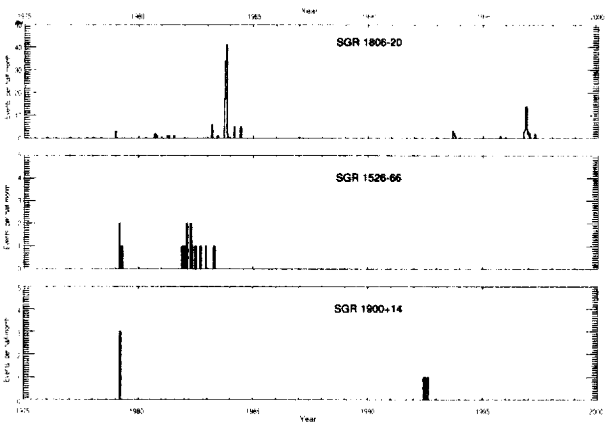


Figure 2.5. The emission history of earliest known SGR's. It is crucial to maintain a hard X-ray monitoring capability to understand these objects.

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 those 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.

A recent triumph in neutron star studies comes from the solution to a long-standing puzzle. The Soft Gamma Repeaters (SGR) are sources of sporadic, varying bursts of hard X-ray emission. The evidence that SGRs are associated with supernova remnants followed by the detection of pulsed emission confirmed the neutron star origin of these sources. For two of the five known SGRs, SGR 1806-20 and SGR 1900+14, detection of pulse periods and spin-down rates allow estimates of magnetic field strengths above 10^{14} G. This establishes the magnetar origin of SGRs. Further observations will reveal what fraction of neutron stars are born as magnetars and explore their relationship to the "anomalous X-ray pulsars". Furthermore, the question of whether SGR's are really being powered by accretion, like the closely related "bursting pulsar", is still open. Not only will neutron star physics benefit from further SGR studies, but the possibility exists that SGR studies may provide insight to the gamma-ray burst mystery

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

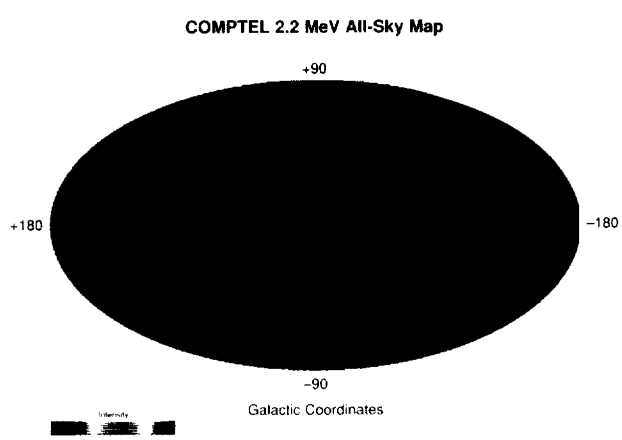


Figure 2.6. This map of 2.2 MeV radiation shows evidence for transient line emission from the white dwarf RE J0317-853..

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. The recent announcement that transient 2.2 MeV line emission was possibly detected by COMPTEL from the strongly magnetized white dwarf, RE J0317-853 could be the beginning of a new era in exploring white dwarfs.

2.2.4 Spin-Down Pulsars

Rotation-powered pulsars — rotating, magnetized neutron stars — are among the brightest persistent sources in the gamma-ray sky, and are among the few sources that have been unambiguously identified in high-energy gamma-rays.

By virtue of their enormous magnetic and gravitational fields coupled with their rapid rotation, pulsars are today well-established, mainly from gamma-ray observations, as being powerful particle accelerators. Pulsars offer a uniquely direct way of being identified with a gamma-ray source, because of their signature pulsations at a predictable pulse period.

Thanks to the successes and timing capabilities of past and present gamma-ray telescopes, today there are certain associations between seven gamma-ray sources and rotation-powered pulsars: the Crab and Vela pulsars, Geminga, PSRs B1055–52, B1509–58, B1706–44, and B1951+32. Tantalizing evidence exists for high-energy gamma-ray pulsations from two more: PSRs B0656+14 and B1046–58.

These identifications have demonstrated that gamma rays hold the key to understanding pulsar emission. The ultimate source of energy for a pulsar is its rotational kinetic energy; gamma-ray observations have proven that pulsars are efficient machines for converting this mechanical energy into non-thermal high-energy gamma-ray photons, with typical conversion efficiencies around 1%, and an efficiency of nearly 10% reported in one case. Understanding how this energy conversion is achieved may well have implications for other astrophysical objects, such as black holes and active galactic nuclei. Yet an understanding of the physics involved has been elusive.

There are two possible locations for the gamma-ray emission regions in pulsars: near the polar cap

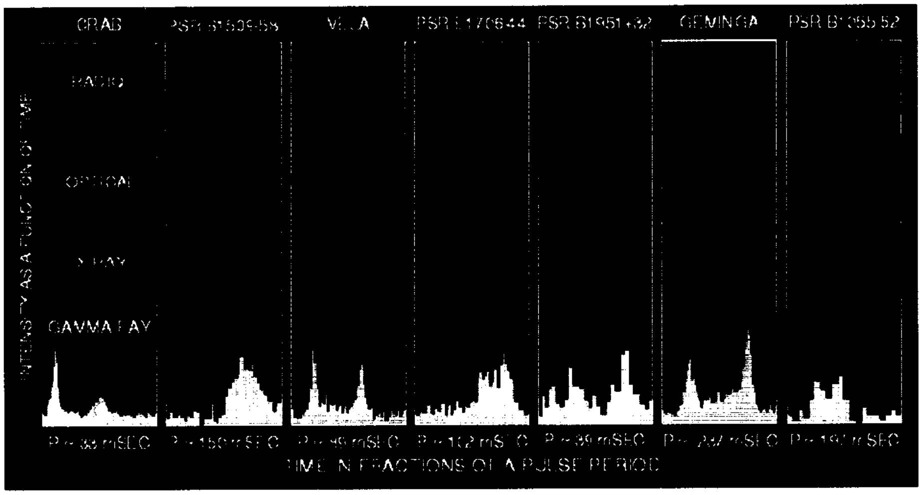


Figure 2.7. These multi-wavelength pulse profiles of the known gamma-ray pulsars show the diverse shapes and energy dependencies which a complete theory of magnetospheric emission must describe.

and in the outer magnetosphere near the light cylinder. Models invoking these different regions predict different high-energy pulse morphologies, spectra, pulse phases as a function of energy, and angular extents of the gamma-ray beams. Though the handful of identified gamma-ray pulsars has placed significant constraints on such models, the issue of where the emission originates has yet to be laid to rest.

Determining which model is correct is important not only for understanding the pulsar emission mechanism, but also because gamma-ray pulsars can provide a window on otherwise 'invisible' pulsars in our Galaxy. Their contribution to the diffuse Galactic gamma-ray emission, their connection to the unidentified EGRET sources (see also Section 2.4), and their total number and hence birth rate in the Galaxy, depend on how many are visible, that is, on their gamma-ray beam size, luminosity and spectrum.

More and more, gamma-ray observations have come to play integral parts of multi-wavelength studies of pulsars. In essence, gamma-ray observations clarify the fate of the spin-down energy and its availability for other processes such as a wind to power synchrotron nebulae, through detection of pulsed and unpulsed emission. For example, the underlying physics of all mechanisms for production of X-rays is ultimately tied to processes that involve gamma-rays in a fundamental way: magnetospheric emission luminosity peaks at gamma-ray energies, and comparisons of X-ray and gamma-ray pulse morphologies, relative pulse phases, and phase-resolved spectra are basic diagnostics; polar cap reheating, a source of soft, thermal X-rays, is likely a result of higher energy processes at higher altitudes that may be responsible for the gamma-ray emission; and pulsar wind nebula emission, which, at least in the Crab nebula (the only one to have yet been studied in significant detail) extends across the electromagnetic spectrum up to TeV energies and signals a population of wind electrons having energies as high as 10^{16} eV.

Aside from the classical pulsar problems, the study of isolated neutron stars in general is undergoing a renaissance, with the realization that these objects can embody even more extreme properties than has been appreciated. In particular, magnetic fields as high as 10^{15} G have been suggested in some unusual sources. Gamma rays are crucial to existing and upcoming multiwavelength efforts to understand generalized isolated neutron star physics, and to unify the population.

The strategy for future observations has been made clear by the foundation laid by past gamma-ray missions. The debate regarding the origin of gamma ray emission in the magnetosphere must be settled by obtaining a significant population of gamma-ray pulsars to study. The gamma-ray properties of pulsar wind nebulae themselves must also be established beyond the single data point of the Crab. The nature of the unidentified Galactic plane gamma ray sources (see also section 2.4) must be better determined, to establish whether they are indeed candidates for young rotation-powered pulsars, and what the implications are for their birth rate. Improvements on the positions will permit searches for either pulsed or unpulsed counterparts at lower energies. Continued monitoring for soft gamma-ray outbursts is necessary for reliable population estimates and magnetar identification.

Significant progress in related areas is being made already and begs for gamma-ray follow-up: in the past year, over 250 new radio pulsars have been discovered in the plane of our Galaxy; many of these sources could be high-energy detectable. In addition, several discoveries of extremely young and energetic pulsars have recently been made at X-ray energies and will be key sources for gamma-ray follow up. Planned radio observatories and X-ray missions will undoubtendly continue to make major neutron-star discoveries whose gamma-ray follow-up is an obvious next logical step; the reverse could easily be true if instrumentation permitted.

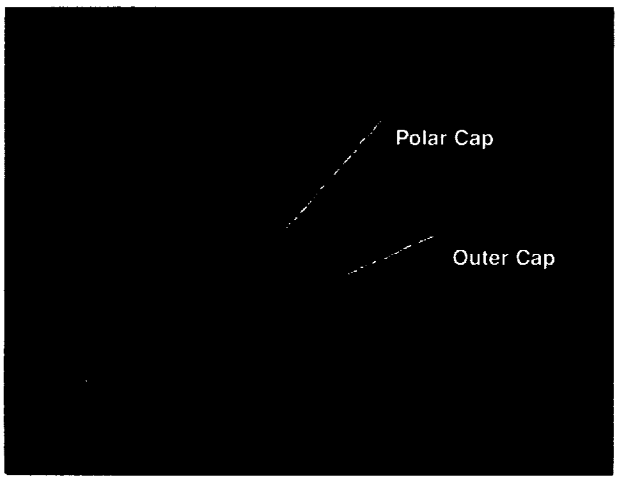


Figure 2.8. *This color coded view of the gamma-ray emission regions of a pulsar magnetosphere shows how the pulse profile can eventually be mapped back to the source. Sensitive tests of emission mechanisms is the result.*

The properties that future gamma-ray instruments must have in order to effectively address the major issues in pulsar and exotic neutron star science are (i) high angular resolution, (ii) large collecting area, and (iii) photon time tagging at the tens of microseconds level. The objectives and requirements for compact object studies are:

Compact Object 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. Constrain the BH population of the Galaxy.
- 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.

Compact Object Requirements:

- Effective area for a high-energy telescope 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, optical/IR, and radio searches for pulsars and black holes in newly discovered transients.
- All-sky monitoring of hard (10–600 keV) X-rays with sensitivity at least two orders of magnitude better than HEAO–1.

2.3 EXTRAGALACTIC ASTROPHYSICS

The Compton Gamma Ray Observatory (CGRO) has contributed substantially to our understanding of Active Galactic Nuclei. Perhaps the most obvious and widely known result is that there are clearly two classes of gamma-ray-emitting AGN in the sky: these are the jet-dominated blazars, and the more ordinary, radio-quiet Seyferts and quasars. The marked differences between the two classes are seen even in the radio and optical data: blazars are dominated by compact, milliarcsecond cores, and the radio and optical emission is strongly polarized. The compact radio cores show superluminal expansion. With the rapid and large-amplitude variability observed in the GeV gamma rays, we now think that the entire emission arises in a jet pointing close to the line of sight, where the emission is strongly enhanced due to the relativistic Doppler effect. The radio and optical emissions are most likely due to the synchrotron process, while the hard X-rays and gamma rays are due to Comptonization, of either the internal synchrotron radiation, or photons external to the jet. The blazar luminosity often peaks in the gamma-ray band above 1 MeV and all CGRO instruments have detected the high energy emissions from several blazars. In the case of radio quiet objects, the overall electromagnetic spectra are quite different. Within the current sensitivity, these spectra do not extend beyond a few hundred keV. Instead, they appear to cut off, such that there are no observed photons at or beyond the 511 keV annihilation line. In many cases, the hard X-rays and soft gamma rays vary on a relatively short time scale, indicating a compact emission region. This implies that they must be produced very closely to the central engine, and are probably the primary form of radiative power in radio-quiet AGN.

2.3.1 Seyferts

The observations by OSSE on CGRO showing a break or an exponential cutoff in the high energy X-ray spectrum of Seyfert galaxies have had enormous impact on our theoretical understanding of the X-ray and gamma-ray emission processes. They rule out purely non-thermal $e^{\pm}$ models and favor thermal or quasi-thermal Comptonization as a mechanism for the X-ray to gamma-ray continuum. A view of the Seyfert nucleus which is consistent with X-ray and gamma-ray observations of CGRO, ROSAT, ASCA, RXTE and *BeppoSAX* indicates that it contains optically-thin, mildly-relativistic, plasma which emits, via Comptonization, a power-law spectrum in X-rays. The plasma is above an accretion disk, which Compton-reflects this radiation and gives rise to a broad continuum peak at ~30 keV and an emission line at ~6.4 keV. The nucleus is embedded in a thick molecular torus. The spectrum observed in the polar directions relative to the torus is the intrinsic power law and Comptonization of the nucleus, identifying Seyfert 1 objects. Viewed from the plane of the torus, the intrinsic spectrum is strongly absorbed by the neutral torus material with column depths of 10^{22} – 10^{25} cm^{-2}. The X-ray emission in these cases are highly absorbed, identifying Seyfert 2 objects; however, the intrinsic power law spectrum and break should be the same as for Seyfert 1 objects. Recent BeppoSAX observations show that obscured AGN may dominate the soft x-ray (ROSAT) source counts by factors of at least 2–4.

Hard X-ray and gamma-ray observations of Seyfert objects thus provide key information in the understanding of Seyfert AGN:

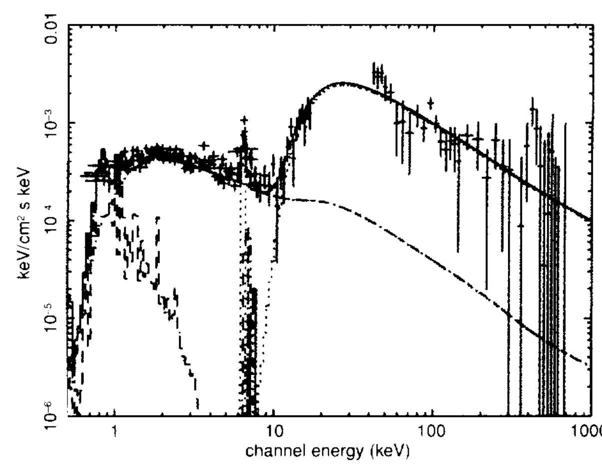


Figure 2.9. *The broad-band spectrum of NGC 4945 using CGRO/OSSE and ASCA data shows the complex behavior including the expected obscuration of low-energy emission. Gamma-ray observations are crucial for fully understanding active galaxies.*

- Broad band coverage to several hundred keV, with response extending to above 511 keV, is required to identify the character of the intrinsic nuclear spectrum and characterize the thermal plasma.
- They determine the extent of non-thermal contributions to the nuclear emissions and the contributions of $e^{\pm}$ pairs.
- They offer the opportunity to discover many new Seyfert 2 AGN which have not been detected in X-ray surveys due to the large absorption in that lower energy band.

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 gamma rays 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 gamma rays 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.

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 93 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.

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 attenuation will begin to occur at energies above 4 TeV but for the most distant objects it will begin to 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 A 2255, A 2256, A 2319, and A 1367. 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 $\sim 3 \times 10^{-6}$ photons $cm^{-2}\ s^{-1}\ keV^{-1}$ in the ~20–60 keV range is needed to make the crucial measurement. The hard X-ray detector (PDS) on BeppoSAX has recently discovered a significant hard excess (>25 keV) above the thermal emission (kT ~ 8 keV) for the Coma galaxy cluster. This implies a cluster magnetic field of ~0.14 microGauss, the first such determination. Higher sensitivity and spectral resolution observations are needed as well as imaging to map the emission and rule out AGN contributions. 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 have 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 one 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.

