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Astrophysics with the 3-DTI Gamma-Ray Telescope

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Abstract: COMPTEL, the medium-energy gamma-ray telescope on the CGRO, made notable progress in the understanding of astrophysical sources of medium energy gamma-rays. The COMPTEL results showed that the emission from these objects is extended and point-like, transient and steady, and includes both continuum and line emissions. The Advanced Compton Telescope (ACT) mission has been proposed to further our understanding of the medium-energy gamma-ray regime. The ACT mission science goals require a medium-energy telescope with 100-fold increase in sensitivity. The challenge is to develop a future gamma-ray telescope with a dramatic improvement in sensitivity to survey the entire range of Galactic and extragalactic medium-energy gamma-ray sources. This improvement in sensitivity can be partially achieved by increasing the effective area compared to COMPTEL. Increasing the effective area above ~10 MeV requires tracking of the electron-positron pair from photons that interact via pair production. Electron tracking also improves the telescope sensitivity at lower energies by reducing the Compton scatter event circle to an arc, effectively rejecting more of the background. We briefly review the COMPTEL science results and discuss how our scaleable 3-D Track Imager (3-DTI) technology is suitable for both an intermediate MIDEX-scale mission with a 10-fold improvement in sensitivity as well as a larger instrument with 100-fold improvement. Such instruments would open up medium-energy gamma-ray astrophysics to many potential new and exciting discoveries.

Medium-Energy Gamma-Ray Astrophysics

The first major full-sky survey in medium-energy gamma-rays was made with the Compton Telescope COMPTEL [1] on the Compton Gamma Ray Observatory (CGRO which flew from April 5, 1991 to June 4, 2000), see Figure 1. The COMPTEL results, in the 0.4 to 30 MeV energy range, addressed a broad range of astrophysics including cosmic particle accelerators, nucleosynthesis and cosmic radioactivity, Galactic diffuse emission, and cosmology. The COMPTEL catalog of sources [2] includes Active Galactic Nuclei & Blazars (Mkn 421, 3C273), Super Nova Remnants (Crab Nebula), Pulsars & Magnetars (PSR 1509-58), and Black-Hole Binaries (Cyg X-1).

Compact objects, such as black-hole binaries and gamma-ray pulsars, possess complex continuum spectra and Doppler-shifted nuclear de-excitation lines that are characteristic of particle acceleration

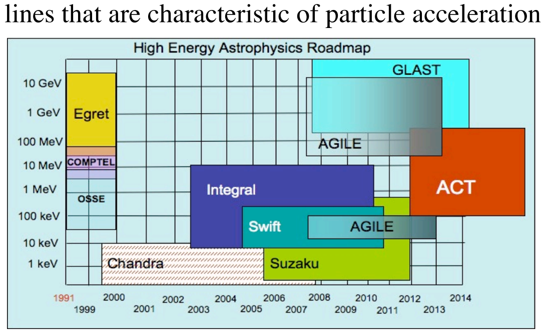

Figure 1: The medium-energy ACT and high-energy Gamma-ray missions are recommended priorities for new mid- and long-range missions.

and are highly variable. In addition, the 1.8 MeV line of ^{26}Al as well as ^{44}Ti, ^{60}Fe, and ^{60}Co show diffuse emission from the inner part of the Milky Way. Chandra observations (0.3-10 keV) show the Galactic center to be a source of variable x-ray emission. New MeV observations with increased sensitivity and high angular resolution will resolve the diffuse emission, monitor sites of CR acceleration, discriminate between such theoretical scenarios as beamed jet emission [3] or outflow solutions due to radiatively inefficient accretion [4], and constrain models of the final evolution of massive stars.

Outside the galaxy, Active Galactic Nuclei (AGN), known to be prodigious producers of gamma-rays, were detected at MeV energies by COMPTEL, and more recently, by Swift/BAT in the 20-150 keV range. A new sub-class of blazars is emerging from the Swift/BAT sky survey and follow-up multi-wavelength observations [5], characterized by bright and variable MeV gamma-ray emission; indeed most of the power appears to be emitted around a few MeV. Improved angular resolution and sensitivity below ~100 MeV will be particularly important in the GLAST era, when several hundreds of extragalactic gamma-ray blazars are expected to be discovered.

