

Astrophysics Challenges of MeV-Astronomy Instrumentation

J.M. Ryan

Space Science Center, University of New Hampshire, Durham, NH 03824 USA

Abstract

Meeting the new challenges of gamma-ray astronomy will be difficult. The variety of sources and the nature of their emissions over a wide range of energy and intensities will undoubtedly require an integrated observatory, or its equivalent, in the fashion of *Compton*. However, for the study of sources in the MeV range, a new Compton telescope will be necessary. It must possess an effective area much greater than COMPTEL, but also reject background more efficiently than COMPTEL. With these properties, one could easily attain an order of magnitude improvement in sensitivity over COMPTEL, opening up numerous investigations while providing a rich catalog of sources for subsequent study. Future goals not only include conducting observations over the wide energy range from 0.3-20 MeV, but also performing the best possible measurements of narrow and broad lines, point sources and extended objects, and steady state and transient sources with a large dynamic range. We review the demands on and the challenges in developing a medium energy Compton gamma-ray telescope that can make significant strides in our understanding of the Universe.

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1 Introduction

Medium-energy or MeV gamma-ray astronomy is naturally set apart from gamma-ray astronomy at other energies because of the technical challenges and the detection techniques associated with it. It is ironic that these measurement difficulties are, in part, related to the richness of the science that can be investigated in this energy range. It is the penetrating power of MeV gamma rays that simultaneously makes these photons valuable as probes of almost all energetic astrophysical objects while making them difficult to stop and measure. The study of nuclear lines from cosmic objects is hindered by the excitation of similar nuclear states in the instrument itself. It is the penetrating power of the photons and the ease in which background photons in this range are generated that make this the

most difficult range to study. Consequently, the scientific veins of knowledge in this MeV range remain largely unmined and are there for the taking once we have the equipment for the task.

Compton telescopes are the preferred instrument for measuring the flux and imaging the sources of objects in the MeV range. The first successful such Compton telescope to be placed on-orbit and conduct fruitful observations was COMPTEL. Albeit with crude resolution compared to X-ray and higher energy gamma-ray telescopes, it imaged the sky in this wavelength band and successfully measured steady state and transient emission from a variety of objects, pushing MeV astronomy onto a higher plateau of scientific sophistication. However, the bar is ever being raised. The standards for scientific investigations in the MeV range are being driven not only by the success with the COMPTEL instrument, but also by the success in the energy bands surrounding it and by the technological advances achieved in the laboratory since the conception of COMPTEL. COMPTEL achieved its success not with large effective areas for detecting MeV photons, but with event acceptance criteria that produced a signal-to-noise ratio that enabled the suppression of the intense background in this range. The next large improvement in sensitivity will occur when we are able to apply efficient background suppressing techniques to an instrument with a large effective area, but for reasons described below, these are often conflicting attributes of a Compton telescope.

The sky as it appears in 10 MeV gamma rays is shown in Fig. 1. The number of unambiguously apparent objects is far less than that at 100 MeV, as seen in a similar image produced with the EGRET instrument (Fig. 2). This is partly due to the poorer angular resolution, but also to the ability to identify sources above the fog generated within the instrument. In the most general terms, the next goal for a Compton telescope in the MeV range is to (1) replicate the EGRET-type richness and fidelity of an all-sky image, (2) enable more critical studies of the types of objects already identified with COMPTEL and (3) enable far more critical studies of emissions confined in time (transient) and energy (lines) while opening up new opportunities for discoveries on a variety of fronts. Such sweeping demands on a next-generation Compton telescope reflect the richness of the science that this energy range embodies and our optimism that with new technology we can make such progress on all science fronts simultaneously.

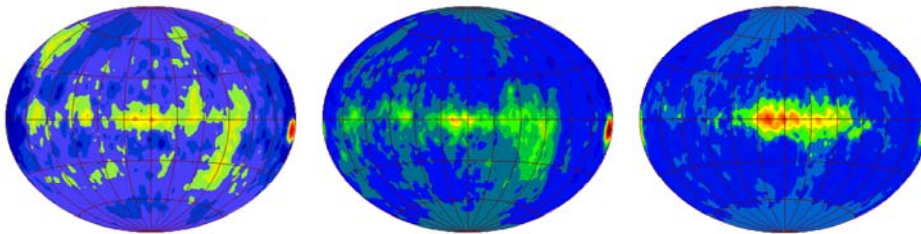


Fig. 1 From left to right: The full-sky image at 1-3 MeV, 3-10 MeV and 10-30 MeV.