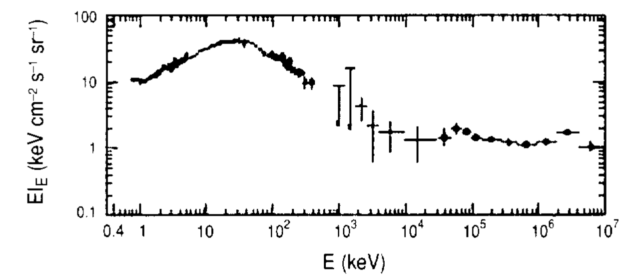


Figure 2.10. The diffuse background from soft X-rays to high-energy gamma rays.

Recent measurements, however, by the COMPTEL instrument on CGRO in the 0.8–30 MeV range, and a careful reanalysis of data obtained with SMM and HEAO–1 have not confirmed the presence of the hump. Above several MeV the spectrum has an energy index of ~1.0 as seen by recent measurements by EGRET.

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 "MeV Blazars" or possibly gamma-ray line and continuum emission from unresolved Type 1a supernovae.

Extragalactic 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 hard x-ray and MeV bands.

Extragalactic Requirements:

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

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

The history of astronomy has been punctuated by breakthrough discoveries — galaxies, quasars, pulsars, and X-ray binaries are examples — where the sources were first seen as "unidentified" objects by telescopes that fell short of having the spatial, spectral, or timing resolution needed to complete the identification. Such a population is now seen in the high-energy gamma-ray sky. In addition to the known source classes of normal galaxies, pulsars, and blazars , the third EGRET catalog contains 170 unidentified sources (out of a total of 271). With this many gamma-ray-luminous objects scattered across the sky, the potential for exciting discoveries is high.

The distribution of unidentified EGRET sources suggests a largely Galactic population. Some possibilities are: (1) radio-quiet pulsars like Geminga. Such pulsars would aid studies of neutron star population and dynamics (see section 2.2.4). (2) cosmic ray concentrations in supernova remnants. Some EGRET sources appear to be associated with SNR and may represent the sources of cosmic ray protons. (3) X-ray binaries. Two tentative identifications suggest that winds or accretion processes may result in gamma-ray emission from binary systems. (4) gamma-ray flare stars. Some EGRET sources appear to be transients not associated with prominent radio or X-ray sources showing similar variability. For all sources near the Galactic plane, problems of source localization and source confusion present challenges to be solved with a future gamma-ray telescope.

Some of the high-latitude unidentified sources are likely to be extragalactic, perhaps unrecognized or radio-quiet blazars (many of the EGRET error boxes do not contain bright, flat-spectrum radio sources), or some other type of active galaxy. The tentative identification of Cen A in the EGRET catalog suggests that other AGN should produce high-energy gamma rays at some level. In all these cases, the gamma rays provide critical information toward understanding the physics of jets (see section 2.3.2).

The most important possibility is that the unidentified sources contain some new type of astronomical object, as many previous classes of "unidentifieds" have revealed. This prospect is one of the strongest incentives to make definitive measurements of the gamma-ray source locations, energy spectra, and time variability.

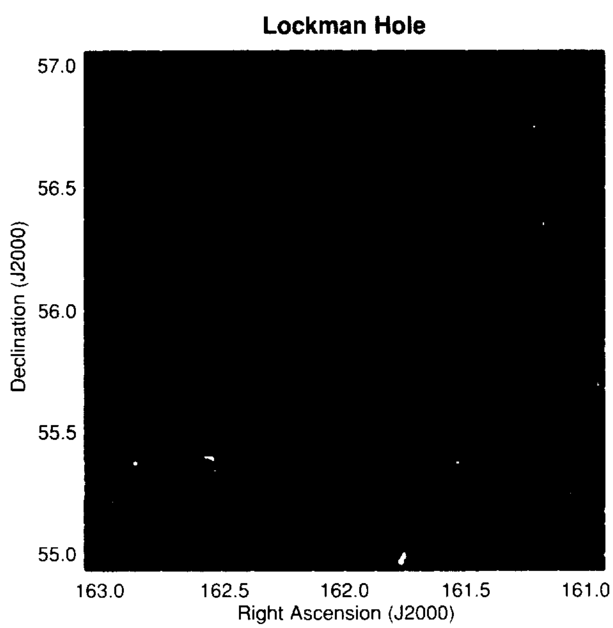


Figure 2.11. This optical image shows the relative sizes of the EGRET and GLAST source localization capabilities. Improvements such as these are critical for identifying counterparts to unidentified sources.

Unidentified 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, and search for pulsations. Measure the energy spectra of unidentified sources over a broader energy range.

Unidentified Requirements:

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

2.5 THE GAMMA-RAY BURST ENIGMA

Despite 25 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 multi-wavelength obscurity. Their isotropy and inhomogeneity have been well documented by BATSE. Discoveries in the last two years have helped to resolve the well known debate regarding the gamma-ray burst distance scale but also heightened the mystery regarding what sort of model, or group of models can provide the enormous energies implied by such a bright event occurring at cosmological distances.

Beginning in 1997, the Italian X-ray mission *BeppoSAX* was able to provide sufficiently accurate prompt locations (about 5') to the ground-based community that fading counterparts in other wavelengths, especially optical and radio, were discovered for a few bursts. To date at least 9 optical counterparts have been detected and red shifts obtained for a half dozen host galaxies (see Table 2.1). It is important to note that, thus far, these bursts have all been of the long complex variety since *BeppoSAX* only triggers on bursts longer than 5 s. Thus we still know very little about the characteristic distance and sources of that discrete group of hard short bursts with mean duration 0.3 s. However, it is now clear that at least a large subset of the long bursts seen by BATSE are at cosmological distance with a mean redshift greater than one. This makes them the most energetic explosions in the universe. As this report goes to press, one of the most recent bursts studied, GRB 990123, at red shift $z = 1.61$ has been determined to have an energy that, if isotropic, would exceed the rest mass energy of the sun turned into gamma-rays within no more than a minute. It may well be that the burst sources are beamed so that the characteristic energy is reduced and the event rate much higher than one per day, but in any case, the puzzles posed to the theorists are as exciting as they are difficult. How can one release so much energy so rapidly and convert it into gamma-rays with such high efficiency? How are the "afterglows" at other wavelengths made? Is there more than one model for gamma-ray bursts? What do we learn about star formation, cosmology, particle acceleration, and black hole physics?

GRB 990123 was also detected by the ground-based ROTSE telescope with an optical magnitude of about 9 during the burst itself. While this was an exceptionally bright burst, certainly in the upper 1% of the brightness distribution, the fact that some bursts have bright counterparts must also affect future mission strategy. Also of significance to mission strategy was a burst that occurred on April 25, 1998 coincident with the onset of a bright Type Ic supernova, SN 1998bw. Because of the relatively large error box of *BeppoSAX* and the possibility of source confusion, the congruence of these two events remains controversial in the community. However if the burst and the supernova (distance 38 Mpc) were the same event, the April 25 gamma-ray burst was about 100,000 times-

TABLE 2.1. GRBS LOCALIZED BY *BEPPOSAX* AND BATSE/RXTE OR RXTE/ASM (COURTESY J. GREINER)

GRB	GRB X-ray position	Error	Instrument	IPNa	XAa	OTa	RAa	IAUC	z
960720	$17^h30^m37^s$ +49° 05.8'	3'	SAX/WFC		n	n		6467, 6569,	
970111	$15^h28^m15^s$ +19° 36.3'	3'	SAX/WFC	y	y	n		6533, 6569,	
970228	$05^h01^m57^s$ +11° 46.4'	3'	SAX/WFC	y	y	y		6572	
970402	$14^h50^m16^s$ −69° 19.9'	3'	SAX/WFC		y	n		6610	
970508	$06^h53^m28^s$ +79° 17.4'	3'	SAX/WFC		y	y	Y	6649, 6654	0.835
970616	$01^h18^m57^s$ −05° 28.0'	40'*2'	XTE/Uly	y	y	n		6683, 6687	
970815	$16^h08^m43^s$ +81° 30.6'	6'*3'	XTE ASM		y	n		6718	
970828	$18^h08^m29^s$ +59° 18.0'	2.5'*1'	XTE ASM	y	y	n		6726, 6728	0.33?
971024	$18^h24^m51^s$ +49° 28.9'	9.0'*1'	XTE ASM		y	n		priv. comm.	
971214	$11^h56^m30^s$ +65° 12.0'	4'	SAX/WFC	y	y	y		6787, 6789	3.14
971227	$12^h57^m35^s$ +59° 15.4'	8'	SAX/WFC		y?	?		6796	
980109	$00^h25^m56^s$ −63° 01.4'	10'	SAX/WFC		n	n		6805	
980326	$08^h36^m26^s$ −18° 53.0'	8'	SAX/WFC	y	?	y		6851	
980329	$07^h02^m41^s$ +38° 50.7'	3'	SAX/WFC	y	y	y	y	6853	~5?
980425	$19^h34^m54^s$ −52° 49.9'	8'	SAX/WFC		y	SN	y	6884	0.0085
980515	$21^h18^m04^s$ −67° 14.9'	5'	SAX/WFC		?			6909	
980519	$23^h22^m14^s$ +77° 15.3'	3'	SAX/WFC	y	y	y	y	6910	
980613	$10^h17^m46^s$ +71° 29.9'	4'	SAX/WFC		y	y		6938	1.096
980703	$23^h59^m07^s$ +08° 35.6'	4'	RXTE/ASM		y	y	y	6966	0.966
980706	$10^h48^m00^s$ +57° 20'	4 deg	COMP/PCA	y	?	n	–		
981220	$03^h42^m34^s$ +17° 09'	2'*4.5'	ASM/Uly	y			y		
981226	$23^h29^m40^s$ −23° 55'	6'	SAX/WFC		y	?		7074	
990123	$15^h25^m29^s$ +44° 45'	2'	SAX/WFC	y	y	y	y	7095	1.60
990217	$3^h02^m52^s$ −53° 06'	3'	SAX/WFC		n	n		7110	

(a) IPN = interplanetary network detection; XA = X-ray afterglow; OT = optical transient; RA = radio afterglow; z = redshift. *(Complete through February 1999)*

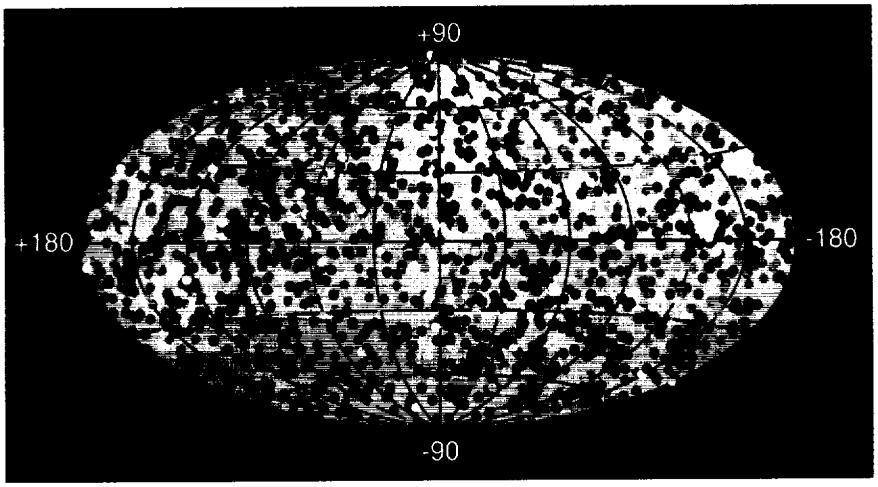


Figure 2.12. Over 2300 gamma-ray bursts have now been detected by CGRO/BATSE.

fainter than most of the other events for which hosts have been determined. there may be a large population of faint bursts beyond the capability of BATSE to detect. Thus, much higher sensitivity (increased by factors -5–20) and angular resolution are needed to probe the logN-logS distribution and possible SN contributions.

Another important relatively unexplored aspect of gamma-ray burst science is their high energy emission. Several bursts have been detected at very high energies, up to 18 GeV, by the EGRET instrument on CGRO. In one case the burst continued at high energy for almost two hours — much longer than at the lower energies seen by BATSE. The mission to accomplish this is the Gamma-Ray Large Area Space Telescope (GLAST). While a complete theory of gamma-ray bursts is lacking, we expect that the panchromatic behavior of bursts, all the way from the radio to 1 TeV, will be very important in unraveling their nature.

Objectives:

- Obtain accurate prompt locations, preferably of order arc seconds, for hundreds of bursts so as to allow prompt follow up studies from the ground to determine distances. It may be that gamma-ray bursts are a diverse phenomenon and we need a large sample to determine the characteristics of the various components.
- Obtain the distances and evidence for or against galactic association for a significant sample of short hard bursts
- Study the very high energy emission of gamma-ray bursts in the energy band 100 MeV to at least 300 GeV. Coordinate the results with behavior at other wavlengths and obtain accurate locations for these high energy bursts as well.
- Search for fainter bursts than seen by BATSE.
- Search for much fainter bursts.

Requirements:

- Arcsecond source locations to allow prompt, deep optical, X-ray and radio counterpart searches.
- Rapid ground based followup
- Sensitivity to high energy photons
- Increased hard x-ray sensitivity (~5–20 BATSE _values) to search for GRBs at high redshift.

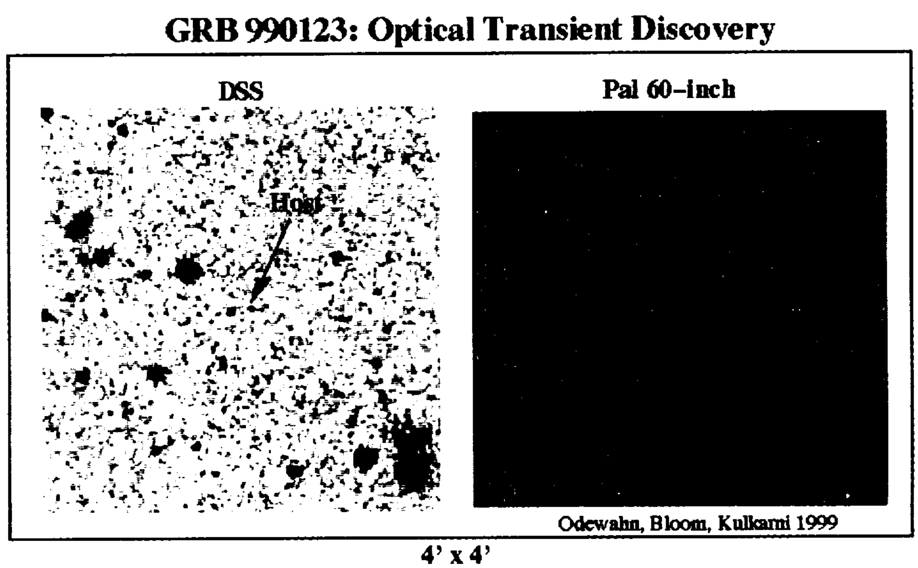


Figure 2.13. Small GRB error boxes have allowed sensitive optical searches for counterparts such as this image associated with a burst detected by BATSE, COMPTEL, and BeppoSAX.

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.

Further gamma-ray work using SMM data 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.

There are also indications, based on gamma ray lines from ^{7}Li and ^{7}Be produced by alpha particle interactions with ambient He, that there are regions in the chromosphere with enhanced He abundance. This also impacts solar atmospheric dynamics.

Concerning the accelerated particles, the gamma-ray work has shown that these particles exhibit large abundance enhancements for the heavy ions, particularly Fe, as well as enhancements of ^{3}He. The latter is based on newly identified lines at 0.937, 1.04 and 1.08 MeV due to the interactions of accelerated ^{3}He nuclei with ambient O. The abundance of ^{3}He in the solar atmosphere is only a few times 10^{-4} relative to ^{4}He. But based on particle observations we know that it 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. The gamma ray observations complement the particle data and thus have important implications for the particle acceleration mechanism.

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.

The planned HESSI mission (launch in 2000) with its Ge detectors will provide important new data on many of the issues mentioned above, including detailed abundance studies and for the first time the imaging of the flare hard X-ray and gamma-ray emissions. Solar flare gamma-ray observations with detectors of even higher sensitivity will allow some entirely new types of investigations. For example, it would be possible to observe in detail the relatively long lived radioactivity (e.g., ^{7}Be and ^{56}Co) produced by accelerated particle interactions in flares, thereby allowing the study of transport and mixing in the aftermath of flares. Finally, the flare observations will 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.

