Perspectives on MeV Astronomy Instrumentation

James D. Kurfess[*]
Naval Research Laboratory, 4555 Overlook Ave. S.W., Washington, DC 20375 USA

Abstract

Although remarkable progress has been made in gamma ray astrophysics recently (witness the recent advances in understanding gamma ray bursts) many of the early scientific objectives remain unfulfilled. This is due primarily to the rather modest improvement in sensitivity (several hundred) from the pioneering balloon observations in the 1960's to the *Compton Observatory* and *INTEGRAL* missions. Important objectives related to supernovae, novae and the search for line emissions from compact objects will benefit from another factor of 100 improvement in sensitivity. Several instrumental techniques to achieving dramatic improvements will be discussed. These include advanced Compton telescopes using detectors with high spectral and spatial resolution, and concepts for Laue collectors and focusing gamma ray telescopes.

Keywords: Gamma-ray astrophysics, Gamma-ray imaging; Gamma-ray spectroscopy; Position-sensitive detectors; Compton imaging.
PACS: 29.40 n;95.55 n;95.85 Pw

1. Introduction

Substantial progress in low-energy gamma ray astrophysics has been achieved recently with instruments on NASA's *Compton Observatory* and the launch of the SPI and IBIS on *INTEGRAL*. These instruments represent an improvement of several hundred in sensitivity when compared to the first gamma ray instruments flown on balloon payloads in the 1960s. This improvement comes from a combination of larger and more sensitive detectors combined with longer observation times enabled by the satellite missions. However, this is a very modest sensitivity gain when compared to the capabilities achieved in other wavelength bands. X-ray astronomy, for example, has achieved a sensitivity increase of about 10^9 from the first rocket observations using collimated proportional counters to the CHANDRA and XMM missions employing focusing optics. Although great progress has been made, many of the original objectives in gamma ray astronomy await the substantial improvement in sensitivity expected of future missions. In this paper, technologies for meeting these improved sensitivities are addressed.

The scientific objectives in MeV gamma ray astronomy include detailed studies of Type Ia and core collapse supernovae, novae, studies of galactic compact objects (stellar-mass black holes, neutron stars), active galactic nuclei (AGN), gamma ray bursts (GRBs), the connection between supernovae and GRBs, the source of the cosmic gamma ray background, and solar activity. Some of these sources are dominated by continuum emissions while others have unique gamma-ray line emission features. Polarization observations should also become an important new technique for understanding the emission mechanisms in many of these objects.

---

[*] Corresponding author: Code 7650, Naval Research Laboratory, Washington, DC 20375-5352; Tel.: 1-202-767-3182; fax: 1-202-767-6473; e-mail: kurfess@nrl.navy.mil

For continuum observations, the energy range from several hundred keV to ~50 MeV should be covered with a sensitivity comparable to that expected with the planned EXIST and GLAST missions at lower and higher energies. For line observations, the emphasis is on the energy range from several hundred keV to about 6 MeV.

2. Instrumentation options

Several options being actively pursued are Compton telescopes, coded apertures, and collecting (Laue) or focusing optics. An Advanced Compton Telescope mission is the highest priority, and will be discussed in more detail.

2.1 Compton Telescopes

The consensus for the next major gamma ray astronomy mission is a Compton telescope operating from several hundred keV to tens of MeV region. An instrument that could provide a narrow line sensitivity of 10^{-7} γ/cm^2-s in a 10^6 s observation is desired. Relative to alternative instruments, a Compton telescope has several advantages. These include a very large field-of-view which could enable nearly full sky coverage every orbit for a zenith-pointed, low-altitude mission. This would provide excellent coverage for transients sources such as discovery of supernovae and novae, gamma ray bursts, AGN outbursts, and extended coverage for long-lived nuclear line emission from supernovae and novae. Relative to coded-aperture instruments, a Compton telescope would provide background reduction from the Compton imaging. It will also provide excellent sensitivity as a polarimeter. Disadvantages include a relatively high background compared to focusing instruments, compromised energy resolution due to the addition of energy uncertainties from multiple interaction sites, and energy and angular resolution limitations imposed by the Doppler broadening phenomenon (Ordonez et al. 1998). In several of the planned approaches, especially those using arrays of solid-state detectors, the presence of passive material within the active detector envelope for structure and electronics is also a disadvantage.

A significant sensitivity improvement relative to CGRO and INTEGRAL requires a dramatic improvement in efficiency relative to COMPTEL. Most approaches to achieving this invoke a more compact design, but often at the expense of giving up time-of-flight background reduction that was important for COMPTEL. Several detector options are under consideration, including use of position-sensitive solid-state detectors such as germanium (Boggs et al. 2003; Johnson et al. 1995), thin silicon (Zych et al. 2003; Kanbach et al. 2003), thick silicon (Kurfess et al. 2003), cadmium-zinc-telluride (CZT) and CdTe (Takahashi et al. (2003), liquid xenon (Aprile et al. 2003), and gaseous xenon (Bloser et al. 2003). Approximately 25-50 g/cm^2 stopping power (one-two gamma ray mean free pathlengths) is required to achieve good efficiencies for Compton scatter instruments in the MeV region. In several proposed instruments, much of the stopping power is provided by position-sensitive scintillation detectors used to detect the Compton-scattered gamma rays.