The COMPTEL results and these recent observations indicate that we are on the threshold of major discoveries addressing fundamental questions of non-thermal and relativistic astrophysics with a new medium-energy gamma-ray mission.

A Future Medium-Energy Gamma-Ray Telescope

A future medium-energy (0.3 – 50+ MeV) gamma-ray mission and telescope with greatly improved sensitivity compared to COMPTEL, INTEGRAL, and EGRET would address, and answer, many of the outstanding questions related to these sources.

A study of the Advanced Compton Telescope (ACT) mission, including several instrument concepts, has recently been completed [6]. The primary science objective assumed for this study report is to detect the ^{56}Co (0.847 MeV) line produced in thermonuclear supernovae (SNe Ia), which will shed light on the dynamics of nuclear burning.

This study report concluded that the baseline instrument should have an effective area of about 10^3 cm^2, broad-line (3%) sensitivity of 1.2×10^{-6} ph cm^{-2} s^{-1} at 0.847 MeV and narrow-line sensitivity of 5×10^{-7} ph cm^{-2} s^{-1}. This performance represents an increase in narrow- and broad-line sensitivity of about 100-fold over COMPTEL. The continuum sensitivity, however, of the baseline instrument, $(1/E)\times10^{-5}$ ph cm^{-2} s^{-1} MeV^{-1}, is only about 10-fold better than INTEGRAL/SPI, which is about 5-fold better than COMPTEL, at 0.847 MeV. The sensitivity, however, decreases with energy and is less than 2-fold better than COMPTEL at 10 MeV.

There is general consensus in the gamma-ray community that a medium-energy mission with a 10-fold, or better, increase in narrow-line, broad-line, *and* continuum sensitivity compared to COMPTEL over the entire medium-energy range would be a highly desirable intermediate step [7]. This intermediate mission would expand on the COMPTEL results, fill in the multi-wavelength coverage gap between INTEGRAL and SWIFT, and AGILE and GLAST, see Figure 1, and substantially advance our scientific understanding of transition between thermal and relativistic processes in the universe.

Design of a Medium-Energy Gamma-Ray Telescope

Maximizing the scientific return from an intermediate mission with 10-fold increase in sensitivity over the entire medium-energy range results in two design requirements for the gamma-ray telescope:

1. Extend the energy range down to 0.3 MeV and up to 50 MeV, or higher, by imaging photons via both Compton scattering and pair production interactions.

2. Maximize the effective area, aperture, energy resolution and angular resolution over the entire energy range while effectively rejecting the background.

These design requirements can best be addressed with a two-detector approach consisting of a three-dimensional electron track imager and a position sensitive calorimeter (PSC) surrounded with an anti-coincidence shield, shown schematically in Figure 2.

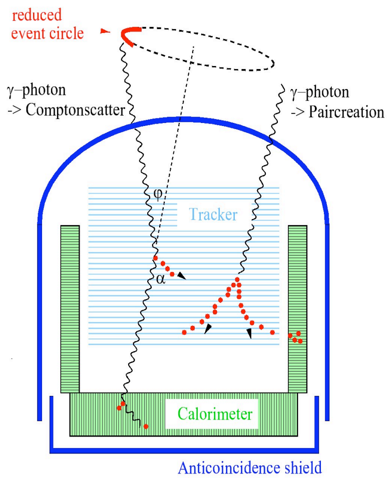

Figure 2: Schematic diagram of a two-detector Medium-energy telescope concept [8]. Electron tracking, required for sensitivity to pair production interactions, improves the sensitivity to Compton scatter interactions by reducing the event circle to an arc.

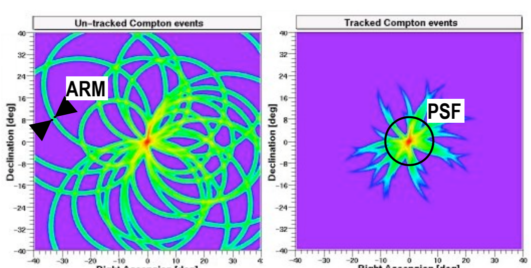

Figure 3: Compton telescope imaging simulations showing the reconstruction of an isolated, (i.e. no diffuse or instrumental background) single point-source without (left) and with (right) electron tracking [8].