CHAPTER 3

Current Program

The current set of missions related to the gamma-ray astronomy program provide a crucial resource. Valuable contributions will continue to be made by this generation of instruments, setting the stage for the instruments in development. This chapter provides an overview of the experiments currently operating, or which will be operating in the next three years.

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 chapters 1 and 2.

Over 700 scientists from 24 countries have participated in the CGRO Guest Investigator program. CGRO continues to operate flawlessly and none of the instruments, except EGRET, has life-limiting consumables. 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 targets of opportunity over the next five years. The science contributions which are anticipated from future CGRO observations are:

- Understanding the GRB mystery. Counterparts may continued to be identified using the near real-time BATSE and COMPTEL notification system and the GRB Coordinates Network (GCN) triggered ground observer network.
- Continue 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 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 .

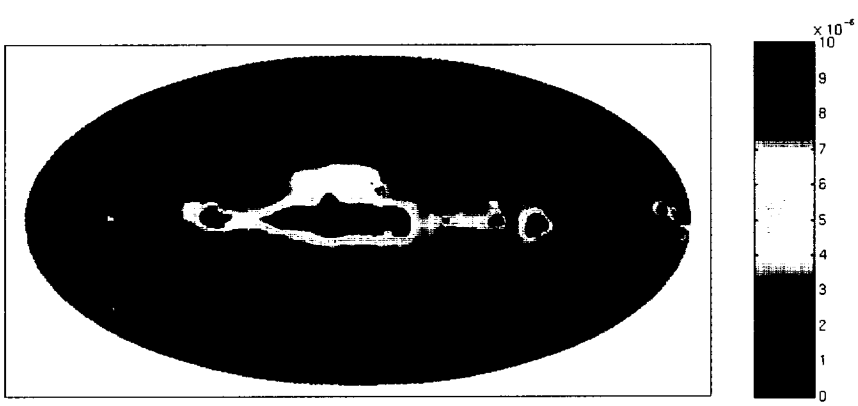


Figure 3.1. This image shows the diffuse glow of high-energy gamma-rays detected surrounding the center of our galaxy by CGRO/EGRET. More sensitive high energy observations are needed to quantify and understand this emission.

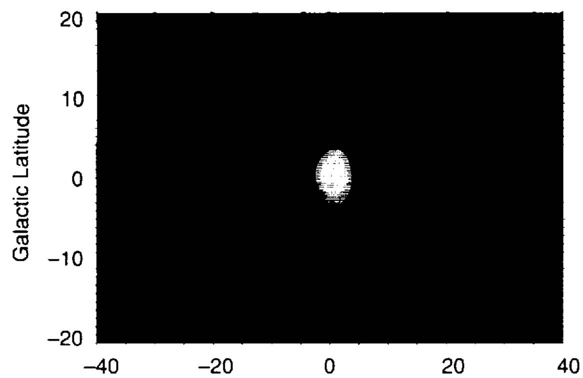


Figure 3.2. An image of the annihilation radiation detected by CGRO/OSSE. The cloud of 511 keV emission coming from the galactic center has surprised observers.

- 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/dE = 500) and imaging (12 arcmin FWHM) in the 15 keV to 10 MeV energy range. The two main instruments on board are a spectrometer (SPI) with high-spectral-resolution germanium detectors and an imager (IBIS) 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 $\sim 5\times10^{-6}$ 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 ~2600 cm^2 and a continuum sensitivity of 4×10^{-7} ph cm^{-2} s^{-1} keV^{-1} (~1 mCrab) at 100 keV. The key scientific objectives of the INTEGRAL include (1) the study of explosive nucleosynthesis in Type I supernovae out to ~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 (Proton rocket) and the United States (tracking, instrumentation). A science data center is located at the Geneva Observatory in Switzerland. The observing program will consist of a Core Program (~30% of the time) and General Program that will have observations chosen from an open competition of proposals submitted by the members of the community at large. The Core Program will be largely devoted to galactic plane scans and a deep exposure of the central radian of our galaxy.

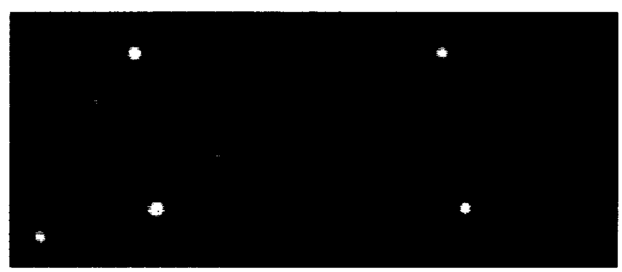


Figure 3.3. These two images from the GRANAT/Sigma instrument show the region around the galactic center at two different times. Sources appear and disappear in this highly active region of our Galaxy. Long-term monitoring of such sources is an important aspect of gamma-ray science.

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 the large collecting area of its instruments which permit sub-millisecond temporal resolution of bright sources, 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.

These characteristics have facilitated several major accomplishments including: discovery of kilohertz quasi-periodic oscillations (QPO) in some 20 accreting neutron star systems, discovery of a millisecond accreting pulsar, discovery of 6 black hole systems, some of which exhibit jets and evidence for general relativistic frame dragging, and the discovery that a soft gamma-ray repeater probably has a superstrong magnetic (2×10^{14} G)

The RXTE spacecraft has an expected orbital lifetime extending at least through 2004 and, since it is not constrained by consumables, may extend for an additional five 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.

This particular combination of large field of view and good angular resolution instrumentation on *BeppoSAX* has facilitated the key observations proving the gamma-ray-burst distance scale to be cosmological. This has been done by providing accurate localization of ~ a dozen GRB X-ray counterparts thereby allowing identification of optical afterglow counterparts.

Despite suffering the loss of two ACS gyros, *BeppoSAX* has been able to maintain functionality and is expected to have a mission life extending at least through the year 2001.

3.4 GAMMA-RAY BURST INSTRUMENTS

BeppoSAX observes ~8 bursts/year in its Wide Field Camera, with location accuracies better than 10'. When the burst position is observed with the Narrow Field Instruments by slewing the spacecraft, fading X-ray counterparts can often be identified and localized to < 1'. The time required to acquire and analyze the data is ~hours. The mission has been approved through 2001.

The Global Coordinates Network (GCN) distributes ~300 GRB positions/year with delays of the order of seconds, determined directly onboard the CGRO spacecraft by BATSE. The error circle radii are ~4°. The "Locburst" procedure, based on rapid ground- based processing of the more intense BATSE bursts, results in ~100 bursts/year with error circle radii as small as 1.6°. The CGRO mission has been approved by the Senior Review through 2002.

The 3rd Interplanetary Network (IPN) consists of Ulysses and the Near Earth Asteroid Rendezvous in deep space, as well as numerous near-earth missions such as CGRO, RXTE, WIND, and *BeppoSAX*. Mars Surveyor Orbiter will join the network in 2001. The IPN observes and localizes ~70 GRBs/year to arcminute accuracies. The time to process and distribute the positions is ~1 day. The IPN will operate through 2001 and possibly until 2004, if the Ulysses mission is extended.

The Rossi X-Ray Timing Explorer All Sky Monitor (RXTE ASM) detects ~3 bursts/year and determines their positions to arcminute accuracy in minutes. In addition, the RXTE Proportional Counter Array is used ~once/month to scan BATSE Locburst positions for fading X-ray sources. When successful, the counterpart position can be determined to ~10' within hours. RXTE has been approved through 2002.

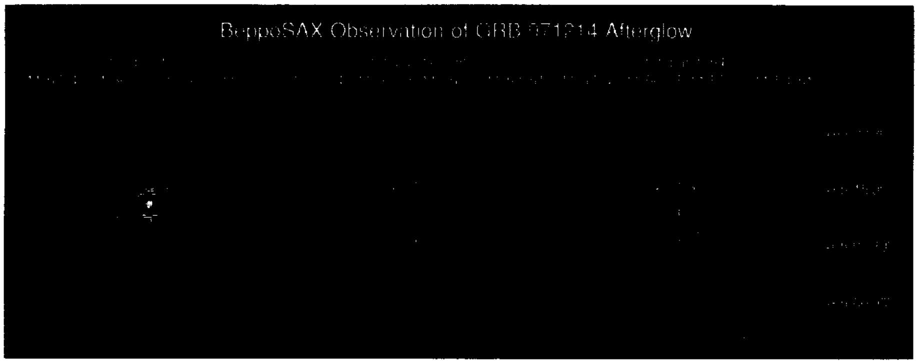


Figure 3.4. Rapid localization of GRB positions continue to allow searches for counterparts. This BeppoSax observation of GRB 971214 is an example of the benefits of the current set of Burst detectors.

Several automated camera systems are now operational, which slew to the position of a burst and image it within ~10 s of the burst onset. LOTIS (Livermore Optical Transient Imaging Survey), ROTSE (Robotic Optical Transient Search Experiment), and TAROT (Rapid Action Telescope for Transient Objects) are three examples. In particular, ROTSE has succeeded in detecting the optical emission from a gamma-ray burst in progress, 990123, which reached m~9.

The High Energy Transient Explorer II (HETE-II) combines a Wide Field X-ray Monitor and a Soft X-Ray Camera to localize ~50 GRBs per year to accuracies of 10" to 5', and transmit them to the ground in near-real-time. HETE-II will be launched into an equatorial orbit by a Pegasus from Kwajalein Island around the end of 1999, with a nominal 2 year mission.

The Cooperative Astrophysics and Technology Satellite (CATSAT) will contain a soft X-ray spectrometer to measure the 0.5–20 keV spectra of ~12 GRBs/y with unprecedented energy resolution. Although CATSAT has only modest localization capability, these spectral measurements will constrain the hydrogen column density towards the sources, and help to answer the question of the locations of burst sources with respect to their host galaxies. CATSAT is planned for launch in 2000, with a nominal one year mission.

INTEGRAL, the International Gamma-Ray Laboratory, can detect bursts with its Ge spectrometer array, with its IBIS imager, and in its anticoincidence shield. Locations for ~20 GRBs/yr can be localized to arcminute accuracy and the positions distributed to observers in < 100 s. INTEGRAL will also be part of the 3rd IPN when it launches in April 2001. The nominal mission lifetime is 2 years.

SWIFT, a dedicated MIDEX mission, has been approved for a 6 month study phase. If selected for flight, it will revolutionize GRB studies by localizing ~300 GRBs/y to arcsecond accuracies, measure their optical spectra, and transmit all data to the ground with delays of seconds to minutes. A nominal 3 year lifetime starting in 2003 is planned.

3.5 HESSI

The High Energy Solar Spectroscopic Imager (HESSI) is a NASA Small Explorer scheduled for launch in July 2000 to observe solar flares through the peak of solar cycle 23. It will explore the causes and characteristics of particle acceleration in flares via the X-ray and gamma-ray emission caused by high-energy electrons (bremsstrahlung) and protons or nuclei (gamma-rays from nuclear excitation).

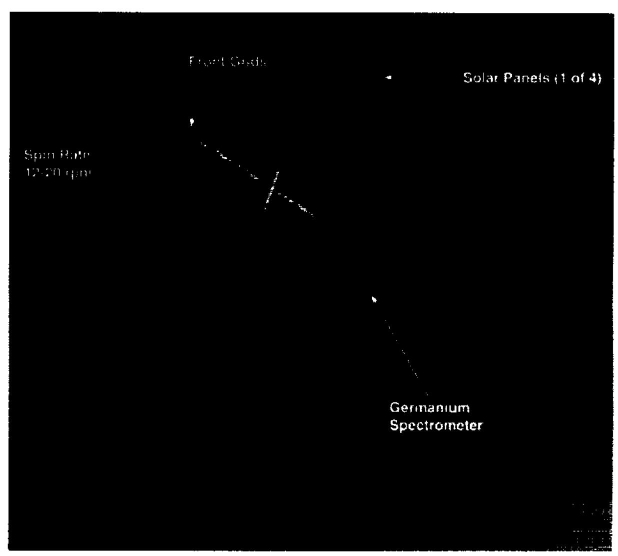


Figure 3.5. A view of the HESSI spacecraft. HESSI will provide high resolution spectroscopy and imaging of Solar flares.

HESSI will achieve spectral resolution of 0.5 to a few keV over more than three orders of magnitude in energy (3 keV to 15 MeV) with a single set of 9 cooled coaxial germanium detectors. Each detector will sit below a pair of grids with a unique spacing, which will modulate the signal from a flare as the whole spacecraft rotates, producing images with 2 arcsec resolution.

HESSI will resolve the shapes of every known solar gamma-ray line except the very narrow 2.2 MeV neutron-capture line, for which its high resolution will provide high sensitivity. Since this line traces proton acceleration, HESSI observations will determine the partition of flare energy between electrons and protons over a wide range of flare fluences. The shapes of nuclear de-excitation lines will probe the angular distribution of accelerated ions, and the width of the 511 keV positron-annihilation line will reveal the temperature (and therefore location) of the annihilating medium. Ratios between lines from different elements will constrain compositions in the accelerated and ambient populations and also constrain the spectrum of the accelerated protons (due to different thresholds for different excitations). HESSI's ability to image at gamma-ray energies will provide the first look at the location and size of the regions where flare protons and secondary neutrons stop.

In addition to gamma-ray observations, HESSI will produce rapid images and spectra of hard X-rays due to bremsstrahlung from accelerated electrons, providing information on their birthplace, motion, and energy loss. Since HESSI is unshielded, it will also perform extra-solar observations, such as the lineshapes of the Galactic 1809 keV and 511 keV lines, spectroscopy of gamma-ray bursts, and pulse-phased spectroscopy of pulsars. It will image the Crab nebula when it enters the solar field of view once a year.

3.6 AGILE

AGILE (Astro-rivelatore Gamma a Immagini LEggero, Light Astro Gamma Imaging Detector) is a high-energy gamma-ray mission proposed to the Italian Space Agency (ASI) Program for Small Scientific Missions. The Mission completed a Phase A study in December 1998. It has been selected for flight, although the final funding decision has not been made at this writing.

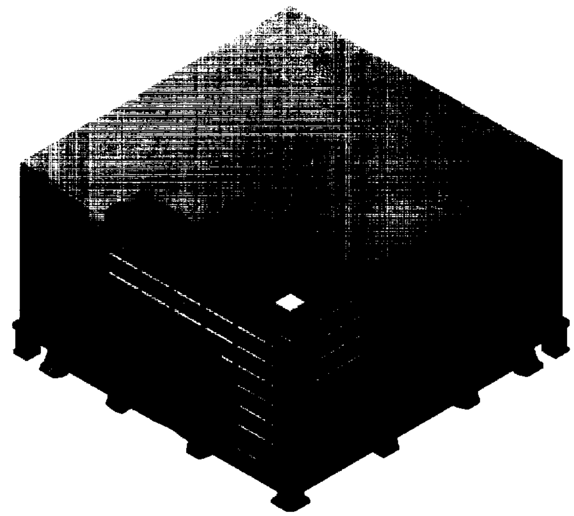


Figure 3.6. *Schematic view of the AGILE telescope. This pair production telescope uses a silicon strip tracker with a plastic scintillator anticoincidence detector and a thin CsI calorimeter.*

AGILE is conceived as a bridge between EGRET and GLAST, covering the energy range above 30 MeV. AGILE has about half the on-axis sensitivity of EGRET but a field of view more than 3 times larger. It will be a valuable tool for studies of bright AGN, GRB, and other gamma-ray transients, where the wide field of view will enable detection of flaring sources that can be coordinated with observations at other wavelengths. AGILE will help optimize the science return from GLAST by identifying those sources that require the much higher sensitivity and broader energy range of GLAST

3.7 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

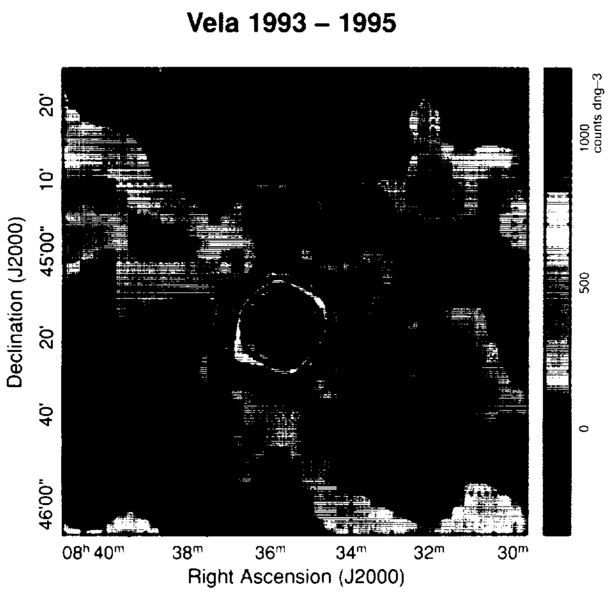


Figure 3.7. This detection of the Vela supernova remnant by the CANGAROO instrument, the third TeV detection of a supernova remnant, shows the continued development of ground-based gamma-ray astronomy. These high-energy instruments are an important complement to their space-based counterparts.