Table 1 provides a subjective comparison of alternative detector technologies with respect to several of the parameters relevant to large volume Compton telescopes.

In the following sections, specific issues that relate to the design, performance, sensitivity, and evaluation of alternative Compton telescope configurations are discussed.

Table 1. Comparison of alternative Compton telescope detector materials

	Solid state			**Liquid**		**Gas**	
	Ge	Si	CZT/CdTe	Xe	Ar	Xe	Ar
Energy resolution	best	good - best	good	poor	poor	??	??
Angular resolution	best	best	good	poor	poor	good	good
Efficiency	good	good	good	good	medium	poor	poor
Doppler impact	medium	best	poor	poor	good	poor	good
Electron tracking (0.5 – 2 MeV)	no	in thin layers	no	??	??	yes	yes
Passive materials	poor	poor	poor	good	good	poor	poor
Event reconstruction	excellent	excellent	excellent	medium	medium	medium	medium
Operating temperature	80K	230K	room temp.	180K	100K	room temp	room temp
Use time of flight?	no	no	no	maybe	maybe	maybe	maybe

2.1.1 Event reconstruction: Compact, high efficiency Compton telescopes will require event reconstruction to determine the most likely energy and direction of the incident gamma ray. The probability with which this can be achieved depends on the energy and position resolution of the detectors, the ability to track the scattered Compton electron, time-of-flight (if it can be implemented), and the fraction of passive material in the detector volume. Background rejection will also depend on the use of active shields, tracking the Compton scattered electron, position and energy resolution, and the amount of passive material. Relative capabilities for alternative detector approaches for some of these the parameters are listed in Table 1.

2.1.2 Background rejection: Background rejection will be a major challenge for future Compton telescopes. Time-of-flight will not be an effective technique in some compact instruments (solid-state detectors) that have the required efficiency to achieve substantial improvements in sensitivity. Therefore, alternative techniques to reduce the background are critical. An effective technique is the use of electron tracking to limit the direction of the incident gamma ray to a small segment of the Compton direction cone. Thin silicon detectors and gas detectors are preferred. However, it is likely that electron tracking for gamma rays below 1-2 MeV will be limited by multiple scattering. This leaves event reconstruction as the primary background reduction technique for the nuclear line region. For this case, the excellent spatial and energy resolution provided by solid-state detectors will be a significant benefit. Of particular importance will be the rejection of internal backgrounds associated with spallation products and neutron capture. For example, spallation products such as ^{22}Na and ^{24}Na were important sources of background in the COMPTEL instrument, and will also be a major problem for a silicon-based Compton telescope. Higher-Z detector materials will have their associated spallation products also. Background associated with neutron capture will also be a problem below ~8-10 MeV, and neutron production will be enhanced in instrument designs that use thick, active shields (e.g. CsI) to reduce unwanted cosmic and atmospheric gamma ray backgrounds. The gamma ray cascades associated with prompt neutron capture will be an important concern for Compton telescopes, especially for the multiple Compton technique discussed below.

2.1.3 Doppler Broadening: A limitation of Compton telescopes is the phenomenon of Doppler broadening. This results from the fact that scattering is not off an electron at rest, as the standard Compton formula assumes, but off of atomic shell electrons. The unknown momentum of the scattering electron introduces an additional uncertainty in the energy of the scattered gamma ray for a given scatter angle, or an associated uncertainty in the angle of scattering if the energy of the incident and scattered gamma rays are known. These additional uncertainties are larger for low-energy incident gamma rays and for higher-Z materials (Zoglauer and Kanbach 2003).

2.1.4 Polarization: Compton telescopes are ideal gamma ray polarimeters. Ryan et al. (2003) describe the capabilities for Compton telescope polarization measurements. A large solid-state Compton telescope is estimated to have the ability to detect 1% polarization in some of the stronger gamma ray sources, and should provide unique information on the emission mechanisms in a variety of gamma sources including AGN, gamma ray bursts, pulsars, and accreting black holes.

2.1.5 Multiple Compton Technique: The effective area for large Compton telescopes can be increased significantly with the use of the multiple-Compton technique. If an incident gamma ray undergoes two Compton scatterings followed by a third interaction, the angle of scattering at the second interaction is determined from the three locations. Given the energy loss at the second interaction site, the Compton formula can be used to determine the energy of the scattered gamma ray from the first interaction, and the energy and direction cone of the primary gamma ray can be determined without the full energy of the gamma ray being absorbed (Kurfess et al. 2000). This technique enables low-Z elements, such as silicon, to be considered. As indicated above, this has advantages from the Doppler broadening perspective. Disadvantages, however, result from the event reconstruction that must accompany multiple scatter events (Kroeger et al. 2003), the compromised energy resolution associated with reconstruction of incident gamma rays that do not deposit their full energy (Kurfess et al. 2000), and the likelihood that an interaction might occur in passive material (structure, electronics). Multiple Compton scattering, of course, is more probable in lower-Z materials. Instrument options that combine low-Z and high-Z detector materials may be an attractive option.

