# The MEGA Project

G. Kanbach [a], R. Andritschke [a], F.Schopper [a], V. Schönfelder [a],
A. Zoglauer [a], P.F. Bloser [b], S.D. Hunter [b], J.A. Ryan [c],
M. McConnell [c], V. Reglero [d], G. DiCocco [e], J. Knödlseder [f]

[a] *Max Planck Institut für Extraterrestrische Physik, Garching, Germany*
[b] *Goddard Space Flt. Ctr., NASA, Greenbelt, MD, U.S.A.*
[c] *University of New Hampshire, Durham, NH, U.S.A.*
[d] *GACE, University of Valencia, Spain*
[e] *IASF/CNR, Bologna, Italy*
[f] *CESR, Toulouse, France*

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**Abstract**

We describe the development of a new telescope for Medium Energy Gamma-Ray Astronomy (MEGA) for the energy band 0.4 - 50 MeV. As a successor to COMPTEL and EGRET (low energies), MEGA aims to improve the sensitivity for astronomical sources by at least an order of magnitude. It could thus fill the severe sensitivity gap between scheduled or operating hard-X-ray and high-energy $\gamma$-ray missions and open the way for a future Advanced Compton Telescope. MEGA records and images $\gamma$-rays by completely tracking Compton and Pair creation events in a stack of double sided Si-strip track detectors surrounded by a pixelated CsI calorimeter. A scaled down prototype has been built and calibrations using radioactive sources and exposures to an accelerator generated $\gamma$-ray beam were performed in 2003. A balloon flight is planned for 2004.

*Key words:* gamma-ray astronomy, medium energies, MEGA
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## 1 Introduction

If we consider the sensitivity of past, present, and scheduled future hard-X- and $\gamma$-ray telescopes as shown in Fig. 1, we realize that a severe deficiency

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*Email address:* `gok@mpe.mpg.de` (G. Kanbach).

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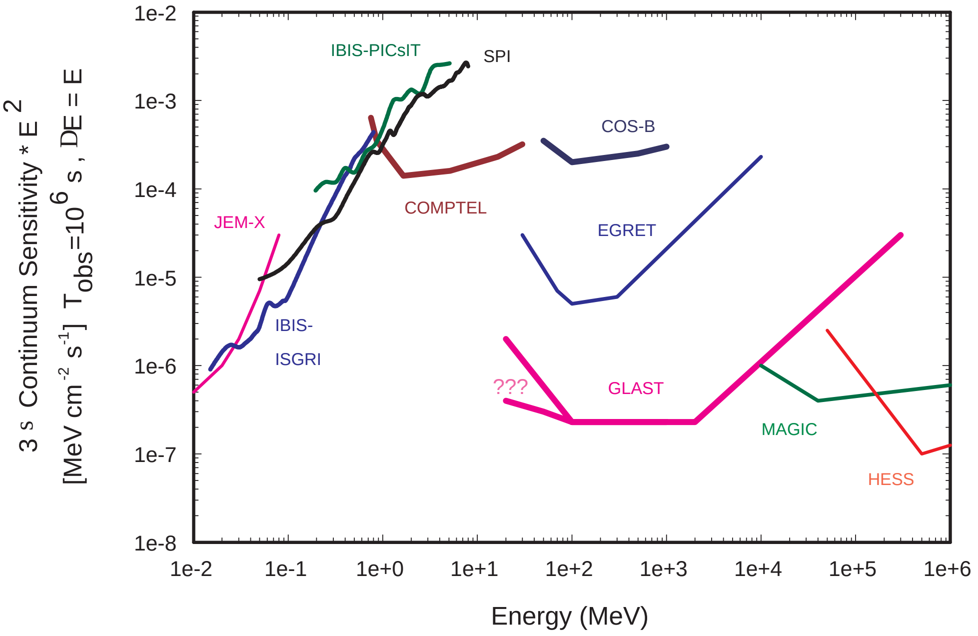