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 with a 109 pixel camera. 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 (e.g. MAGIC) can be built with an energy threshold as low as 10 GeV.

3.8 ULTRA 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 *BeppoSAX* 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.

The development of an Ultra-Long Duration (100d) Balloon program has been initiated as the Olympus Program. This would build on the long duration (LDB) program (10-14d) and allow gamma-ray science and missions with capabilities comparable to MIDEX-class missions. For example, a hard X-ray imaging sky survey at the ~1mCrab level could be conducted in two such flights (northern and southern) and enable relatively long continuous exposures on individual sources at

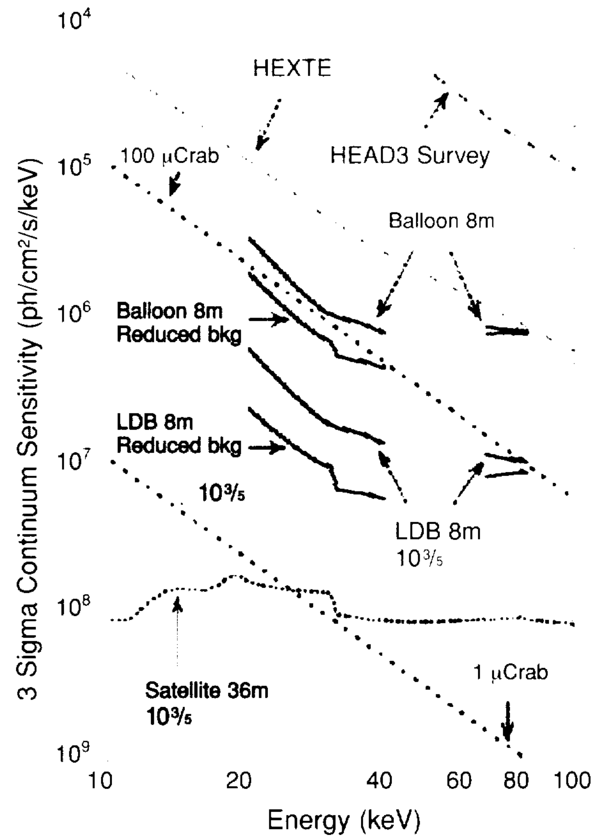


Figure 3.8. The promise of long-duration balloon flights is shown in this plot of the sensitivity of the InFocus hard X-ray imaging instrument. As with many other proposed experiments, balloons provide an inexpensive method for instrument development and scientific return.

relatively low and constant backgrounds. The GRAPWG urges that NASA continue the development of both LDB and ULDB flight capabilities with expanded support for payload development in both the UNEX and SMEX programs. Alternatively, a separate LDB/ULDB mission line should be established under the Explorer Program. International agreements for over-flight (particularly in the northern hemisphere) must be pursued immediately. Over-flight concerns would be made less difficult if NASA also increased its implementation of balloon flight control and flight termination/landing systems (e.g. parasails) which are now relatively developed (e.g. for DoD) but have not been incorporated in scientific ballooning. The balloon program, and particularly the ULDB program, will enable:

- rapid, relatively low-cost, development of large missions for cutting-edge science and space qualification for possible future orbital missions (e.g. ISS)
- continuation of development of instruments, and researchers (graduate students, postdocs, etc.) for the future missions in HEA

3.9 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.

CHAPTER 4

Future Missions

A particularly exciting set of new missions in the time frame beyond the next three years are planned in gamma-ray astronomy. In this chapter, we describe those missions in the current Strategic Plan (GLAST, Constellation-X HXT) as well as the follow-on missions which will capitalize on their successes.

4.1 MISSIONS IN THE 1998 OSS STRATEGIC PLAN

4.1.1 GLAST

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 20 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 or scintillating fiber 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. The mission to accomplish this is the Gamma-Ray Large Area Space Telescope (GLAST — http://glast.gsfc.nasa.gov/).

For the baseline mission parameters given in Table 4.1, a factor of 30 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.

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. Rolloffs in AGN spectra above 1 GeV may be caused by pair production against the intergalactic photon field and may be used to study the extragalactic background light as a function of redshift.
- *Unidentified Gamma-ray Sources.* Determine the type of object(s) and the mechanisms for gamma-ray emission from the unidentified EGRET gamma-ray sources by precisely measuring their positions, spectra, and variability. For many of these sources, direct periodicity searches for gamma-ray pulsars will be possible.

- *Isotropic Background Radiation.* Determine if the high-energy background is resolvable into point sources or if there is a truly diffuse component, by deeply surveying high-latitude fields.
- *Gamma-Ray Bursts.* Provide constraints on physical mechanisms for gamma-ray bursts by detecting high-energy radiation from about 200 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.

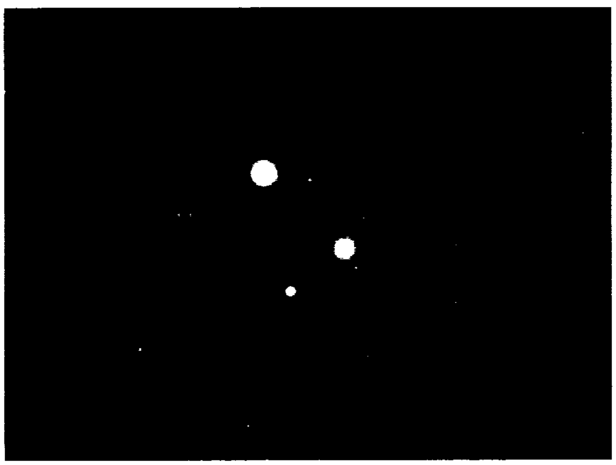


Figure 4.1 *This simulation of the GLAST view of the anticenter shows the spectacular detail the improved GLAST sensitivity will provide.*

- *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 distributions 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.

TABLE 4.1. CHARACTERISTICS OF THE GLAST MISSION

QUANTITY	GLAST REQUIREMENT
Energy Range	20 MeV–300 GeV
Energy Resolution[1]	10% (100 MeV–10 GeV)
Effective Area[2]	8000 cm^2
Single Photon Angular Resolution – 68%[3] (on-axis)	<3.5° (@100 MeV) <0.15° (E>10 GeV)
Field of View[4]	2 sr
Source Location[5,7] **Determination**	1-5 arcmin
Point Source Sensitivity[6,7] (>100 MeV)	$4 \times 10^{-9}\ cm^{-2}\ s^{-1}$
Mission Life	5 years, with no more than 20% degradation
Telemetry Downlink — Orbit Average	300 kbps 1 kbps near-realtime
Telemetry Uplink	4 kbps
Pointing Accuracy	2° accuracy 30 arcsec knowledge
Observing Modes	Rocking zenith pointing Pointed mode

1 *Equivalent Gaussian sigma, on-axis.*
2 *Peak effective area, including inefficiencies necessary to achieve required background rejection.*
3 *Space angle for 68% and 95% containment.*
4 *Integral of effective area over solid angle divided by peak effective area. Geometric factor is Field of View times Effective Area.*
5 *Range: bright sources to sources of 10^{-8} ph $cm^{-2}\ s^{-1}$ flux at >100 MeV.*
6 *Sensitivity at high latitudes after a 2-year survey.*
7 *Derived quantities delimited by double-lined box*

4.1.2 CONSTELLATION X

The Constellation X mission is a high throughput, broad-band X-ray facility emphasizing spectroscopic observations of a wide variety of astrophysical sources, ranging from stars to galaxy clusters. The primary science goals emphasize spectroscopy in the soft X-ray band (0.1–7 keV), which is rich in absorption and emission features from nearly all charge states of all cosmically abundant metals. However, unambiguous interpretation of the atomic features often requires measurements at hard X-ray energies (10–40 keV) to characterize any accompanying non-thermal continuum (i.e. in supernova remnants, AGN and stellar flares). For this reason, Constellation-X will include the focusing Hard X-ray Telescope (HXT), based on Wolter-I or conical approximation optics, to extend sensitive continuum observations above 10 keV (see http://constellation.gsfc.nasa.gov). Independent of the goals emphasized for the soft X-ray spectroscopy telescopes, compelling motivation for the HXT is provided both by the existence of sources whose energy output peaks in this range, and by astrophysical processes which are uniquely observable there. HXT observations therefore uniquely address a number of scientific investigations identified as priority objectives of the GRAPWG. Below we illustrate a few of the many examples:

Scientific Objectives Unique to the HXT

- *Heavily Absorbed AGN and the X-ray Background.* The energy density of the X-ray background peaks at ~30 keV; less than 15% of this total energy density can be accounted for by the ROSAT AGN population. If AGN comprise the XRB, then most must have huge absorbing columns (N_H ~10^{22}–10^{25} cm^{-2}). Surveys by XMM, ABRIXAS, and AXAF, limited to energies less than ~10 keV, will only probe absorbing columns up to a few times 10^{23} cm^{-2}. With its much higher sensitivity, the Constellation-X HXT can survey IR-selected AGN, probing faint and high-redshift AGN populations thus far inaccessible in the X-ray band. The data will also provide a probe of the geometry of the absorbing material.
- *Non-Thermal Emission from Galaxy Clusters.* The HXT will enable us to measure the inverse Compton scattering radiation predicted in clusters of galaxies. Combined with radio measurements, the hard X-ray observations will yield a lower limit on the intracluster magnetic fields independent of equipartition or equal energy hypotheses. Detection of the nonthermal emission in clusters has significant impact on the underlying cosmological models through the estimation of the cosmological parameter Ω. It also affects cooling flow arguments, since the presence of the magnetic field can suppress the conduction of the cooling gas. Many clusters are believed to have formed through merger events as predicted in hierarchical large-scale structure models. As a result, due to the collision of subclumps and merging effects, shocks of very high temperature can be produced in the ICM. The hard X-ray observations will also shed light on the nature of clusters that show evidence of extremely high temperatures.

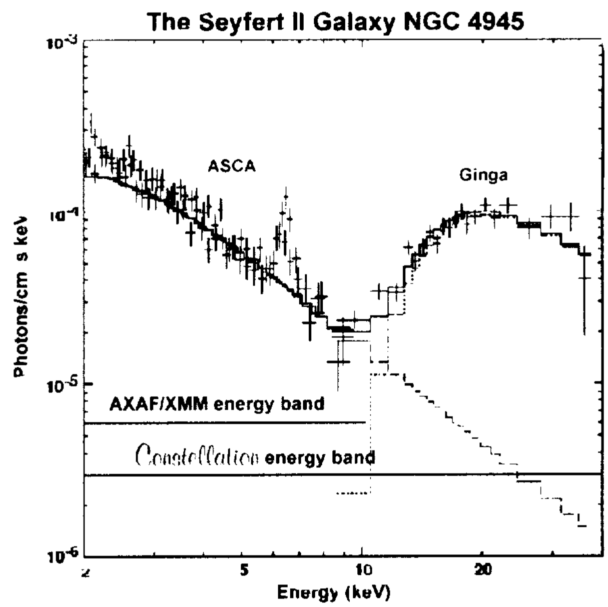


Figure 4.2. This plot of the spectrum of NGC 4945 as compared to the Constellation-X HXT sensitivity shows the value of extending the spectral coverage of such objects to hard X-rays.

- *Hard X-ray Source Populations in the Local Group.* Compact stellar remnants such as accreting X-ray pulsars and LMXBs (with hard Comptonized tails) have energy output peaking (in νf_ν) above 10 keV. These sources both inform us about the endpoints of stellar evolution in binaries and sample stellar populations as a function of Hubble type of the host galaxy. With high sensitivity and hard bandpass, the HXT can probe these highly absorbed and hard stellar populations throughout the Local Group.
- *Shock Acceleration in Young Supernova Remnants.* In addition to the soft thermal X-radiation produced in the shocked ejecta, the spectra of young supernova remnants like Cas A and Tycho exhibit hard X-ray 'tails' extending to ~50 keV. This high energy emission may be due to diffusive shock acceleration of particles at the shock front. The diffusive acceleration theory provides an unambiguous determination of the magnetic field distribution at the SNR shock, from spatially-resolved radio and

hard X-ray maps. The broad bandpass and superior sensitivity allow the HXT to map this non-thermal emission.

4.2 MEDIUM RANGE NEW MISSIONS

4.2.1 High-Resolution Spectroscopic Imager (HSI)

As described in Section 2.1, gamma rays emitted by the radioactive decay of material synthesized in SNe provide one of the few direct observational tools available for probing the physics of the explosion itself, the compact object formation, as well as the production and dispersion of heavy elements. While detection of ^{44}Ti in two young SNR, and the measurement of radioactive decay lightcurves of Cobalt in SN 1987A have given hints of the potential diagnostic power of such observations, detections to-date have been limited to a small number of sources. In addition with few exceptions, spectral resolution has been insufficient to measure Doppler shifts and line widths, and spatial resolution too coarse to map the distribution of the emission in typical remnants. For example, Cas A, one of the two remnants detected in ^{44}Ti to-date, is ~5arcmin in diameter, and requires sub-arcminute imaging capability to discern features at interesting levels.

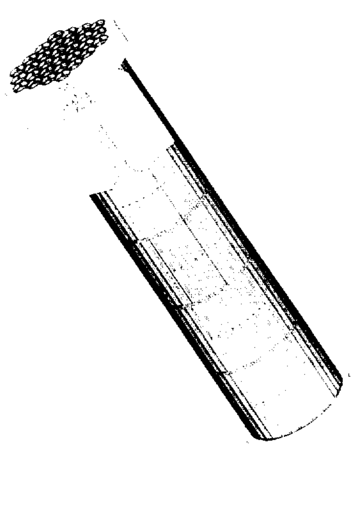


Figure 4.3. Experiments extending the energy range of focusing telescopes to as much as 170 keV, represented by this drawing of the HSI mission, can address many nuclear astrophysics objectives.

The recent laboratory demonstration of hard X-ray focusing optics, and the possibility of extending these techniques to higher energy, into a region containing several key gamma-ray lines (^{44}Ti (68,78 keV), ^{57}Co (122 keV), ^{56}Ni (158 keV)), provides compelling motivation for planning a dedicated focusing mission with sensitivity up to E ≥170 keV. With moderate extensions of existing multilayer optics and Germanium detector technologies, a focusing telescope with collecting area ≥500 cm^2 (1–170 keV), 10" spatial resolution, and 700 km/s (68/78 keV) (450 km/s) (158 keV) spectral resolution is achievable on an intermediate size mission with a new start compatible with the 2006–2008 timeframe. The signal-limited, high spatial and spectral resolution afforded by this mission could address, in addition to many other diverse goals, several of the top nuclear astrophysics objectives identified in Section 2. We briefly describe the scientific goals of this mission below:

Nucleosynthesis and Dynamics in Type II SNe.