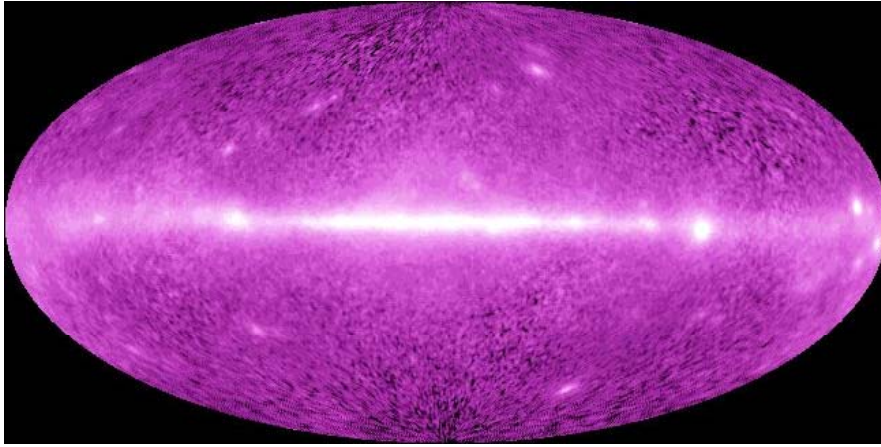


Fig. 2. The full-sky image above 100 MeV.

Without going into detail about the type of objects responsible for the emissions, since this is captured by other papers in this collection, we note that the sources that interest us are both resolvable and unresolvable, steady and transient, and exhibit either continuum or line emissions, and most combinations thereof. The challenge we have put before ourselves is to conduct productive and exciting science for all such problems with a single instrument. Few will argue that more focused objectives can be addressed far more effectively once progress has been made on a broad range of science objectives with a powerful survey instrument. To truly reap the benefit of a more powerful survey instrument in the MeV range, those observations must be supported by observations in nearby energy bands as well as in the radio, optical and infrared. With missions such as GLAST, SWIFT or EXIST that may be present when a next-generation Compton telescope will fly, coordinating observations should be a goal among as many gamma-ray instruments as possible.

2 Why Compton Telescopes?

Compton telescopes, by design and construction, have the advantage of a large signal-to-noise ratio in an energy range where the backgrounds are intense on a space platform. Coded-mask telescopes (e.g., IBIS) or collimated spectrometers (e.g., OSSE) operate by modulating this intense background, either in the space or time domains. They can be made large and excel at detecting intense transients, or point sources where the relevant background is relatively small. They suffer when the flux to be measured is weak or distributed over a large solid angle. Because they do not require coincident detections within the instrument they are unusually susceptible internal activation such as the 511 keV radiation generated internally, obscuring the flux of this important astrophysical line. In general they work best below 1 MeV where the flux is relatively strong when compared to the spectrum of the background.

Flux concentrators or imaging gamma-ray telescopes can achieve high signal-to-noise ratios but do so at the expense of field of view, making them ideal for studies of weak point-like sources, but poor for a survey. They can now be constructed for energies below 100 keV, although conceptual focusing telescopes above 1 MeV are under consideration (Skinner 2003).

By virtue of the Compton process, a Compton telescope can have a large field of view and because a single photon interaction does not fully absorb the photon energy, multiple detections are required thereby reducing the effect of single-site background events within a detector. However, if the instrument is not optically thick then the multiple interaction requirement greatly reduces the efficiency of the instrument making a physically large instrument, in effect, a small one. The other complication is that the geometrical effect of the detection process and the energy of the gamma ray are intertwined as articulated in the Compton formula. This implies, for example, that both the detector energy resolution and the detector spatial resolution both influence the angular resolution of the full instrument.

As was found during the COMPTEL experiment, the multiple interaction requirement did not eliminate background. In fact, background that mimics a multiply scattered gamma ray from an astrophysical source is plentiful in low-earth orbit. The knowledge and control of this background limited the sensitivity of the COMPTEL instrument for weak steady state sources (Schönfelder, 2003). The challenge is thus to simultaneously design a Compton telescope with excellent background rejection properties (much better than COMPTEL) with a large effective area (much greater than COMPTEL). Partial success can be achieved by doing either one of these, but a major increase in sensitivity will only come by achieving both these goals.