Fig. 1. Sensitivity of $\gamma$-ray telescopes: Past: COMPTEL, COS-B, EGRET; Present: INTEGRAL JEM-X, IBIS, SPI, MAGIC, HESS; Future: GLAST

exists for the foreseeable future in the energy range from a few 100 keV up to several 10's of MeV. The successful COMPTEL (0.7-30 MeV) and EGRET ($> 50$ MeV) telescopes on the Compton Gamma-Ray Observatory (deorbited in June 2000) performed the first complete all-sky surveys (Schönfelder, 2003) and set the foundations of modern $\gamma$-ray astronomy. The next survey at $\geq 30$ MeV, with $\sim 30$ times the EGRET sensitivity, will be done with GLAST (launch expected in 2006) and a planned mission like EXIST (10-600 keV, see Hartmann et al., 2003) will improve previous surveys in the hard X-ray range. Not all telescopes depicted in Fig.1 can be considered 'survey-type' missions (INTEGRAL and the TeV installations have limited fields of view) but the GLAST and EXIST projects are intended as survey and monitor missions. We consider the ability to conduct all-sky surveys also in the low to medium gamma-ray energy range as a major scientific goal for the successor mission to COMPTEL. Many sources (e.g. blazars, binaries, novae, bursts) are extremely variable in this band and can only be discovered and monitored with a continuous all-sky telescope. Emission structures in the local and galactic interstellar medium (e.g. radioactive clouds; galactic arm structure) extend over large angular scales and can only be fully mapped with a wide-angle instrument. The goal of the MEGA project is to meet this challenge and improve the sensitivity of COMPTEL by about an order of magnitude using modern detector technology. The energy coverage should also be extended up to energies of $\sim 50$ MeV to overlap with the GLAST instrument.

Key parameters of a full MEGA space instrument are an effective area of

$\sim 100\ cm^2$, a large field of view of ~ 130°, angular and energy resolutions of ~ 2° and ~ 8% (all FWHM at ~ 2 MeV) respectively. If operated on a zenith pointing satellite MEGA will be an ideal continuous all-sky monitor providing data on transient sources, on cosmic high-energy accelerators, nucleosynthesis sites with $\gamma$-ray lines, and map the large-scale structures in the Galaxy and beyond. This paper outlines the development of a small scale prototype and the concept of a space mission for MEGA.

## 2 Design of the MEGA Telescope and its prototype

Figure 2 shows the principle of the MEGA telescope. Compton scattering below ~ 8 MeV and electron-positron pair production at higher energies dominate the interaction of photons with matter in the medium-energy gamma-ray band. The primary interaction produces long-range secondaries whose momenta and energies must be measured in order to reconstruct the incident photons. An effective detector must not only trigger on both types of events but also suppress background events very effectively. MEGA, like previous Compton and pair creation telescopes, will employ two separate detectors to accomplish the task: a tracker, in which the initial Compton scatter or pair conversion takes place and the trajectories of the electrons are imaged, and a calorimeter, which absorbs, localizes, and measures the secondaries. For Compton interactions, the vertex position, energy and momentum vector (for incident energies above ~ 2 MeV) of the electron are measured. The scattered photon interactions are recorded in the calorimeter. From the positions and energies of the correctly sequenced interactions the incident photon direction is computed from the Compton equation. The primary photon's incident direction is either constrained to an "event circle" (untracked primary electron) or to an "event arc" as shown in figure 2. The differential Klein Nishina cross-section for Compton scattering is strongly dependent on the polarization of incident $\gamma$-ray photons. Scatters occur preferentially perpendicular to the direction of the electric vector of the incoming photon. The strongest azimuthal modulation in the density of scattered photons will be detectable for $\gamma$ energies of 1-5 MeV and scatter angles of $20 - 60°$. This will make a Compton telescope with a calorimeter covering a large solid angle a unique polarimeter for $\gamma$-radiation. Further details on $\gamma$-ray polarization can be found in Ryan et al., 2003. In the case of pair production, the incident photon converts into an electron-positron pair in the tracker. The momenta of the pair particles are tracked and determine the incident photon direction. The total energy is given by the total deposit in the tracker and/or the calorimeter.