Detailed mapping of the radioactive decay from ^{44}Ti in young SNRs provides a sensitive probe of several important parameters in Type II and Type 1b SNe. Because ^{44}Ti is synthesized near the mass cut, its production and ejection are very sensitive to the explosion mechanism and the ejecta dynamics. The ^{44}Ti spatial distribution can also be used to reveal global asymmetries present in the initial SN event. Besides revealing the global asymmetries, the clumpiness and velocity profiles of the ^{44}Ti

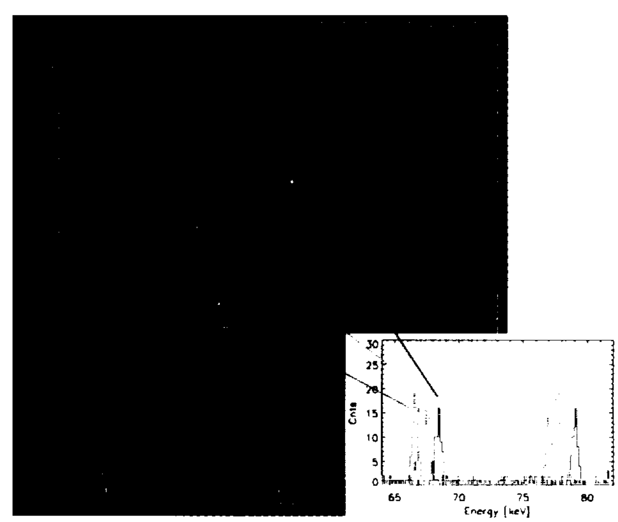


Figure 4.4. Simulated 100 ksec map of the Cas A SNR in ^{44}Ti emission (68/78 keV). The model assumes an axisymmetric, clumpy explosion which is clearly spatially resolved. The velocity distributions of individual knots (here assumed to be 3000 km/s (blue), –5000 km/s (orange), and –2000 km/s (yellow)) can also be clearly determined.

would provide valuable information on ejecta mixing. This information is unique to the radioactive decay measurements: overall Ca and Ti elemental abundances measured in the optical and infrared are dominated by ^{40}Ca and ^{44}Ti production in regions outside the mass cut. Figure 4.4 shows the detailed mapping of the Cas A remnant that could be carried out in a 100-ksec observation with a focusing system.

Explosion Mechanism and Dynamics in Type Ia SNe.

As described in Section 2, direct observation of the ^{56}Ni decay emission (the center of the nuclear abundance peak of degenerate nuclear burning) is a key diagnostic for understanding the SN Type Ia mechanism. Outside of the degenerate conditions of the WD, ^{56}Ni is unstable and decays to ^{56}Co with a mean lifetime of 8.8 days, producing dominant emission lines at 158 keV (100%) and 812 keV (86%). The daughter nuclei then decay to ^{56}Fe with a mean lifetime of 111.3 days, producing the well known emission lines at 847 keV (100%) and 1238 keV (68%). The $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ decay chain powers the SN light curve during the first few

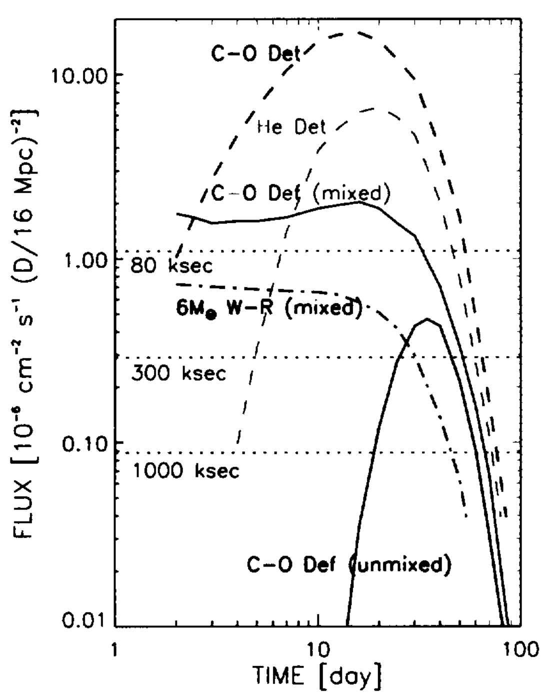


Figure 4.5. *^{56}Ni 158 keV emission line flux evolution for several Type I SNe models. Fluxes are presented for the first 100 days after the explosion for a source at 16 Mpc (Virgo Cluster). The instrumental sensitivity (5 sigma) is shown for 80, 300, and 1000 ksec observations (short dash lines). Fluxes are adapted from Chan and Lingenfelter (1991).*

hundred days of the event. As illustrated in Figure 4.5, the time-dependence of the ^{56}Ni (158 keV) emission is extremely sensitive to the explosion model, as are the line centroids and widths. A focusing experiment is capable of making detailed lightcurves of these lines out to D > 16 Mpc, even for the weakest case (assuming no mixing).

TABLE 4.2. Characteristics of the HSI Mission

Effective Area	700 cm^2 (68 keV) 400 cm^2 (156 keV)
Angular resolution	10"
Energy range	2–170 keV
Spectral resolution (E/DeltaE)	160 @ 158 keV
Line sensitivity (10^6 s)	^{44}Ti 6.5×10^{-8} ph/cm^2/s (5 sigma) ^{156}Ni 8×10^{-8} ph/cm^2/s (5 sigma)
Continuum sensitivity (10^6 s)	3×10^{-8} ph/cm^2/s/keV (@50 keV, E/DeltaE = 0.5, 5 sigma)
Optics	Graded multilayer Wolter
Detectors	Ge pixel
Focal length	6–8 m
# modules	14
TOTAL S/C mass	1000 kg
Power	200 Watts
Launch	Delta II (7320)

AGN.

A high-energy focusing mission would provide 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. Observations in the energy band from 20–170 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).

ICM IN CLUSTERS.

As described in Section 3.3.2, hard X-ray observations can provide a direct measurement of the magnetic field strength in galaxy clusters. Because thermal emission will dominate in many cases at E < 60–70 keV, extending sensitivity to energies higher than planned for Constellation-X is crucial. The excellent flux sensitivity and good angular resolution make focusing telescopes ideal for this important measurement.

POPULATION STUDIES IN THE LOCAL GROUP.

Studying the compact stellar remnants, such as weakly magnetic ($B \lesssim 10^9$ 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 another goal possible only with a focusing instrument. Such studies would both inform us about the endpoints of stellar evolution in binaries and sample stellar populations as a function of the Hubble type of the host galaxy.

4.2.2 ENERGETIC X-RAY IMAGING SURVEY TELESCOPE (EXIST)

The hard X-ray sky, defined broadly as from 10 keV–600 keV, is both relatively poorly explored and yet rich in promise. This is the energy range where fundamental transitions from primarily thermal to primarily non-thermal sources and phenomena are expected, and where compact objects are usually most variable. Thus over the next decade, the scientific case is compelling for one or more missions in this broad band. Here we briefly outline the case for first a broad-band sky survey mission followed by a focussing mission (section 4.2.1) 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 $\sim 10^3$ times fainter with ROSAT but only up to energies of 2.5 keV. The German ABRIXAS mission (launched April 28, 1999) was planned to extend the soft X-ray sky survey up to ~10keV with ~0.1mCrab sensitivity and ~3arcmin resolution but with limited temporal coverage and essentially no monitoring capability. Although a spacecraft power failure aborted the mission after launch, it is likely (and highly desirable!) that Germany will re-fly an ABRIXAS2 by c. 2003. At energies above ~600 keV, the sky has been imaged with COMPTEL and EGRET. The need is therefore acute for a sensitive hard X-ray (~10–600 keV) all sky imaging survey to close the gap and achieve sensitivities comparable to ABRIXAS (i.e. 0.1mCrab or below).

Energetic X-ray Imaging Survey Telescope (EXIST) on ISS

Conceptual Layout of EXIST on ISS Integrated Truss Assembly

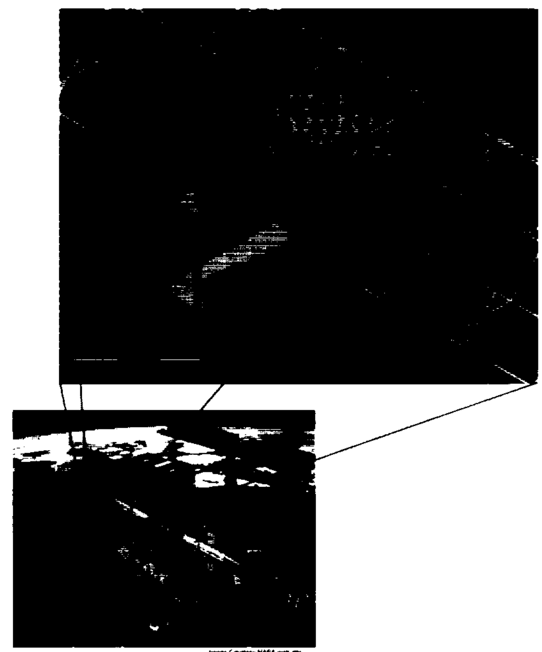


Figure 4.6. The EXIST telescope assembly would mount to one of the Payload Attach System points on the S3 segment of the truss.

An all-sky hard X-ray (HX) survey mission at high sensitivity must be imaging to avoid the source confusion problems that have plagued the collimated HX detectors on HEAO$_1$ and OSSE. Angular resolution of at least 15 arcmin is needed, particularly in the galactic plane (where SIGMA discovered the black hole candidate GRS1758-25 only 40arcmin from the bright soft X-ray binary GX5^{-1}) but also at high latitudes (where SIGMA discovered the HX source GRS1227+025, possibly identified with a z = 0.57 QSO, and only 20arcmin from 3C273.) The desired HX survey sensitivity (~0.05mCrab), and current estimates of AGN number counts at 5–10 keV from BeppoSAX (section 2.3.1) suggest a detection density of ~0.25/square degree (or ~10,000 all-sky). Thus a reasonable confusion limit (resolution at ~1/40 expected source density) suggests ~5arcmin as the needed deep HX survey resolution, with source locations correspondingly finer (e.g. $\lesssim$1arcmin for $\gtrsim$5sigma detections).

An imaging deep all-sky HX survey should also provide unprecedented sensitivity and temporal coverage for time variablility studies since the HX sky is so inherently time variable. With only ~100mCrab sensitivity, BATSE has demonstrated the power of broad temporal coverage for both transients and pulsar studies. The HX survey should therefore have all-sky coverage each orbit and would then greatly extend (but not be replaced by) X-ray (2–10 keV) all sky monitors (e.g. MAXI, planned for the JEM on ISS) which will be less sensitive to outbursts of obscured AGN (e.g. Seylls) and Blazars as well as heavily obscured galactic transients.

The Energetic X-ray Imaging Survey Telescope (EXIST) was selected as a New Mission Concept (NMC) by NASA in 1994 and has been studied as have several other HX survey telescope concepts proposed for MIDEX missions. The deep HX survey mission requirements for sensitivity (to match ABRIXAS), energy range and temporal coverage can be met with a very large area array of coded aperture telescopes which would almost certainly exceed the MIDEX envelope but could make very effective use of the International Space Station (ISS). A generalized EXIST mission concept for ISS is shown in Figure 4.6 and would yield survey sensitivities shown in Figure 4.7.

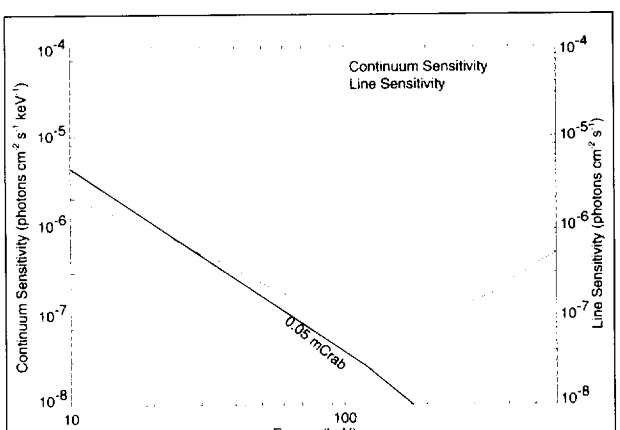


Figure 4.7. *The hard X-ray sensitivity for the EXIST concept as an instrument on the International Space Station.*

The key Scientific Objectives for such a deep HX survey mission would include:

- *Obscured AGN and Diffuse Hard X-ray Background:* The recent exciting discoveries of obscured AGN made by BeppoSAX and ASCA (cf. section 2.3 and fig. 2.9) point to the need for an unbiased HX survey to map the entire sky. The narrow-field instruments, and follow-on focusing HX telescopes, will observe limited samples but not select the most extreme (obscured) ones which require the widest field coverage at any limiting survey sensitivity. A complete HX-selected sample will not only allow their contribution to the cosmic diffuse background radiation (fig. 2.10) to be measured, but will also constrain the accretion history of the universe as measured by the complete sample of accretion luminosities it would detect. This more complete census of BH luminosities may have far-reaching implications for galaxy formation.
- *Blazars and the Diffuse IR Background:* Since the HX Blazars have their synchrotron emission peaks in the HX band, monitoring and measuring their break energies in coincidence with the wide-field capabilities of GLAST and followup studies with ground-based TeV telescopes (e.g. VERITAS) can constrain the intrinsic GeV/TeV spectral shape and thus the cosmic diffuse IR background from measured spectral breaks in their gamma-ray inverse Compton components.
- *Studies of Black Holes on All Scales:* A deep HX survey will probe the emission mechanisms and geometry closest to black holes: from stellar mass BHs in the numerous transients it would discover, through the large sample of massive BHs it would discover in AGNs. High sensitivity and spectral resolution out through 511 keV will allow the contribution of pairs to hoth quiescent and (particularly) flare emission in both AGNs and galactic black hole candidates to be measured and the contribution of BH transients to the diffuse 511 keV emission in the Galaxy to be established.
- *Gamma-ray Bursts at the Limit:* GRB sources thus far identified (section 2.5) are at cosmological distances and may probe star formation as well as the most extreme explosions in the universe. The faintest GRBs may thus probe both the extremes of the GRB luminosity function (e.g. beaming effects) and the SFR at largest redshifts. The

desired high sensitivity (~0.05mCrab in 10^7s) and wide-field (~2sr) for the survey yield a GRB detection sensitivity some 20X better than BATSE. Thus without further flattening of logN-logS below the BATSE limits, GRBs might be detected at a rate of ~6/day, and the most luminous events (e.g. GRB990123) could be detected at z ~ 10.

- *Supernova Rate in Galaxy From ^{44}Ti Galactic Survey:* High sensitivity maps from stacked survey images of the galactic plane at high (~2%) energy resolution will also enable a much deeper (10X) search for ^{44}Ti (68,78 keV) emission from obscured SNR than will be possible with the INTEGRAL galactic plane survey. With an all-sky line sensitivity of ~2 x 10^{-6} photons/cm^2-sec at ~70 keV, or ~30X below the COMPTEL detection of Cas-A, obscured SNR could be detected throughout the Galaxy at similar ages (~300y) and the galactic SN rate constrained. Candidates could then be mapped at higher spatial resolution in followup narrow-field HX focusing telescopes.

Whereas the Burst Alert Telescope (BAT) on Swift could conduct valuable survey and partial monitoring up to ~150 keV at ~1mCrab sensitivity, it is not optimized for HX surveys (e.g. its fixed pointings will engender flat fielding limits) or high time resolution imaging (e.g. pulsar timing would not be possible for the onboard detector binning planned for BAT) and a dedicated deep survey mission is needed. INTEGRAL, with its relatively narrow field (10^{-16}deg) imagers, will conduct only limited surveys without all-sky monitoring. Thus the GRAPWG recommends a high sensitivity and wide-field imaging HX survey mission be carried out within the next decade with the following capabilities and approximate instrument parameters:

Both the desired wide-field (monitoring) and extended energy range (and thus shielding) of this HX survey preclude its placement as the top detector of a large area Compton telescope (Table 4.4). Such a deep survey mission would ideally be flying prior to, or coincident with, the Constellation-X mission and its pointed HXT. Blazar and GRB studies would be optimized if it were at least partially simultaneous with GLAST. As precursors to this mission, there could be lower sensitivity initial surveys carried out by Swift/BAT (2003) and prototype survey instruments flown on both LDB and ULDB balloon missions (2002–2005).

