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The MEGA Project for Medium Energy Gamma-ray Astronomy

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Abstract The Medium Energy Gamma-ray Astronomy (MEGA) telescope concept will soon be proposed as a MIDEX mission. This mission would enable a sensitive all-sky survey of the medium-energy gamma-ray sky (0.4–50 MeV) and bridge the huge sensitivity gap between the COMPTEL and OSSE experiments on the Compton Gamma Ray Observatory and the visionary Advanced Compton Telescope (ACT) mission. The scientific goals include compiling a much larger catalog of sources in this energy range, performing far deeper searches for supernovae, better measuring the galactic continuum and line emissions, and identifying the components of the cosmic diffuse gamma-ray emission. MEGA records and images gamma rays by completely tracking Compton and pair creation events in a stack of double-sided Si strip detectors surrounded by a pixellated CsI calorimeter. A prototype instrument has been developed and calibrated in the laboratory and at a gamma-ray beam facility. We present calibration results from the prototype and describe the proposed satellite mission.

Key words: gamma-rays: observations — instrumentation: detectors — instrumentation: polarimeters — space vehicles: instruments

1 INTRODUCTION

In the field of gamma-ray astronomy there is an urgent need for a new mission in the medium-energy ($\sim$ 0.4–50 MeV) range to follow up on the success of the COMPTEL telescope on the Compton Gamma-Ray Observatory (Schönfelder et al. 1993). This energy band is crucial for the study of a rich variety of high-energy astrophysical processes. The goal of the Medium Energy Gamma-ray Astronomy (MEGA) project is to meet this need, using modern detector technology to improve on the sensitivity of COMPTEL by a factor of ten.

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The need for new mission in medium-energy gamma-ray astronomy is illustrated in Figure 1, which shows the point source sensitivity of COMPTEL compared to that of past, present, and future instruments in neighboring energy bands.

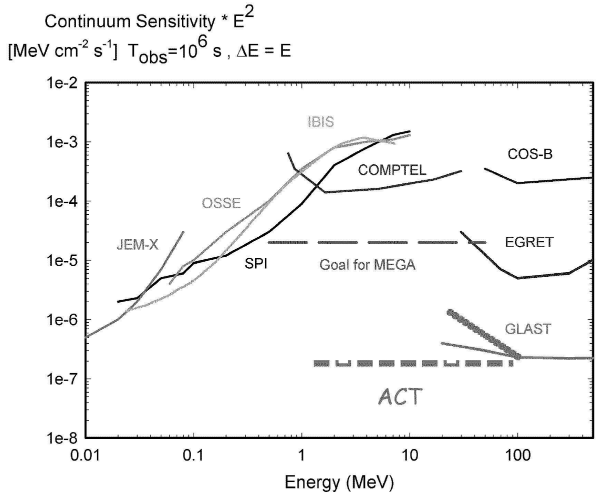

Fig. 1 Sensitivity curves for recent and current gamma-ray and X-ray telescopes, showing the sensitivity goal for a MEGA satellite mission.

The "sensitivity gap" from 0.5–50 MeV is evident. In contrast, above 100 MeV development has proceeded through three successive generations of instrumentation (COS-B, EGRET, and now GLAST, scheduled to launch in 2007), each achieving about a $10\times$ improvement in sensitivity. A similar path of development is needed in the medium-energy band. The 2003 NASA Structure and Evolution of the Universe Roadmap calls for a mission known as the Advanced Compton Telescope (ACT) to achieve a factor of $\sim$100 better sensitivity than that of COMPTEL. This mission is currently the subject of a NASA Vision Mission Concept Study. This Concept Study is critically evaluating advanced detector technologies and developing sophisticated Monte Carlo simulation tools to determine how ACT can be designed. It is already clear that the technical challenges are formidable. In terms of the higher energy instruments, developing ACT now is the equivalent of going directly from COS-B to GLAST. An intermediate step is required that MEGA is designed to fulfill. A sky survey at a sensitivity that repeats what EGRET provided at 100 MeV will identify new objects that will be targets of ACT. At the same time, MeV objects that are or were merely detected with COMPTEL or INTEGRAL can now be studied quantitatively and in some detail. This is the goal of the MEGA project (Kanbach et al. 2005).