The design of MEGA is based on numerical simulations (GEANT3 and -4) as well as experimental developments. In the concept (Figure 2) the tracker contains 32 layers of double-sided Si detectors (thickness $500\mu$m, area $6 \times 6$

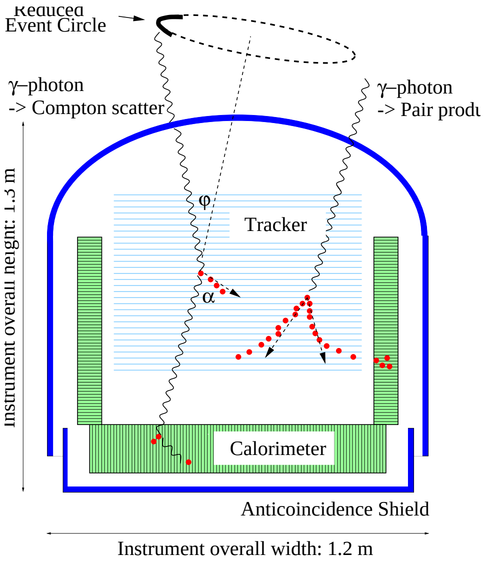

Fig. 2. Detection principle (Compton scattering with and without electron tracking, pair creation)and schematic layout of the MEGA $\gamma$-ray telescope

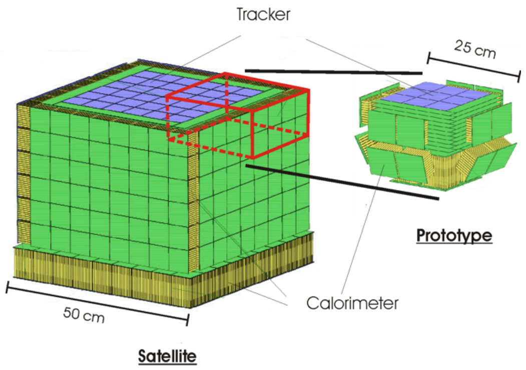

Fig. 3. Monte Carlo (Geant 3) models of a MEGA satellite telescope and the scaled down prototype detector (25% area, 33% depth)

cm$^2$ each wafer, 6 × 6 wafers/layer) and the pixelated CsI calorimeter is 8 cm deep on the bottom and 4 cm on the side walls. The cross-section of the CsI bars is 5 × 5 mm$^2$. These choices were partly motivated by the decision to construct a representative prototype detector (also shown in Figure 2) of about 1/4 area and 1/3 of the depth of the final telescope.

The prototype tracker contains 11 layers with 3 × 3 arrays of 500 $\mu$m thick silicon wafers, each 6 × 6 cm$^2$ in size and fitted with 128 orthogonal p and n strips on opposite sides (470 $\mu$m pitch). The strips are biased using the punch-through principle and AC-coupled via metal strips separated from the strip implant by an insulating oxide/nitride layer. The strips from adjacent wafers in the $3 \times 3$ array are wire-bonded in series and read out by 128-channel TA1.1 ASICs, creating a total position-sensitive area of 19 × 19 cm$^2$. At 20° C a typical energy resolution of 15-20 keV FWHM, a position resolution of 290$\mu$m (measured with muon tracks), and a time resolution of $\sim$ 1$\mu$s was achieved.

The prototype calorimeter consists of 20 modules, each with an array of $10 \times 12$ CsI(Tl) scintillator bars of cross-section 5 × 5 mm$^2$. They are read out with monolithic 10 × 12 arrays of Si PIN-diodes and low-noise, self-triggering front end electronics. The length of the bars (the depth of the calorimeter) was chosen to correspond to the stopping power needed to absorb the scattered photons at different angles, i.e. large scattering angles result in low energy secondary photons which are stopped in short crystals while forward scattering leaves energetic secondaries that require a deep calorimeter. The upper side modules are 2 cm deep, the lower side wall 4 cm, and the bottom calorimeter is

8 cm deep. Depending on type, the energy resolution of the calorimeter varies between 40 and 100 keV for 0.5-1.3 MeV photons. Overall the calorimeter covers about 40% of the solid angle in the lower hemisphere of the prototype.

The MEGA prototype contains 8448 and 2880 data channels in the tracker and calorimeter respectively. A satellite telescope with the same pixelation contains more than ten times this number of data channels. Data acquisition from this large number of channels demands highly integrated, low power electronics. The front-end containing the integreated pre-amplifiers (TA1, IDEAS, Oslo), read-out repeaters, opto-couplers, a FPGA based trigger processor and power supplies for electronics and detectors are custom developments. The back-end with the signal transceivers, analog-to-digital convertors, and an on-board computer (OBC) with mass storage (10 GB hard disk), is based on VME modules. The data acquisition and detector control software operates on a PC Linux system (Pentium III, 850 MHz). A coarse estimate of the effective area of the prototype at a few MeV results in about 2 $\text{cm}^2$.