Table 4.3: Deep HX Survey Mission (EXIST) Parameters

Energy range:	–600 keV
Sensitivity (5 sigma; 10^7sec)	0.05 mCrab (5–100 keV); 0.5mCrab (100–600 keV)
Field of view	40deg × 160 deg
Angular resolution	5arcmin
Source locations	<1arcmin
Energy resolution	2% (60 keV); 1% (500 keV)
Temporal resolution	100% sky each orbit; 1microsec imaging
Telescopes	8 coded aperture telescopes (40deg FWHM, each) at fixed offsets (20deg, each)
Detectors	10,000 cm^2 CdZnTe (0.5cm thick), 400 × 400 pixels, each telescope
Mass	2500 kg
Power	1.5kW
Telemetry	1.2mbs; 32 kbs (compressed daily survey)
Mission implementation	Zenith-pointing (+/–80deg) telescopes in LEO (ISS?); combined 160deg (FWHM) FOV perpendicular to orbital direction
Mission life	2 years+ (>2 sky surveys at limiting sensitivity)

4.2.3 Advanced Compton Telescope (ACT)

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

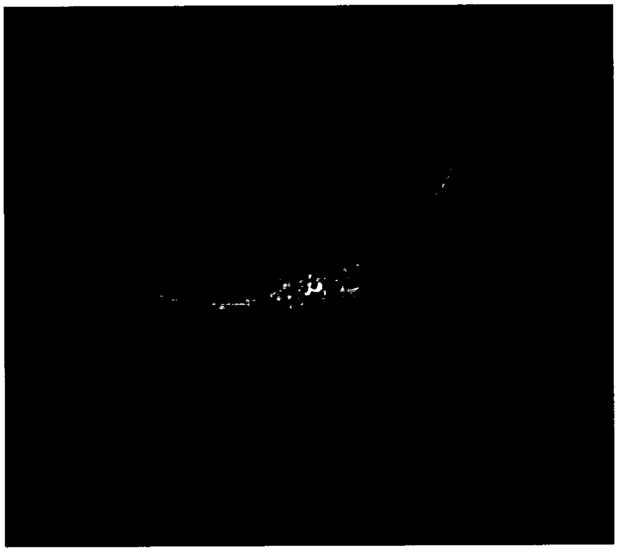


Figure 4.8. The characteristic structure of a Compton Scatter telescopes point-spread function is apparent in this simulation. The intersections of the event circles defines the location of a point-source.

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, and 3) 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 3 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 narrow line. 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 production. 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, and 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 106 s observation. Investigating the physics of SN Ia in Virgo will require greater sensitivity. A meaningful search for lines from ^{60}Fe, estimated at an intensity at least a factor of 10 below ^{26}Al, is likely to be beyond INTEGRAL's reach and detailed study of both the diffuse and central galactic pair annihilation lines will be somewhat limited by the large 0.511 MeV background feature.

Development of a nuclear astrophysics mission that applies new technology to improve sensitivity and to address the deficiencies in the current and planned instruments is the priority of gamma-ray astronomy. Such a mission would address key scientific priorities which have been identified by the scientific community: 1) understanding of the evolution of stars, in particular the SN Ia and core-collapse SN, 2) understanding the origin of the elements through quantitative understanding of the physics of SN and their associated nucleosynthesis, and 3) understanding of the behavior of matter under extreme conditions — investigations of the environment and processes associated with black holes of all sizes (AGN and galactic microquasars). The goal of the development would be an intermediate mission new start in the 2008–2010 time frame. The characteristics of such a mission are summarized in Table 4.4. 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 an advanced Compton telescope (similar to COMPTEL on CGRO) using the newly emerging solid state detector technologies, such as Germanium or CdZnTe strip or pixel detectors. Liquid Argon or Xenon detectors also have interesting characteristics for MeV astronomy missions. In the Compton telescope configurations, the good position resolution of solid state strip or pixel detectors and the excellent energy resolution of Ge and possibly CdZnTe are critical in reducing the background and thus providing the sensitivities indicated in the table.

The priority objectives of this mission include:

- *Understand Type Ia Supernovae explosion mechanism and dynamics.* The mission would measure the structure of SN Ia via ^{56}Co and ^{56}Ni emissions to probe the nature of progenitors and explosion dynamics. Since SN Ia are used as meter sticks to measure the size and shape of the universe, key measurements of SN properties vs. galaxy type could be made as well as cosmic star formation rates vs. redshift. With typical expansion velocities of 5000 km/s expected for the radioactive debris, this implies that a broad line (dE/E ~ 3%) sensitivity of about 10^{-6} photons cm^{-2} s^{-1} in a few days is needed to detect ^{56}Co lines from SNe Ia to distances of 70 Mpc. Based on current discovery rates in the optical, this translates into about 6–8 SNe/yr, each detectable over a period of about 6 months.

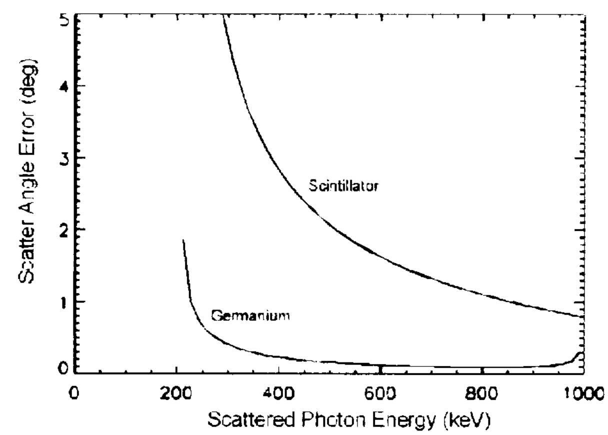


Figure 4.9. The errors in scatter angle for a Compton scatter telescope are directly related to source localization capability. As shown in this figure, advanced materials such as Germanium which provide superior spatial resolution can reduce the errors in reconstructing the source direction.

- *Map the Galaxy in nucleosynthetic radioactivity.* 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, and discover sites of galactic supernovae. The 100-fold improvement in sensitivity and angular resolution over COMPTEL should permit localization of young individual star clusters by the core collapse supernova remnants they contain.

- *Map 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 MeV positron annihilation radiation associated with ^{56}Co production. Diagnostics of the physical properties can be provided by the line profiles and positronium fraction. Positrons are also excellent diagnostics of many high-energy/compact environments. Electron-positron pairs should be created in the intense magnetic fields at the polar caps of pulsars and are expected components in galactic jet sources (microquasars) similar to AGN jets.

Science Objectives of secondary priority are:

- *Use gamma-rays to understand the dynamics of Galactic Novae.* Detection of nuclear emission lines from novae would provide critical tests of the models of novae as thermonuclear runaways on white dwarfs. Early γ-rays from ^{13}N and ^{18}F are the most direct measure of the burning and dynamics. CNO-rich novae should be detectable in later γ-rays from ^{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.

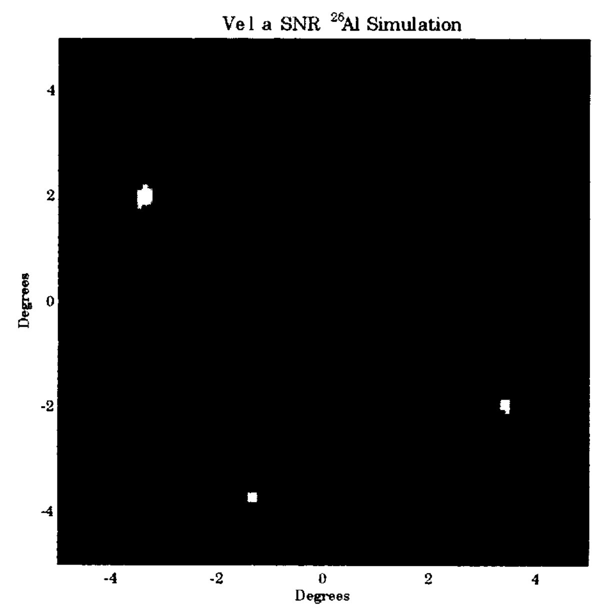


Figure 4.10. Simulation of the structure in ^{26}Al radiation which might be seen from a galactic source such as the Vela supernova remnant by a next generation Medium-energy instrument.

- *Cosmic Ray Interactions with the Interstellar Medium.* Mapping of the galaxy will detect nuclear gamma ray line emission from galactic cosmic ray interactions with the ISM and molecular clouds. These measurements would provide perhaps the only way to study the low-energy (10s of MeV/nucleon) Galactic cosmic rays and their substantial contribution to the ISM total energy budget. Fluctuations would be expected near particle acceleration regions such as in supernovae/cloud interactions. Continuum measurements in the MeV band will map the galactic cosmic ray electron distribution and energy extent.

- Active Galactic Nuclei. The high energy emission of many blazar AGN have their peak energy content in the 1–20 MeV range. These energies also provide some of the most compelling tests for relativistic beaming from γ–γ transparency arguments and the Elliot-Shapiro relation. The detection of e+/e– annihilation radiation would provide dramatic measurements of the conditions in the innermost regions near the central engine. These pairs might be produced through γ–γ pair production in Seyfert AGNs or indicate the presence of antimatter in the jet plasma in the case of blazars.
- *Gamma Ray Pulsars.* These powerful accelerators produce e^+/e^- in copious numbers from photon-magnetic field, photon-photon and interactions with the stellar surface. The detection, redshift and shape of an annihilation feature would probe the environment of the production and annihilation sites.

The principle behind the Advanced Compton Telescope is to measure the energy and position of two gamma ray interactions, from which the arrival direction of the incoming photon is constrained. Conceptually this is done using two detectors, shown in Figure 5.2. The direction of the scattered gamma ray is determined from the positions of the two interactions, and the energy loss in the two interactions uniquely determines the scatter angle (Φ in the Compton formula).

$$\cos\Phi = 1 - \mathrm{mc}^2\left(\frac{1}{E_2} - \frac{1}{E_0}\right)$$

Thus, the direction of the incoming gamma ray is restricted to a cone centered on the direction of the scattered gamma ray, with an opening angle equal to the scattering angle. Figure 5.3 shows a simple cartoon of the telescope, gamma ray interactions, and the reconstructed cone.

Reconstruction of the gamma ray sky is accomplished by the superposition of many such events. Figure 4.8 shows a simple "ring-sum" image reconstruction of a point source in a laboratory demonstration. This experiment was performed using two imaging germanium detectors. The D2 detector was moved to four different locations to simulate a larger array of detectors, hence the four bands of rings in the image. The limiting sensitivity of the Compton instrument can be understood from the ring-sum, determined essentially by the number of rings that pass through the location of the source. The reconstruction algorithms used by COMPTEL on the Compton Gamma Ray Observatory are much more sophisticated and deconvolve the sidelobes or "point spread function" from the image. The same reconstruction techniques also apply for data from the ACT.

The sensitivity and reconstruction ability are directly related to the sharpness of the ring that describes the possible photon arrival directions. Two factors contribute to the sharpness: 1) ability to measure the direction of the scattered photon, and 2) the ability to measure the Compton scatter angle Φ. Good position resolution in the detectors relative to the spacing between the detectors determine the uncertainty, $d\Phi$, in the scatter direction. The detector energy resolution determines the $d\Phi$ contribution to the measurement of the cone angle, given by the formula shown below, where E1 and E2 are the energies in the two detectors, and E0=E1+E2 is the incident energy. It is clear that good energy resolution is needed in both detectors to minimize $\Delta\Phi$, and thus improve the ring sharpness.

$$\Delta\Phi = \frac{mc^2}{\sin\Phi}\left\{\frac{\Delta E_1^2}{E_0^4} + \Delta E_2^2\left(\frac{1}{E_2^2} - \frac{1}{E_0^2}\right)^2\right\}^{1/2}$$

The importance of energy resolution is apparent in Figure 4.9 that compares a Compton telescope using germanium detectors with a telescope similar to Comptel that uses NaI scintillators. The comparison is made for 1 MeV photons. The most useful events scatter by ~45 degrees or less, which corresponds to greater than 635 keV on this plot. The uncertainty in the scatter angle is more than an order of magnitude smaller in the germanium instrument for most of the scattered photons. The number of background events that are consistent with a source location are fewer if the rings are sharp, thus background events are easily identified and rejected. Efficient background rejection is critical to achieving high point source sensitivity.

Table 4.4. Characteristics of the ACT Mission using a High Resolution Compton Telescope

Energy Range	300 keV–20 MeV (Compton mode) 25–500 keV (Coded aperture mode)
Energy Resolution	<3 keV @ 2 MeV
Detector Area	~10,000 cm^2
Field-of-View	~60 degrees (Compton) ~10 degrees (Coded aperture)
Point Source Localization	~5 arcmin
Line Sensitivity	~2×10^{-7} cm^{-2} s^{-1} (1 MeV, Narrow Lines)
	~1×10^{-6} (SN Ia lines, broadened)
Continuum Sensitivity	~1×10^{-5} cm^{-2} s^{-1} MeV^{-1} (0.5 MeV)
Mass	3500 kg (320 kg active mass)
Power	2500 W
Telemetry	3 Mbps
Mission Life	>2 years
Orbit	Low inclination LEO
Spacecraft Pointing	30 arcsec knowledge
Operating Modes	Pointed observation mode any direction, any time

The superb performance of the ACT is shown in the simulated image shown in Figure 4.10. This simple ring-sum image is of the Vela SNR with a hypothetical distribution of ^{26}Al. The total amount of ^{26}Al in the simulation is derived from the COMPTEL measurements. Each of our four knots receive 3% of the total flux with the remaining 88% a broad gaussian distribution in the center. The simulation represents the image that would be produced with a 2 week observation using the ACT telescope described in Table 4.4.

The energy domain of this mission could be extended to lower energies by the inclusion of a coded-aperture telescope above the Compton telescope. The top detector array of the Compton instrument provides a large array of position-sensitive detectors for hard X-ray measurements; in this energy band photo-electric absorption dominates Compton scattering in many detector materials. Simply by placing a relatively thin, low-mass coded aperture above this detector plane to create a coded aperture instrument in the energy range 20 keV to ~300 keV. Such an instrument, with approximately 10 degree field of view, would have excellent continuum sensitivities. Careful simulations of this dual instrument configuration would be needed to verify that the coded aperture mask did not adversely affect the performance of the Compton Telescope. Preliminary studies of this configuration are encouraging in that regard.

The recent developments in gamma-ray detector technology show the way to advanced Compton telescope concepts which provide the significant advance in sensitivities needed to address the broad range of exciting scientific investigations listed above. These sensitivities for nuclear line detections are ~2×10^{-7} cm^{-2} s^{-1} for narrow lines and ~1×10^{-6} cm^{-2} s^{-1} for broadened lines as in SN Ia. The development of such a mission requires key investments in the detector technologies but also in the simulations of the instrument designs and their background radiations.

4.3 LONG RANGE NEW MISSIONS

4.3.1 Next Generation GRB (NGGRB)

In the coming years, missions such as CGRO, *BeppoSAX*, HETE-II, CATSAT, and the Interplanetary Network will be the workhorses which assure that the momentum we have gained in GRB studies is not lost.

After that, the next big step in gamma-ray burst studies will be to accelerate the identification of multiwavelength counterparts. Today, we rely on ground-based photometric observations of ~arcminute burst positions to produce optical positions which are precise enough to position optical spectrometers (arcseconds), and delays of hours or more are routine. Swift, a gamma-ray burst MIDEX currently in Phase A study, will eliminate these delays with its onboard multiwavelength instrumentation. A wide-field gamma-ray camera gives arcminute positions for ~300 bursts per year to a sensitivity better than that of BATSE. The spacecraft then slews in 20–70 seconds to point sensitive narrow-field X-ray and optical telescopes at the burst location. These instruments study the burst afterglow and provide rapid arcsecond positions for further ground-base follow-up.

At high energies, GLAST has the valuable capability to study the very high energy gamma-ray emission associated with bursts, first discovered by EGRET. To do this, the mission must have a modest gamma-ray burst experiment, which is currently part of the instrument complement.

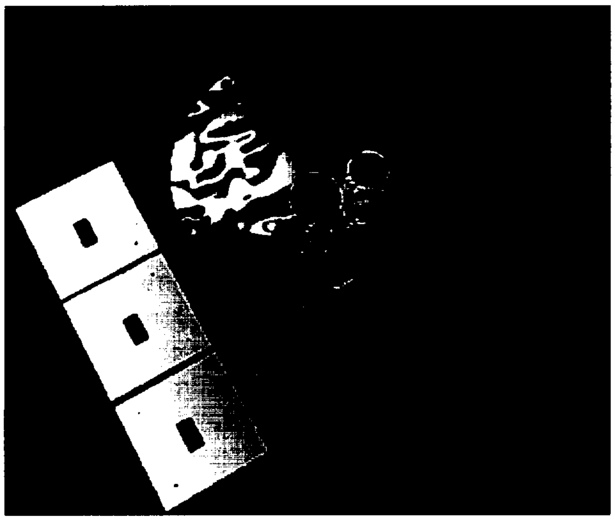


Figure 4.11. A view of the Swift satellite along with the three science instruments.

The recent ROTSE results on prompt optical emission from one burst, GRB 990123, dramatically demonstrate that ground-based, rapidly slewing telescopes can greatly enhance our understanding of the GRB emission mechanisms. Indeed, a network of such telescopes can support not only Swift, but also GLAST observations of AGNs.