3 How do we do this?

The basic Compton scattering process is shown in Fig. 3. The initial scatter of the gamma ray provides a measure of the recoil electron energy while the scattered-photon momentum vector direction is measured by the interaction locations in the separate detectors. With a *full-energy* measure of the *scattered* photon, these data can be combined to produce an *event annulus* on the celestial dome that encompasses all possible originating directions. The width of each annulus is determined by

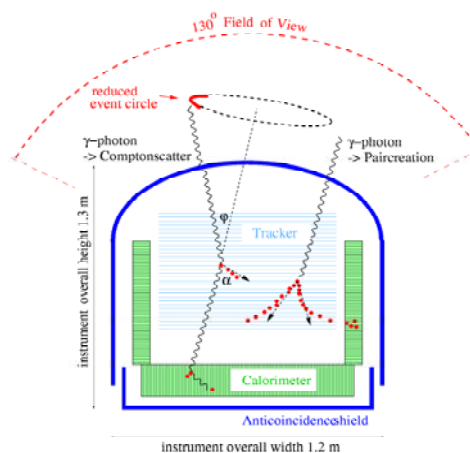


Fig. 3. Compton scatter schematic (Kanbach 2003).

the energy resolution of the detectors. The error in the location of the center of the annulus is determined by the spatial resolution of the detectors.

COMPTEL achieved its good signal-to-noise ratio by requiring a coincidence between two independent detector triggers and measuring the time of flight between the two photon interactions over a distance of 1.6 m, the separation of D1 and D2, the detector systems designed for the successive scatters (Schönfelder et al. 1993). The time-of-flight measurement allowed one to distinguish gamma rays traveling in different directions but traversing the same path. However, this large separation of the detectors resulted in a small acceptance angle for the once-scattered photon. To improve this solid-angle factor the independent detecting elements must be moved closer to one another. This, in turn, makes a time-of-flight measurement difficult. Several new designs have detecting elements separated by a few cm or less (Kanbach et al. 2003, Zych et al. 2003), a time-of-flight separation of much less than 1 ns. Therefore, one must supplant the time-of-flight measurement with one that is at least as effective in suppressing background.

The result of the basic Compton imaging process is illustrated in Fig. 4, an unsophisticated but illustrative example of the concept. This is the quick look image of the 5 May 1991 cosmic gamma-ray burst acquired by COMPTEL. As the figure shows, the intersection of the event annuli occurs at the direction of the source.

Two complications arise in applying this technique generally. The first is that the full energy of the scattered photon may not be measured so that the corresponding inferred scatter angle is too small, with the result that the annulus misses the source direction. The second complication is that the solid angle of these annuli represent the solid angle in which background can intrude on the source signal, because similar annuli can be drawn for background events with some of them falling over the source location. For the example shown in Fig. 4, the signal strength was far greater than the background, thus one does not see annuli that do not intersect the burst location. This points the way to two methods to better suppress background.

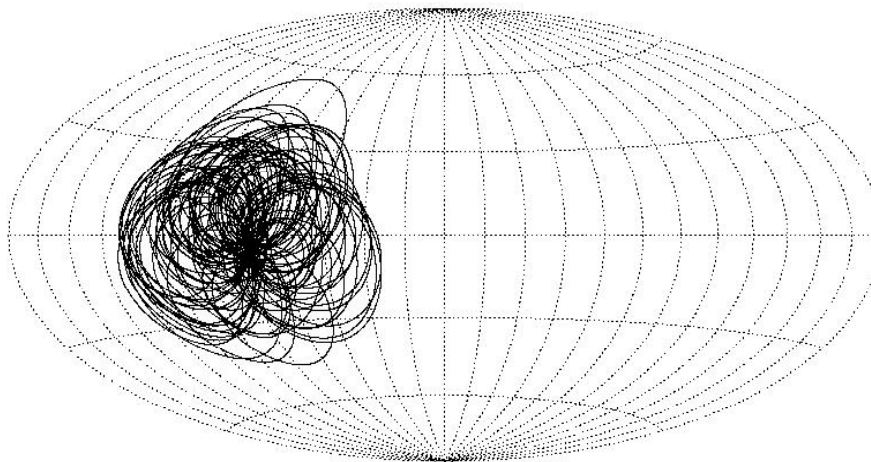


Fig. 4. An “event annulus” image of the 5 May 1991 cosmic gamma-ray burst.

(1) If the full energy measurement of the scattered photon is assured, the radius of the annulus will always be correct and furthermore (2), if the energy resolution of the detectors is good and the uncertainty in the interaction locations is small (fine grained spatial resolution), the width of the annuli will be small, decreasing the solid angle from which background can intrude. (3) The solid angle of the annuli can be further reduced also by measuring the momentum of the first recoil electron. This has the effect of collapsing the annulus to an arc, the length of the arc being a function of the quality of the electron measurement. These represent the major competing methods for background rejection in new designs. In other words, by using some combination of these methods in a compact Compton telescope design one has, in principle, an instrument with a large field of view, a large efficiency by virtue of its compactness, and a means by which background is effectively suppressed. Keep in mind that when we speak of background originating from a certain solid angle, we refer not only to real gamma-rays from that part of the sky, but also virtual photons (i.e., internal background) that produce the same data signature as real photons from that part of the sky. To achieve a major improvement in sensitivity one must effectively suppress this background.