A photograph of the prototype detector integrated on a robust support structure, which allows to transport and handle the telescope in beam test calibrations and on a balloon payload, is shown in Zoglauer et al., 2003. More details on the MEGA prototype can be found in Kanbach et al., 2003. A $\gamma$-ray detector with similar characteristics to MEGA, the project “TIGRE”, is under development at the University of California, Riverside (Bhattacharya et al., 2003).

## 3 Calibration and Balloon Flight

After completing integration and lab testing of the MEGA prototype, a beam calibration of the detector was performed in April/May 2003. Photon beams from the High Intensity Gamma Source (HIGS) facility at the Free Electron Laser Laboratory of Duke University, NC (see Andritschke et al., 2003) provided excellent probes to determine the detector response. The telescope was exposed to monoenergetic beams with energies from 0.7 to 50 MeV and at inclination angles from 0 (axis) to 180 (from behind). A total of about 15 million events were recorded in the beam test and are currently being analyzed. Preliminary results are given in Andritschke et al., 2003, and Zoglauer et al., 2003.

In 2004 a ballon flight is planned for the MEGA prototype. This project, designated “MEGABALL”, will be jointly conducted by the groups at MPE, University of New Hampshire, Goddard Space Flight Center, GACE, Valencia, Spain, and IASF, Bologna, Italy. The National Scientific Ballooning Facility (NSBF/NASA) will perform the flight either from Palestine, TX or Ft. Sum-

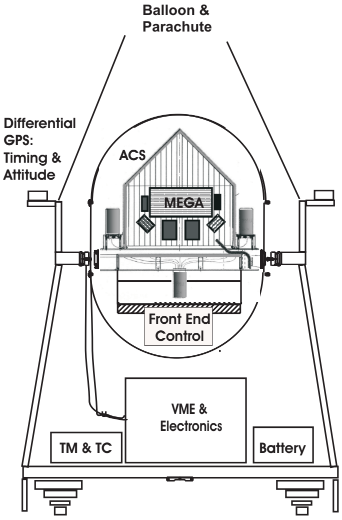

Fig. 4. Balloon payload configuration of the MEGABALL $\gamma$-ray telescope

Fig. 5. Photograph of the MEGABALL detector inside the open pressure vessel

ner, NM. Depending on the season and site of the launch, we expect at least a 10 hour flight at a float altitude of 38-40 km. Figure 4 shows a schematic cross-section of the balloon payload. The MEGA prototype telescope will be at the core of the payload enclosed in a pressure vessel. It will be surrounded by an anticoincidence shield (ACS) to veto charged particles of cosmic and atmospheric origin. The ACS is made of 0.5" plastic scintillator plates (Bicron BC 412) which are read out through wavelength shifting fibers and PMTs (spare units from the EGRET satellite project). The telescope, front-end electronics, repeaters and optocouplers, are housed in the upper pressure container. A second pressurized container holds the back-end and command electronics. The attitude of the telescope is not actively controlled but will be measured in short time intervals ($\sim$ 0.5s) with a differential GPS, which will also supply the absolute time to be included in the event records. The principal goal of MEGABALL is to demonstrate this technology in a realistic background radiation environment. Although the long-term radiation effects of a space mission, like buildup of radioactivity in the satellite structure, are absent during a balloon flight, the prompt radiation effects from cosmic rays and their showers in the upper atmosphere ( including neutrons, protons, muons and electron-photon showers) present a formidable challenge to any $\gamma$-ray telescope. The efficiency in suppressing such a background will be of utmost importance for estimating the sensitivity of a space instrument.