We have much to learn from missions like Swift, and that knowledge will undoubtedly provoke more questions. Among them are:

- is there a population of bursts an order of magnitude or more weaker than the ones we are observing? If so, what are their distances?
- do bursts have low energy X-ray iron line emission, as suggested by recent observations?
- can bursts be studied by their emission outside the electromagnetic radiation band (e.g., neutrinos)?

The GRAPWG encourages further development and timely flight opportunities for the next generation of gamma-ray burst experiments.

4.3.2 Next Generation High-Energy Gamma Ray (NGHEG)

We expect a significant revolution in our understanding of the high-energy universe through the GLAST mission. One thing that is already understood is that the spectral energy distribution peaks in high-energy gamma rays for many sources including young pulsars, blazars and at least a large fraction of the unidentified sources. For blazar AGN, source variability demands that a multiwavelength approach should take advantage of simultaneous observations. It would be highly beneficial to maintain a high-energy capability beyond GLAST to provide an essential component for studying such varying sources in concert with future, sensitive telescopes at other wavelengths.

Furthermore, it is likely that other fundamental physics will need to be tested beyond the capabilities of GLAST. For instance:

- Using blazars and the high energy components of GRB's as cosmological probes.
- Mapping our Galaxy, clouds, supernova remnants, and nearby galaxies for cosmic ray sources at arcmin resolution.
- Identifying the counterparts of steep-spectrum and confused high-energy gamma-ray sources that require sub-arcmin positioning. It is already clear from EGRET that not all the sources are blazars and pulsars.
- Pursue aspects of astroparticle physics (high-energy lines from exotic particles, neutrino correlation, etc) beyond the capabilities of GLAST.

4.4 SUBORBITAL PROGRAM

The future of gamma-ray astronomy will continue to depend on the balloon program for the development of new instruments and techniques for major missions. The advent of UNEX opportunities for Long Duration Balloons (LDB) and eventually Ultra-LDB should provide significant alternatives to space for investigations requiring large or heavy instruments. In addition, ballooning provides a critical function in the education and training of students in all aspects of mission design, planning and implementation and is thus essential for the future vitality of NASA. Ballooning provides opportunities for critical "hands-on" experience that is simply not practical in today's environment of highly schedule and cost constrained missions.

Historically, the role of the sub-orbital program has been particularly important for gamma-ray missions, with all the instruments on CGRO (for example) having heritage in the balloon program. 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 keV line emission, ^{56}Co line emission from SN 1987A, 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 promising development of superpressure balloon technology, the long-sought goal of ultra-long duration balloon flights (~100 days) of large payloads (~3000 lb) appears to be finally within reach. The GRAPWG strongly endorses the current push to develop this capability as a viable alternative for implementation of UNEX class missions. To ensure the timely success of this effort, progress is needed in several areas including mechanical, power, communication and recovery systems and the maintainance of overflight agreements. The GRAPWG encourages NASA to pursue innovative approaches to these problems through support of the balloon program and by extending payload development opportunities to the user community.

4.5 SPACE STATION

Gamma-ray astronomy can potentially benefit from the opportunity for locating instruments, which are necessarily massive and often have substantial power and telemetry requirements, on the Space Station. Its high-inclination orbit will have large particle backgrounds, but might not preclude all instrument concepts. Narrow field, pointed telescopes would be problematic, unless detached from the station, but broad-field, survey or monitor instruments are possibilities. For example, a very large area, hard X-ray survey instrument might have otherwise unattainable capabilities. Also, a low-density gas time projection chamber could operate as a Compton telescope with electron tracking in the nuclear line regime. To achieve the sensitivity discussed herein, its size might require construction in space, with the Space Station the obvious location. Frequent launch opportunities might also make tests of prototypes for future major missions feasible. We recommend that NASA commit resources to study the suitability of instrument and mission concepts discussed in this report for the Space Station, and make the available opportunities clear to potential investigators.

CHAPTER 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.

5.1.1 MULTILAYER MIRRORS

The familiar technical challenge to extending traditional grazing incidence optics into the hard X-ray band (E /10keV) 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, g, on a given mirror shell is related to the focal ratio by g = 1/4 x (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 materials employed be chemically compatible for forming

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

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 (photo-electric) 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

Figure 5.1. This slide shows part of the coded aperture mask for the INTEGRAL IBIS instrument.

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., BAT on Swift) or mission concepts studied (e.g. EXIST) 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 Telescopes

Compton telescopes have been used since the early 1970's for making astronomical observations and measurements above 1 MeV. The first orbiting Compton telescope, COMPTEL, on the CGRO 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 first 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. The second is that if the time-of-flight is measured between the triggered detectors, then only photons traveling in the proper direction (forward or backward) need be accepted for further analysis. The third advantage is that although the efficiency of the instrument is low (two scatters are required and one pays the price in effective area), it greatly reduces internal or local background. However, when the direction of the recoil photon is not measured, but only the energy deposits, as with COMPTEL, background still comes from the local sources and the true cosmic photons from nearby points on the sky.

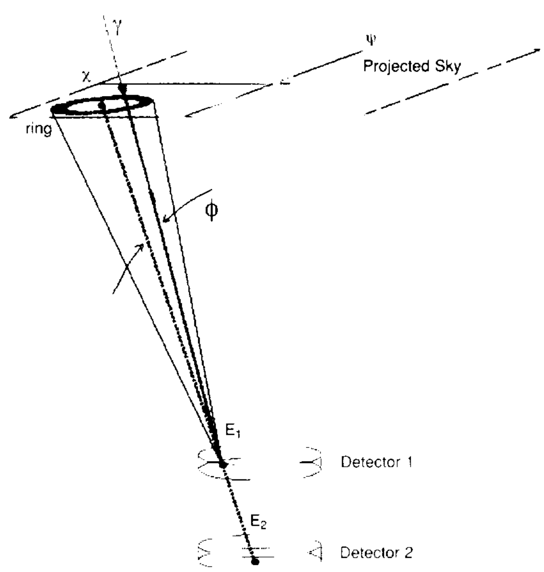


Figure 5.2. A representation of the operating mechanism of a standard Compton Scatter telescope. Measuring the momentum of the scattered electron in the upper detector can collapse the annulur shape of the point spread function to a more standard (and smaller) circle.

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 construct an "event circle" and 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 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 MeV region is home to strong sources of background that competes with the declining spectrum of cosmic sources. In the design of a Compton telescope the lack of knowledge of the recoil electron momentum vector allows real photons from other points on the sky, i.e., on the event circle, to have the same data signature as a photon from the true source. The key to future Compton telescope advances is to increase the instrument's effective area but, more importantly, to reduce background rates, both internal and external.

Although low, significant background exists in present day Compton telescope data, primarily from multiple-photon cascades produced by energetic neutrons. These cascades when they take place near the forward detector can produce signals in both detectors with the proper time-of-flight. These prompt cascades coupled with multiple-photon radioactive decays are the dominant backgrounds in COMPTEL. These background events fog any good image of the sky, or worse, if not controlled, produce artifacts. Three measures individually or together can ameliorate this background. The first is that the track of the recoil electron in the forward detector can be measured, thereby collapsing the "event circle" to an arc segment or a point. This requires tracking technology similar to that being proposed for GLAST or with liquid-xenon "drift chambers." This technique is effective above a few MeV, above the range where electron scattering is strong. This is generally above the range of most nuclear lines. At these energies different production processes in space are responsible for the emission, so that the objects that are bright at a few MeV (the continuum) may not be bright at many tens of MeV, and are likely different from those emitting nuclear lines.

The second method of reducing background is to reduce the width of the "event circle." Superior energy resolution is necessary for this technique. When the full recoil photon energy is absorbed in the rearward detector, the event circle passes directly through the incident direction vector and its small width brings in minimal background. Solid state detectors, e.g., germanium, are ideal for this. However, it is important to fully absorb and measure the scattered photon so that the narrow event circle contributes only to the source and not the background of other points on the sky and that event circles from other (sometimes far removed) points on the sky, likewise, do not interfere with the source measurement. The fine energy resolution of Ge also would greatly improve the signal-to-noise of diffuse narrow line sources. (The benefit to point source narrow lines has already been realized in the narrow event circle and cannot be realized a second time for point sources.) These first two methods of reducing background are also accompanied by finer angular resolution performance, thereby improving the positioning and resolution of sources while also improving the signal-to-noise ratio. Angular resolutions of a several arc minutes is attainable with technology currently under development producing a corresponding improvement in signal-to-noise ratio.

Lastly, in any Compton telescope design the passive material around the primary scatterer must be minimized, because it is the source of the local background.

The ideal Compton telescope design would be in the form of an electron-tracking forward detector with germanium resolution and with the high density electronics necessary to support the large number of data channels. Such an ideal configuration may not fall within the constraints of a new mission, but it is important to note that (1) an electron-tracking Compton telescope will undoubtedly provide significantly better performance than existing Compton telescopes in the nuclear line region where electron tracking is not efficient and similarly (2), a non-electron-tracking high-resolution Compton telescope will undoubtedly provide significantly better performance in the continuum regime above the nuclear lines, where electron tracking is efficient. In this case the choice must be made based upon the available technology and its ability to adapt to the wide range of energies, backgrounds and detection processes that are present in the MeV range. In other words, the different scientific goals of measuring the nuclear lines and the continuum emission may be achieved by either an electron tracking telescope or one that does not perform electron tracking, albeit with different levels of success. This is especially true given that there are likely few opportunities for measuring intrinsically narrow nuclear lines.

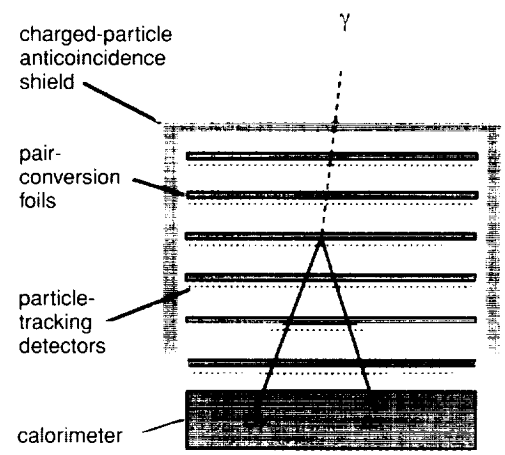


Figure 5.3. Cross-section of a pair-conversion telescope. The four basic elements — anticoincidence, pair converter, pair trackers, and a calorimeter — have not changed in decades. What has changed is the emergence of new detector technologies allowing vastly improved sensitivity.

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, CAT, HEGRA, and CANGAROO telescopes are all active now, and new telescopes (e.g., CELESTE, STACEE, MILAGRO) begin operation in 1999. Within a few years it is expected that these will be joined by VERITAS, HESS, MAGIC and CANGAROO IV.

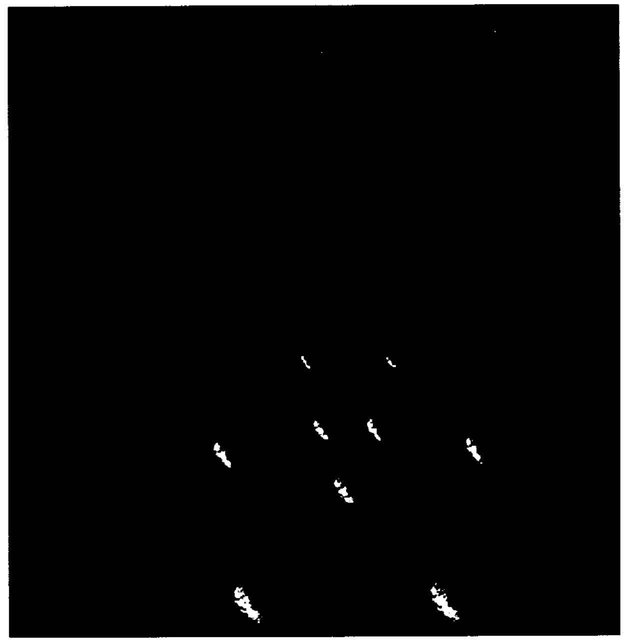


Figure 5.4. This artist's conception of the proposed VERITAS instrument is one example of the future direction of ground-based gamma-ray astronomy.

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 scintillators and photomultiplier tubes. Dramatic progress is now obtainable in this field because of new and developing technologies influencing 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. 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 suitable 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 (though PIN CdTe and PIN CdZnTe have best performance so far). 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 must be 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 micro-m 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 CdTe detectors are: the INTEGRAL imager; the Swift and EXIST mission concepts; and several recently-proposed balloon instruments such as In-Focus.

5.2.1.2 Germanium

Germanium remains the only solid state detector capable of high-resolution spectroscopy in the nuclear energy band. It is also the only semiconducting detector that can be made in large volumes, ~10 cm diameter. These are the reasons it has been used in satellite (HEAO C–1 and INTEGRAL) and balloon missions (Bell/Sandia, Lockheed/MSFC, GRIS, Hexagone) requiring both the best possible energy resolution and large collecting areas. However, the next generation of instrumentation is also going to need fine imaging capabilities that standard large volume co-axial detectors do not provide. These instruments must combine fine angular resolution with high sensitivity well beyond that of INTEGRAL. Planar configurations of germanium detectors with strip or pixel electrodes are being investigated. Both of these concepts achieve good position and energy resolution for applications in coded-aperture or Compton telescope imaging systems. Germanium detectors with 2-mm spatial resolution have been demonstrated in the laboratory in a device measuring 5x5x1 cm in volume. Even larger devices with finer spatial resolution are possible. The principle challenge will be to make large arrays of germanium detectors with high reliability and a reasonable cost. Production of the detector quality germanium material is already a routine manufacturing process. Cost savings will be realized by improvements in the contact technology and device packaging or handling procedures. A germanium 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 germanium also reduces the background by improving the angular resolution in Compton telescopes so that the sensitivity improves proportionally with resolution for point sources, not simply as the square root of resolution in an INTEGRAL-like spectrometer.

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 m m 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 in sizes up to ~9 cm x 9 cm, although 6 cm x 6 cm is more common. Si strip detectors are applicable to both Compton and pair telescopes.

5.2.1.4 Liquid Xenon

Xenon, in its liquid or highly compressed gas phase, is a very good detector material for gamma rays. Large area xenon detectors can be realized in a variety of configurations, using either the ionization or scintillation properties, or both. The basic requirement is ultra pure material, with one part per billion level of electronegative contaminants. A configuration which is particularly advantageous for the detection of high energy gamma-rays is a Time Projection Chamber (TPC) as three-dimensional

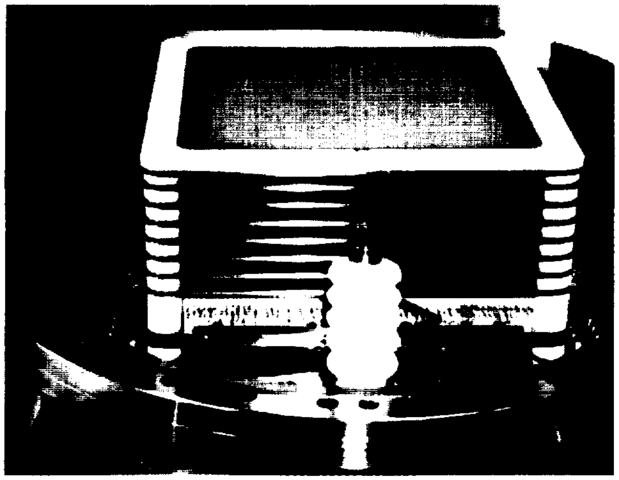


Figure 5.5. A prototype of a Compton scatter telescope with a liquid Xenon Time Projection Chamber as the upper and lower layer.

tracking device and homogeneous calorimeter. In a LXeTPC, such as the 10 liter detector (see Figure 5.5) used in the balloon-borne Liquid Xenon Gamma-Ray Imaging Telescope (LXeGRIT), both charge and light signals are detected to measure the energy and the spatial coordinates of every ionizing event within the sensitive volume. For MeV gamma-rays, which lose energy in multiple Compton scatterings before a final photoabsorption, the knowledge of the energy deposit and the localization in 3D of all interaction points allow a complete reconstruction of each event history. This event imaging translates directly into an effective discrimination against background, independent of the spatial or spectral extent of a celestial source.