2.1.6 Simulations: With several alternative technologies competing for Compton telescope applications, extensive and accurate simulations of the various instrument capabilities becomes essential. Fortunately, Monte Carlo codes to provide these simulations have steadily improved (Weidenspointner et al. 2003; Kippen 2003). Of particular importance and difficulty is the accurate estimate of backgrounds, background rejection, and event reconstruction efficiencies for the high-efficiency, compact designs. Accurate estimates of neutron-induced background, and techniques to reject these backgrounds are of particular concern in Compton instruments. Simulations will also be very useful in comparing instrument performance with and without scintillator shields and in evaluating the preferred orbit for selected missions.

2.2 Coded Aperture Telescopes

The SPI and IBIS instruments on INTEGRAL, along with the SIGMA instrument flown earlier on GRANAT, represent the first coded-aperture gamma-ray telescopes flown in space. Relative to Compton telescopes, the sensitivity of coded aperture instruments improves approximately as the square root of the area or mass of the instrument. Therefore, achieving significant improvements in sensitivity would require massive and expensive missions. One advantage of coded-aperture instruments is the ability to provide substantially better angular resolution than

Compton telescopes (in part due to the Doppler broadening discussed above). The thick masks that are required at MeV energies, however, demands a small field-of-view if good angular resolution is required. For example, the RHESSI mission uses fine Fourier grids to achieve tens of arc-second imaging of solar flares in the MeV region (Smith et al. 2003). Also, coded-aperture instruments are better suited at energies below several hundred keV, such as the hard X-ray EXIST mission described by Hartmann (2003). Improved solar gamma ray imaging might be achieved with the combination of coded-aperture and Compton imaging to provide high spatial and spectral resolution and good efficiency in a single instrument.

2.3 Focusing Telescopes Two instrument options that hold promise for much improved sensitivity are the Laue collector (von Ballmoos et al. 2003) and Phase Fresnel Lenses (Skinner 2001; Skinner 2002). Both techniques use scatterers or lenses that enable collection and/or focusing of gamma rays onto a small position-sensitive detector. Thus, signal to background is dramatically improved. The former uses Bragg scattering in transmission and has been demonstrated both in the laboratory and on recent balloon flights. The latter uses the slightly less than 1 index of refraction to focus gamma rays. A substantial drawback for each of these techniques is the very narrow bandwidth, typically about 1%, of the lenses. The phase Fresnel lens also has a very long focal length, about 10^6 km at 1 MeV, which will require implementation of station keeping technologies and widely-separated spacecraft. But with large area lenses that could be easily fabricated, sensitivities of 10^{-8} to 10^{-9} γ/cm^2-s should be achievable.

3. Summary

Several options are available for making significant improvements in MeV astronomy instrumentation. An Advanced Compton Telescope is widely considered to be the highest priority new mission based on significant improvements in sensitivity using compact, high efficiency designs, a large FoV for full sky coverage, improved energy and angular resolution relative to COMPTEL, and improved techniques for background rejection using electron tracking and event reconstruction. Sensitivity improvements of 25-100 compared to CGRO and INTEGRAL promise explosive growth in low/medium gamma ray astronomy, including the first extensive observations of supernovae and novae, and the first significant capabilities for polarization measurements. Even better sensitivities are on the horizon with focusing instruments such as the Phase Fresnel Lens for dedicated observations of gamma ray lines from point sources.

4. Acknowledgements

This work was supported by the Office of Naval Research and the National Aeronautics and Space Administration.

References

Aprile, E., et al., this volume, (2003)
Bloser, P., et al., this volume, (2003)
Boggs, S., et al., AIP Conf. Proc. **587**, 877 (2001)
Hartmann, D., et al., this volume, (200)
Johnson, W.N., et al., Proc. SPIE **2518**, p. 74-84 (1995)
Kanbach, G., et al., this volume, (2003)
Kippen, M., this volume, (2003)
Kroeger, R.A., et al., Proc. SPIE, **4851**, pp. 1236-1245 (2003)

Kurfess, J.D., et al., AIP Conf. Proc. **510**, 789-793 (2000)
Kurfess, J.D., et al., Nucl. Instr. Meth. in Phys. Res. A, **505** 256-264 (2003)
Ordonez, C.E., et al., IEEE Nuclear Science Symposium, vol. **2** 1361-1365 (1998)
Ryan, J., et al., this volume, (2003)
Skinner, G.K , A&A **375** 691-700 (2001)
Skinner, G.K, A&A **383** 352-359 (2002)
Smith, D., et al. this volume, (2003)
Takahashi, T., et al., this volume, (2003)
Von Ballmoos, P., et al., this volume, 2003.
Weidenspointner, G., et al., this volume (2003)
Zoglauer, A., and Kanbach, G., Proceedings of SPIE, Volume **4851**, pp. 1302-1309 (2003)
Zych, A., et al., this volume, (2003)