2 SCIENTIFIC OBJECTIVES

The medium-energy gamma-ray band is of particular importance for a wide variety of high-energy astrophysical problems, specifically those involving nuclear, non-thermal, and relativistic processes. The production of elements in massive stars and supernovae results in unstable isotopes, such as ^{26}Al and ^{44}Ti, that produce radioactive decay lines in the MeV range. Compact objects, including black hole binaries and gamma-ray pulsars, possess Doppler-shifted nuclear de-excitation lines as well as continuum spectral slopes, breaks, and cutoffs in the gamma-ray band that are characteristic of relativistic particle acceleration and are highly variable. Outside the galaxy, active galactic nuclei (AGN) are prodigious producers of gamma-rays, some especially so in the MeV range. These sources are also highly variable, and therefore must be monitored constantly. Continuous monitoring is also needed to study gamma-ray bursts, which produce the bulk of their energy around 1 MeV. Solar flares exhibit the most complex gamma-ray spectra in the sky. In addition to such discrete sources, both galactic and extra-galactic diffuse gamma-ray emission exists as well. The former arises from both cosmic-ray interactions in the interstellar medium and radioactive material ejected from supernovae; the latter is likely the superposition of distant AGN and supernovae. The combined instruments of CGRO provided a first taste of all these phenomena, but many were only marginally detected. For example, ^{56}Co line emission from SN1991T, the only supernova Type Ia possibly seen in gamma-rays, was detected by COMPTEL at the 3–4 σ level (Morris et al. 1998), and about half of the 10 "MeV blazars" are also seen near COMPTEL's detection threshold. Larger samples with higher significance of all these phenomena, together with continuous monitoring, are needed to learn more. Finally, many of the phenomena described above probably produce gamma radiation that is at least partially polarized. A gamma-ray telescope based on Compton scattering is in principle sensitive to polarization and thus offers a new diagnostic tool for the study of high-energy astrophysical processes (McConnell & Ryan 2004).

3 THE MEGA DESIGN AND PROTOTYPE

Two physical processes dominate the interaction of photons with matter in the medium-energy gamma-ray band: Compton scattering at low energies, and electron-positron pair production at high energies, with the changeover near 10 MeV for most detector materials. In both cases the primary interaction produces long-range secondaries whose momenta must be measured.

MEGA, like previous Compton and pair creation telescopes, employs two independent detectors: a tracker (D1) made of double-sided Si strip detectors, in which the initial Compton scatter or pair conversion takes place, and a calorimeter (D2) made of pixellated CsI detectors, that absorb and measure the energy of the secondaries (see Fig. 2).

For Compton interactions, the incident photon scatters off an electron in the tracker. The interaction position and the energy imparted to the electron are measured. The scattered photon interaction point and energy are recorded in the calorimeter. From the positions and energies of the two interactions the incident photon angle ϕ is computed from Compton kinematics. The primary-photon incident direction is then constrained to an event circle on the sky. For incident energies above about 2 MeV the recoil electron usually receives enough energy to penetrate several Si layers, allowing it to be tracked. This further constrains the incident direction of the photon to an arc (the reduced event circle in Fig. 2). This electron-tracking ability is the primary advantage of the MEGA concept: it reduces the angular area from which each photon could have come, which greatly lowers the contamination from background events. In the case of pair production, the incident photon converts into an electron-positron pair in the tracker. These two particles are tracked and determine the incident photon direction. The total energy is then measured through the deposits in the tracker and/or the calorimeter.