A double-scatter Compton telescope based on a coincidence of a liquid Argon TPC as converter and Compton electron tracker, at a fixed distance from a LXeTPC as calorimeter and imager, has been proposed for a substantial improvement in sensitivity and angular resolution over COMPTEL. An alternative approach, which would add fine spectroscopy to the submillimeter quality imaging of a TPC is to operate with high-pressure xenon gas below the critical point. This would also remove the cryogenics requirements of the liquid TPC approach. A baseline design of a Compton telescope realized with a low-pressure XeTPC as converter and electron tracker, surrounded by high-pressure XeTPCs for calorimetry and 3D imaging, is also under study. With an energy resolution of 5 keV FWHM at 1 MeV, a spatial geometrical one), resolution of 300 microns, a large effective area (a substantial fraction of the a field-of-view limited only by the presence of external structures, and a compact size of about 2 cubic meters, this approach can meet the observational requirements of a next-generation nuclear line astrophysics mission.

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.

CHAPTER 6

Supporting Programs

The scientific goals of the gamma-ray astronomy program cannot be achieved without support beyond mission opportunities. Supporting programs in theory, data analysis, and other complementary disciplines are vital to achieving the breakthroughs possible in the next decade.

6.1 DATA ANALYSIS

The recent exciting discoveries in gamma-ray astrophysics are the results of detailed data analysis and correlative studies of past and currently operating U.S. and foreign missions, as well as theoretical studies. However, MO & DA funding is presently inadequate to cover, for example, the CGRO mission, and much excellent science will simply not be done with this great observatory in the coming years. The GRAPWG recomments augmenting the MO & DA funding, and also strongly supports both the Astrophysics Data Program, and the Long-Term Space Astrophysics Program, which are key elements in many correlative, multi-wavelength, and single mission data analysis efforts. To put these results into context, theoretical investigations into the nature of exotic high-energy sources is also essential.

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 Cerenkov 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

Figure 6.1. A view of the HEGRA gamma-ray telescope. Ground based facilities continue to multiply and improve.

The VERITAS approach is not unique among atmospheric Cerenkov 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 (MAGIC), and 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 (CELESTE, STACEE and Solar-Two). Mention should also be made of large water Cerenkov systems e.g., MILAGRO which are most useful as burst monitors and for all-sky surveys.

Radiation Imaging Telescope Array System); this is a logical development of the imaging atmospheric Cerenkov concept and consists of an array of seven 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., $2x10^{-12}$ photons cm^{-2} s^{-1} at 100 GeV. It would also have excellent spectral resolution. VERITAS will be built in Southern Arizona; similar arrays will be built in the southern hemisphere: the German-French HESS in Namibia and Japanese-Australian Super-CANGAROO in Australia.

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 will be continually upgraded to achieve maximum sensitivity before the launch of an EGRET successor.

CHAPTER 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.

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 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.

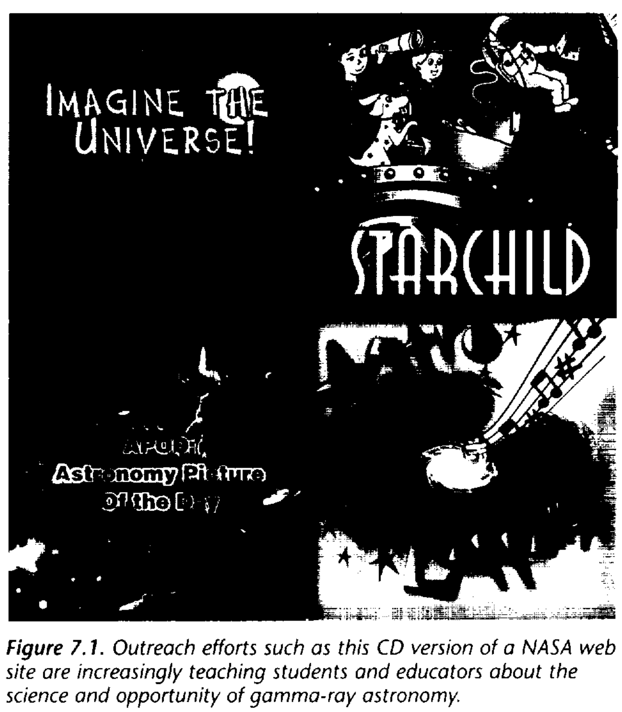


Figure 7.1. Outreach efforts such as this CD version of a NASA web site are increasingly teaching students and educators about the science and opportunity of gamma-ray astronomy.

CHAPTER 8

Recommended Program

The preceeding chapters have described the scope and status of gamma-ray astronomy. This field is, of course, part of a broader enterprise — that of Space Sciences as a whole. While gamma-ray astronomy has its own history and logic, it must also be assessed as part of this wider effort. To that end, the goals and priorities presented in the Executive Summary are repeated here, with an eye to their relevance to the overall goals of NASA's Space Sciences Program.

Our reference point is the 1997 Space Science Strategic Plan (http://spacescience.nasa.gov/strategy/1997/sseplan.htm). This represents a coherent summary of the goals of NASA's science themes. In particular, the list of Science Goals in this plan lends itself to a direct comparison with our priorities. The NASA Science Goals are:

1. Understand how structure in our Universe.(e.g., clusters of galaxies) emerged from the Big Bang.
2. Test physical theories and reveal new phenomena throughout the Universe, especially through the investigation of extreme environments.
3. Understand how both dark and luminous matter determine the geometry and fate of the Universe.
4. Understand the dynamical and chemical evolution of galaxies and stars and the exchange of matter and energy among stars and the interstellar medium.
5. Understand how stars and planetary systems form together.
6. Understand the nature and history of our Solar System, and what makes Earth similar to and different from its planetary neighbors.
7. Understand mechanisms of long- and short-term solar variability, and the specific processes by which Earth and other planets respond.
8. Understand the origin and evolution of life on Earth.
9. Understand the external forces, including comet and asteroid impacts, that affect life and the habitability of Earth.
10. Identify locales and resources for future human habitation within the solar system.
11. Understand how life may originate and persist beyond Earth.

As reflected in the Executive Summary, the recommendations of the GRAPWG are divided into three categories: science priorities, mission priorities, and other recommendations. Below, we further describe these priorities and indicate which of NASA's Science Goals are addressed by each.

8.1 1997 GRAPWG MISSIONS

In the previous GRAPWG report, the top-priority was given to the GLAST high energy gamma-ray mission to follow on the discoveries of the EGRET instrument on CGRO. Other high priority missions were a focusing hard X-ray telescope and a next-generation nuclear line and MeV continuum mission. For Explorer-class missions the top scientific opportunities were found to be for gamma-ray burst observations and hard X-ray surveys. Some of these missions have now been started by NASA: GLAST is in the OSS strategic plan for new start in 2002; the Swift gamma-ray burst MIDEX has been selected for Phase A study with final selection of two missions to fly out of five studies to be made in September 1999. Also, the OSS strategic plan contains the top mission of the X-ray community, Constellation X, which has a focusing hard X-ray telescope (HXT) onboard that achieves some of the objectives identified by the GRAPWG for a focusing hard X-ray mission.

The GRAPWG finds that the scientific case for GLAST, Constellation-X HXT and Swift has grown since 1997. The GRAPWG continues to give its STRONGEST ENDORSEMENT to these mission, which are the backbone of NASA's future program in hard X-ray and gamma-ray astronomy.

8.2 TOP PRIORITY SCIENCE TOPICS

The GRAPWG identifies the following PRIORITIZED list to be the most compelling science topics that future hard X-ray and gamma-ray missions can address beyond those covered by GLAST, Constellation-X HXT and Swift. These are areas in which hard X-ray and gamma-ray astronomy offers unique capabilities for advancing our understanding of the universe. Each science topic is followed by a list of areas in which key contributions are expected.

The HIGHEST PRIORITY science topic is:

1. Nuclear Astrophysics: Sites of Gamma Ray Line Emission

Gamma-ray astronomy holds the promise of revolutionizing studies of nucleosynthesis in our galaxy and beyond. Through the detection of nuclear lines, sites of nucleosynthesis can be studied and elemental abundances can be measured. In addition, the configuration and dynamics of the emitting gas can be determined. Topics for future missions include:

- Abundance yields of explosive nucleosynthesis
- Mass cut between SN ejecta and core
- Supernova and nova explosion physics and dynamics
- Sites of nucleosynthesis in the Galaxy and universe
- Cosmic nucleosynthesis rate from redshifted SN Ia lines
- Supernova rate in the Galaxy
- Better understanding of SN Ia cosmological distance scale calibration
- Cosmic ray interactions with interstellar gas
- Positron diagnostics of compact objects

Other high priority topics are:

2. Gamma Ray Bursts

Appropriate to their nature, gamma-ray burst studies continue to change quickly and dramatically. The increasing number of counterparts at lower energies when coupled with the impressive BATSE database are leading to a new era in GRB studies. Aside from the intrinsic astrophysics of GRB's, bursts will become an important probe of the early universe. NASA Science Goals (1), (2) and (4) are related to GRB studies. Topics for future missions include:

- Links to star formation
- Evolution and populations of massive stars
- Possible sites of black hole formation
- New GRB populations and mechanisms
- Probes of dusty matter in distant galaxies
- Probes of the intergalactic medium out to high redshift

3. Hard X-ray Emission from Accreting Black Holes and Neutron Stars

Hard X-ray and gamma-ray studies of accreting sources are becoming increasingly critical for full understanding of these objects. Detections of galactic and extragalactic black hole systems at high energies provide a laboratory for studying black holes across a wide range of masses. Topics for future missions include:

- First population study of absorbed Seyfert 2's
- Constraints on blazar spectra and diffuse IR background
- Non-thermal components in galactic transients
- Jets associated with galactic BH's and AGN
- Black hole parameters (spin, mass)
- Accretion physics

4. Medium Energy (500 keV–30 MeV) Emissions:

Distinct from nuclear lines, the continuum emission in the medium energy range has been shown to be important for understanding nonthermal emission from objects such as pulsars and AGN and sites of cosmic ray interaction with gas. This relatively unexplored band ties together studies at MeV and GeV energies. NASA Science Goals (2) and (4) are addressed by this science. Topics for future missions include:

- Search for MeV blazars and spectral studies to understand emission
- Pulsar physics through broad-band spectral studies
- Components of diffuse galactic emission
- Extragalactic diffuse emission in poorly measured MeV band
- Nonthermal components from accretion-driven sources
- Cosmic ray interactions with the ISM

8.3 TOP PRIORITY MISSION RECOMMENDATIONS

Figure 1 shows the mission roadmap that the GRAPWG has developed for hard X-ray and gamma-ray astronomy. In addition to the three missions mentioned above, the GRAPWG finds three near-term missions and two long-term concepts to be the most exciting for addressing our top-priority science topics. These are as follows.

ADVANCED COMPTON TELESCOPE (ACT)

The HIGHEST PRIORITY major mission recommended by the GRAPWG is ACT, a high-technology MeV line and continuum Compton telescope mission operating in the 500 keV to 30 MeV range. With a factor of 30 improvement in sensitivity compared to CGRO and INTEGRAL, it promises detailed studies of sites of nucleosynthesis in the universe and a deep survey of continuum sources. The optimum configuration of large imaging detector arrays based on either semiconductor or high density rare gases is being studied to enable a mission in this challenging energy band. The mission addresses science areas (1), (2) and (4) in the above list.

Two other high-priority missions are of particular interest in the coming decade for accomplishing our science goals.

HIGH-RESOLUTION SPECTROSCOPIC IMAGER (HSI)

A high priority intermediate or enhanced MIDEX class mission recommended by the GRAPWG is HSI, a focusing optics telescope operating in the 10 to 170 keV range. With a factor of 100 improvement in sensitivity compared to RXTE, this mission will answer key questions on the nature of accretion onto neutron stars and black holes and will allow detailed studies of sites of nucleosynthesis in the universe. New multilayer mirror technology will enable the upper energy bound of the mirrors to be as high as 200 keV. The mission addresses science areas (1) and (3).

ENERGETIC X-RAY IMAGING SURVEY TELESCOPE (EXIST)

A high priority intermediate or enhanced MIDEX class mission recommended by the GRAPWG is EXIST. A factor of 100 improvement in sensitivity compared to the only previous all-sky hard X-ray survey (HEAO-1) will allow discovery of the predicted, but so-far unobserved, class of absorbed Seyfert 2's that are thought to make up half of the total inventory of AGN's. A large area array of new-technology solid state detectors, used in conjunction with a wide field-of-view coded aperture, will cover the 10-500 keV region and address science areas (2) and (3). The International Space Station is a possible platform for such an instrument.

Complementing these missions will be projects which will extend and improve upon those already in the strategic plan.

NEXT GENERATION GAMMA-RAY BURST MISSION (NGGRB)

The GRAPWG believes that gamma-ray bursts will continue to be one of the most important and fascinating areas of astronomical research for tens of years to come. A mission will be needed in the post HETE-II and Swift era to further this field. Emphasis in that time frame may involve observations of nonelectromagnetic radiation such as gravitational waves and neutrinos and will certainly involve multiwavelength electromagnetic instrumentation. To correlate these data with known properties of bursts and to monitor the sky for infrequent special events, it will be essential to have a continuous gamma-ray burst monitor in space. The GRAPWG recommends that such a mission, NGGRB, be identified in NASA's program.

Next Generation High-Energy Gamma-ray mission (NGHEG)

The discoveries of GLAST will produce strong interest in the astronomical community in high energy gamma-ray phenomena and will undoubtedly raise new fundamental questions. The band width of the high energy range is huge, from 30 MeV to 300 GeV, and overlaps with the growing number of very high energy (TeV and PeV) ground-based observatories. The GRAPWG recommends that a mission called NGHEG be identified in NASA's program to follow on GLAST. GLAST will address NASA Science Goals (1), (2), (3), (4) and (7).

8.4 GAMMA-RAY BURSTS

The GRAPWG is particularly intrigued by the gamma-ray burst problem and the promise that bursts offer for fundamental studies in astrophysics. There are multifaceted implications that bursts have on many future missions. Below are listed some topics and recommendations on gamma-ray burst astronomy. What follows benefits NASA Science Goals (1) and (2):

- HETE-II should be flown on schedule.
- The Swift GRB MIDEX mission, now in Phase A, should have high priority for flight.
- Support should continue for the Interplanetary Network as an effective means for deriving arcminute GRB locations.
- Support should continue for BATSE and the Gamma-ray burst Coordinate Network (GCN).
- The GRB monitor currently planned for GLAST will greatly enhance its GRB capabilities.
- Synergism between space-borne GeV GRB observations and ground-base TeV observations should be recognized and exploited.
- A global network of small, dedicated GRB robotic telescopes should be developed.
- Support for a network of co-ordinated 1–3 meter telescopes to establish lightcurves over the first few days.
- Time on major ground- and space-based observatories should continue to be provided for GRB follow-up observations.

8.5 OTHER RECOMMENDATIONS

Gamma-ray astrophysics is a broad enterprise covering many efforts. The GRAPWG recommends that the following items receive special consideration:

- Technology Development: Many exciting new technologies are arising in gamma-ray astronomy, including multilayer mirrors, Laue lenses (Bragg concentrators), complex coded masks, solid-state pixel and strip detectors, rare gas and liquid detectors, and VLSI electronics. These form the backbone and future of our field. The GRAPWG strongly recommends a vigorous program of technology development for hard X-ray and gamma-ray astronomy.
- TeV Astronomy: Aside from their independent successes, ground-based observatories will provide an important complement to future high energy gamma-ray missions such as GLAST. The GRAPWG endorses the continued development of TeV telescopes with low energy thresholds.
- Balloon Program: The ultra-long duration balloon (ULDB) program offers great potential for both instrument development and significant science in gamma-ray astronomy. The GRAPWG recommends strong NASA support for LDB's and ULDB's.
- International Space Station: The GRAPWG views the ISS as an opportunity for gamma-ray research. It is particularly well suited for wide-field instruments and long-term monitors.
- Optical Telescope Support: Many areas of gamma-ray astronomy research, particularly gamma-ray bursts and AGN studies, benefit from a multiwavelength approach. In particular, optical telescopes can provide important monitoring capabilities which are difficult to achieve at other wavelengths. The development of a network of optical telescopes capable of near-continuous observation of gamma-ray transients is supported by the GRAPWG.
- Data Analysis and Theory: Making the most of the rich databases expected from future missions is an important concern of the GRAPWG. Adequate support for data analysis and theory is a cost effective way of maximizing the return from current and future experiments.

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