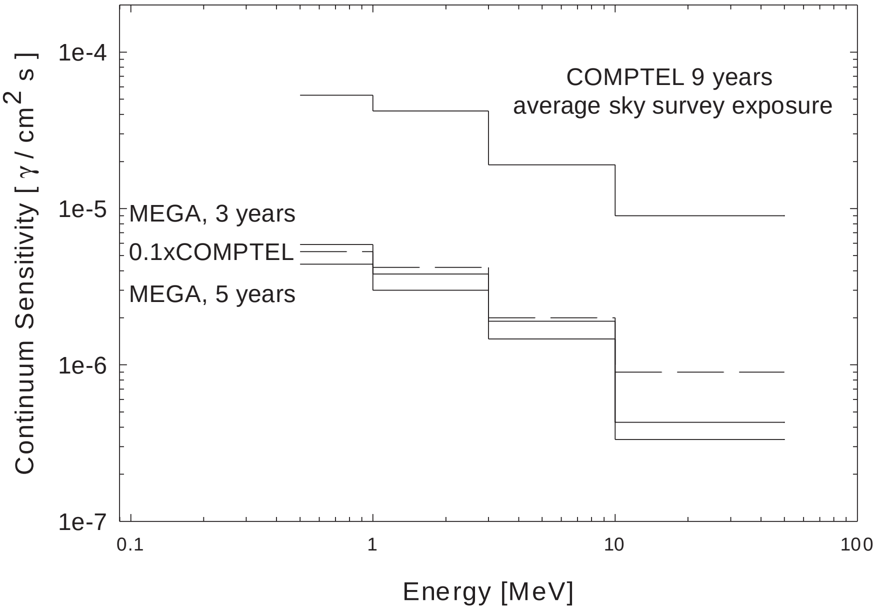

Fig. 6. Sensitivity achieveable with a MEGA satellite telescope during a 3 or 5 year mission.

## 4 A MEGA satellite mission

Based on the MEGA concept and prototype a small satellite mission has been studied (pre-phase A study, DJO, 2000). The satellite detector will have a mass of about 650 kg and dimensions of 1.3m diameter by 1.1m length. Placed on a standard small satellite platform the payload has a launch mass of about 950 kg, a diameter of 2.0 m, and a length of 2.3 m. The electrical power requirement will be ∼400 W, and the average telemetry rate about 50 kbit/s. The development time of MEGA to launch could be about 5 years and an orbital mission of 3-5 years should be foreseen. MEGA would best be operated overlapping with GLAST. This leads potentially to a high scientific return due to the complementary energy bands of the two missions. For MEGA a low-earth equatorial orbit (∼500 km), providing an environment with low particle background, should be foreseen. From such an orbit MEGA could perform all-sky scans with the axis always pointed close to zenith. The large field-of-view describes a wide path of exposure during each orbit and allows the telescope to monitor most of the sky continuously for transient sources. Real-time telemetry would further enhance the science because fast alerts for transient sources could be issued. The survey sensitivity of MEGA was estimated with an assumed orbital background about 3 times higher than the COMPTEL background. The realism of this assumption will have to be investigated in more detailed background simulations, once the mass and material compositions of MEGA and the orbit are defined more accurately. The sensitivities for MEGA in 3 and 5 years of operation compared to the average sensitivity of the COMPTEL all-sky survey are shown in Figure 6.

A coarse estimate of the number of sources detectable in a MEGA sky survey predicts that about 100 unidentified EGRET sources will be seen. The number of known pulsars at MeV energies should rise to about 10 and about a dozen compact galactic binary systems, containing black holes like Cyg X-1, will be detected. In extragalactic space about 100 blazars and more than 10 radio and Seyfert galaxies will be visible. Gamma ray bursts should be imaged in the large field of view of MEGA about once every two days. In all of these high-energy sources magnetic fields and relativistic electrons are likely to play a major role in the emission of $\gamma$-rays . Therefore we expect the radiation to be polarized. MEGA with its demonstrated sensitivity to polarization could open new parameter space for the study of such objects.

The observation of sites of nucleosynthesis, either from explosive events like Novae and Supernovae, or through their radioactive debris in SNRs and the galactic diffuse radioactivity are the second key science objective for MEGA. We expect to detect $\sim$ 5 Novae and 2-3 SNe each year. About 5 young hidden galactic SNRs should be discovered through their $^{44}$Ti emission. Detailed mapping of galactic star formation regions will allow to investigate the production of elements in massive stars. The origin and composition of the diffuse cosmic background at MeV energies is still mysterious and not well understood. At about 5 MeV a transition from predominantly thermal (Seyfert galaxies) to non-thermal ('EGRET Blazars') sources is observed. A major part of the background intensity could be made up by faint, merged AGNs. Radioactivity from distant SNe, radio galaxies, new 'MeV' blazers, or clusters of galaxies could also be important components of the background.

In conclusion one can view MEGA, with its sensitivity improvement of about a factor of 10 with respect to the pioneering COMPTEL and the additional capabilities for polarization studies, as the logical stepping stone to a future "Advanced Compton Telescope" (GRAPWG Report, 1999), which again would improve the sensitivity by an order of magnitude.

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