A prototype of the MEGA telescope has been constructed in the laboratory at MPE in Garching, Germany (Fig. 3). The prototype tracker has 10 layers of double-sided Si strip detectors, each made up of 3×3 Si wafers (each wafer 6 cm $\times$ 6 cm, 500 μm thick, with a pitch of 470 μm; Bloser et al. 2003). The calorimeter comprises 20 modules of CsI detectors, each with a 10×12 array of crystals either 2 cm, 4 cm, or 8 cm deep (Schopper et al. 2000). The 8 cm crystals have PIN diodes on both ends, which allows the depth of the photon interaction to be determined by the ratio of output light. Both the tracker and calorimeter detectors are read out by identical front-end ASIC chips (TA1.1 chip by IDE, self-triggering with 128 channels). The data acquisition is performed with custom-made front-end control units, trigger processing card, and power supplies, together with laboratory VME electronics and a VME-based single-board computer. The individual detector units must be calibrated individually using laboratory radioactive sources, and then the entire telescope may be tested using higher energy sources and a coincident trigger.

4 PROTOTYPE CALIBRATION RESULTS

From January to March 2003 the prototype was calibrated with laboratory sources (^{22}Na, ^{137}Cs, ^{88}Y) in the near field. In April/May 2003 it was calibrated at the High Intensity Gamma Source (HIγS; Litvinenko & Madey 1995) at Duke University (Durham, North Carolina) in the far field (Andritschke et al. 2004; Zoglauer et al. 2004a, 2004b). The latter calibration used mono-energetic ($\Delta E/E < 2\%$) and 100% polarized pencil beams at different energies (0.7, 2, 5, 8, 10, 12, 17, 25, 37 and 49 MeV) and different incident angles (0°, 30°, 60°, 80°, 120°, 180°). Based on these data, preliminary imaging properties of the telescope

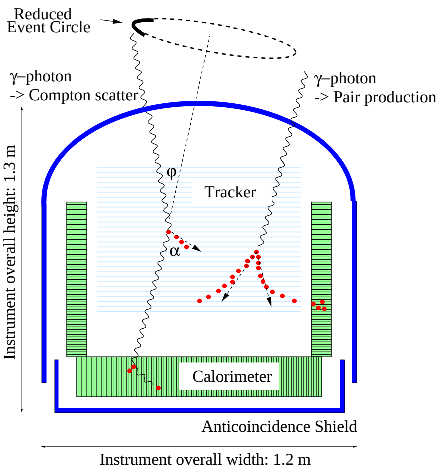

Fig. 2 Schematic of the MEGA telescope showing the kinematics of gamma-ray interactions.

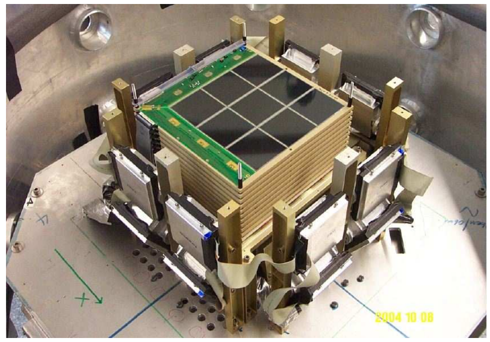

Fig. 3 The MEGA prototype including Si strip detectors (D1) and CsI detectors (D2).

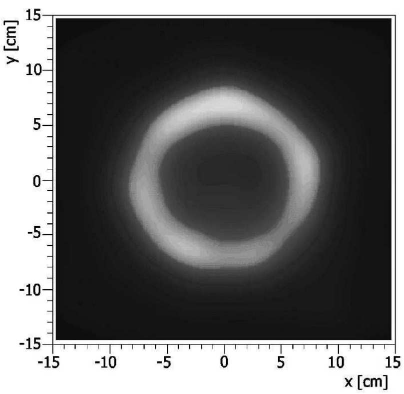

Fig. 4 The time-averaged image of two gamma-ray sources moving in a circular path in the field of view.