A general recommendation also is apparent, that is, that as many independent measures as possible of the interacting photon should be made. This increases the dimensionality of the data that may allow background features to be isolated in a multi-d data space. An example of this effect was the report of 3-7 MeV emission from the Orion Nebula using COMPTEL data (e.g., Bloemen et al. 1995). After the initial reports, subsequent studies (Bloemen et al. 1999) showed that the vast majority of the 3-7 MeV signal derived from a volume of data space that was heavily occupied by background events from the decay of internally generated ^{24}Na . Only through careful examination of the data space could the origin for the 3-7 MeV emission be ascertained. However, a problem with expanding the dimensionality of the data is that by making numerous independent measurements one increases the data volume and the telemetry requirements, since, at least during the early stages of a mission, the background rejection occurs in the data analysis.

The background that a Compton telescope experiences arises from a variety of sources. These sources for COMPTEL were reviewed by Weidenspointner et al. (2001) and Kappadath (1998). Among others, the three backgrounds that were the most difficult to reject in the COMPTEL data were those that (1) came from random coincidences of independent triggers in the different detector systems, (2) those that came from the multiple photon decays of induced radioactivity, such as ^{24}Na and (3) multiple photon decays of excited nuclei. In this last form of background, neutrons from either the spacecraft or the earth would excite a nucleus in passive material surrounding D1, the first detection system. The excited nucleus then decays on the time scale of picoseconds from a pseudo-continuum of states releasing multiple gamma rays that occupy almost exactly the same volume of data space as celestial photons. Background (1) had time-of-flight values identical to celestial photons, while backgrounds (2) and (3) had imperceptibly different time-of-flight values from real gamma rays. All other measured quantities could easily fall within acceptable values. Each form of background affected its own energy

range and depended on either the overall count rate, the history of transits through the South Atlantic Anomaly or the instantaneous neutron flux, all time variable phenomena.

4 Conclusions

The challenges and recommendations (without regard to our ability to implement them) for a new instrument are thus:

Discriminate between gamma rays traveling in either direction. This is important since for an earth-orbiting instrument the flux of real gamma rays coming up from the earth far exceeds that from the sky.

With a large field of view and a high efficiency, the frequency of chance coincidences will increase dramatically over what COMPTEL experienced. This frequency will also be larger even when scaled to the true gamma ray event rate, thereby reducing the signal-to-noise ratio. *The coincidence window must be as small as possible.* This means that the detectors must be fast.

Reduce the flux of neutrons that can produce prompt background decays. In a low-earth orbit this can only be accomplished by *minimizing the spacecraft mass*. Some of this background can be eliminated in data analysis as described above. *For a large step toward this goal, one might consider a Compton telescope separated from its supporting spacecraft bus and also far away from the earth and its contaminating albedo neutron flux.*

The instrument must be constructed with the minimum passive material. Minimizing such mass reduces the rate of activation in the radiation belts and also reduces the prompt background (3).

The first scattering detector must be constructed from a low atomic number material. As described by Kippen (2003), the effect of the non-zero momentum of the s-shell electron introduces a Doppler shift in the energy of the scattered photon energy. This is a significant problem below 1 MeV, a target for scientific studies because of the 511 line from the Galaxy.

Perform the best measurement possible on the first-scattered photon to achieve the correct radius for the event annulus.

Perform a full energy measurement of the gamma ray if possible.

Use detectors with the best reasonable energy resolution to keep the width of the annuli as narrow as possible.

Perform as many independent measurements of the photon triggered event as is practical.

The COMPTEL instrument results for weak sources were limited by the control of the background. Of course, all the background types mentioned above are time variable or rate variable making better background handling difficult. We should expect any new mission to encounter similar background variability and control

problems, but if the background level is systematically lower, the sensitivity for weak sources will improve correspondingly.

Conducting sensitive and precise measurements of celestial sources in the MeV range will require a next generation survey instrument to do to this part of the spectrum what EGRET did for gamma-ray astronomy above 100 MeV. Such a sensitive survey will spawn more focused studies with other survey instruments and smaller field-of-view telescopes. However, to acquire the instruments necessary for this next step, two technical challenges must be met. The first is that the next Compton telescope must have a large effective area, several times the size of COMPTEL, while it must simultaneously have better background rejection than COMPTEL. While computations of the effective area of new telescopes is relatively straightforward (and have been done by some researchers) realistic computations of the background are much more elusive but are equally important in conceiving the next telescope in the MeV range.

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