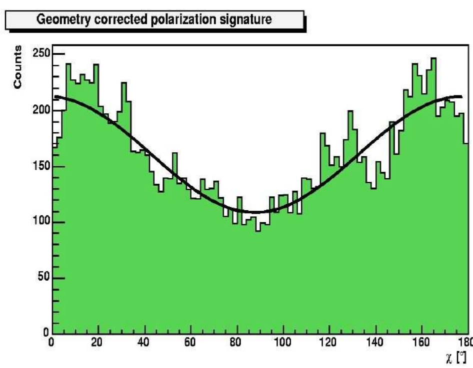

Fig. 5 Geometry-corrected distribution of the azimuthal scatter angle for 100% polarized photons (710 keV).

were determined. These are the most thorough calibrations of a prototype advanced Compton telescope ever performed.

The image reconstruction is performed using an unbinned maximum-likelihood method called *list-mode maximum-likelihood expectation-maximization*, which originally was developed for medical imaging of a SPECT camera (Wilderman et al. 1998) and later adapted for astrophysics (Zoglauer 2000; Zoglauer et al. 2005). This method uses different event types (tracked and un-tracked Compton events as well as pair events) in one image while preserving all measured information.

The imaging capabilities of the MEGA prototype are demonstrated in Figure 4 (Zoglauer et al. 2004a).

Two ^{88}Y sources were mounted on a rotating propeller located 27 cm above the center of the tracker to simulate an extended source. The sources moved in a circular path of radius 7 cm. This corresponds to an angular diameter of $\sim$29° at infinity. The image contains 138 000 Compton events in the energy range from 0.8 to 1.0 MeV. The non-uniformities in the image are artifacts of the instrument response, an effect that should be correctable.

The reponse of the MEGA prototype to 100% polarized radiation at the HIγS calibration is shown in Figure 5 (Zoglauer et al. 2004b). Since photons tend to Compton-scatter at right angles to their electric field vector, Compton telescopes are inherently sensitive to polarization (McConnell & Ryan 2004). The polarization is characterized by the modulation factor $\mu = (N_{\max} - N_{\min})/(N_{\max} + N_{\min})$, where $N_{\max}$ and $N_{\min}$ are the number of counts at the maximum and the minimum of the azimuth distribution. With the 100% polarized beam $\mu_{100} = 0.31 \pm 0.03$ (Fig. 5). Monte Carlo simulations predict $\mu_{100} = 0.304$.

The extensive laboratory and HIγS calibrations prove that the MEGA technique of detecting gamma rays works for a large energy range over a wide field of view. Good imaging and polarimetry capabilities have been demonstrated. Further tests are planned with the prototype to investigate background rejection techniques.

5 THE MEGA MISSION

A mission built around a Compton telescope like MEGA would fit within the NASA MIDEX envelope in terms of mass, power, and cost. The tracker would contain 32 layers, while the calorimeter would be 8 cm deep on the bottom and 4 cm deep on the sides. The ideal orbit for the MEGA mission should be a variation of a zenith pointing equatorial orbit. The advantage of such an orbit is that the spacecraft and instrument avoid the South Atlantic Anomaly, minimizing the activation in and around the instrument, while keeping the Earth's atmosphere as far from the instrument aperture as possible. Except for the celestial poles, the sky will get complete coverage without the complexity of regular attitude control and pointing. Dedicated pointings for bursts and targets of opportunities may still be possible at the expense of complicating spacecraft operations and spacecraft complexity.

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DISCUSSION

CARLOTTA PITTORI: You said that in MEGA you have calorimeters also on the lateral sides. Don't you have the problem of contamination of the signal due to the backsplash from the calorimeter?

BLOSER: The photon can scatter in the calorimeter back into the tracker, but we can usually recognize this in the event reconstruction, especially with the information from the electron track.