The two detector approach, with an electron track imager not only enables imaging of photons that interact via pair production, it also enables true imaging of photons that Compton scatter by reducing the single photon point spread function (PSF) from a circle on the sky to an arc, see Figure 3. The area of the PSF is reduced which improves the telescope sensitivity since the number of background photons is proportional to area of the PSF, see Figure 4. Electron tracking also increased the sensitivity of the telescope by allowing photons which Compton scatter at large angles to be included [9].

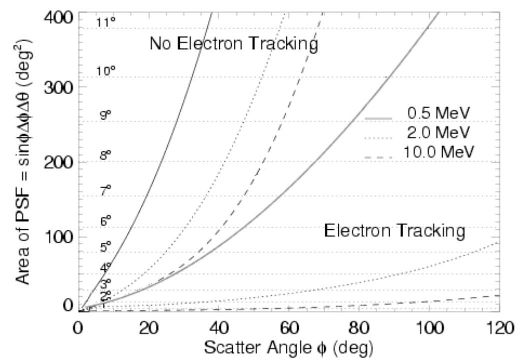

Figure 4: The area of the PSF, and corresponding radius, as a function of scatter angle for a medium-energy telescope with, and without, electron tracking for various gamma ray energies. The area of the PSF is dramatically reduced by electron tracking for all but the smallest scatter angles.

Medium-Energy Gamma-Ray Telescope Design

The advantages of electron tracking for a medium-energy gamma-ray telescope has motivated our development of the three-dimensional track imager (3-DTI), a large volume gas time projection chamber, for gamma-ray imaging [10]. The gas volume is a homogenous, fully active medium which reduces scattering of the Compton scatter electrons or electron-positron pairs, especially for low-energy photons allowing their initial direction of to be measured. A 2-dimensional micro-well detector provides X- and Y-coordinate readout. The 3rd spatial dimension comes from timing the arrival of the ionization charge. The 3-DTI provides the position of the photon interaction and the initial three-dimensional directions of the recoil electron and electron-positron pair. The 3-DTI also provides moderate, $\Delta E/E \approx 2\%$, energy resolution of electrons that stop in the gas volume. The PSC provides the Compton scatter angle of the photon and its energy, and the energy and position of higher energy electrons.

Development of the 3-DTI and PSC for an intermediate mission is described by Link et al. [11] and gamma-ray imaging with the 3-DTI is discussed by Son et al. [12], both in these proceedings.

We have developed a MIDEX-scale medium-energy gamma-ray telescope concept based on our 3-DTI technology [11]. Simulations show that this concept, the Three-Dimensional Compton Telescope (3-DCT), will provide a 10-fold increase in narrow-line, broad-line, and continuum sensitivity over COMTEL [9] as well as resolution of extended emission over the medium-energy range, see Figure 5. This instrument concept is scalable and can be readily increased to provide a 100-fold sensitivity increase for a follow-on mission.

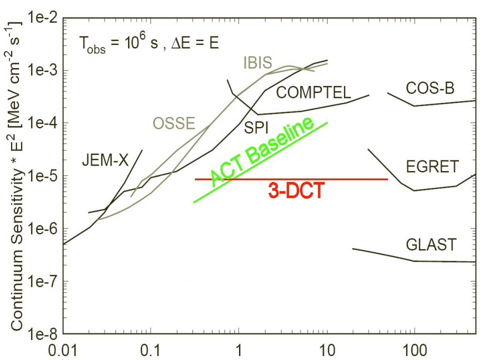

Figure 5: Continuum sensitivity of current and future X- and gamma-ray instruments. The 3-DCT, our Midex-scale telescope, will provide sensitivity comparable to EGRET.

Conclusions

The 10-fold increase in sensitivity of our MIDEX-scale 3-DCT telescope provides an increase comparable to EGRET, which established the field of high-energy gamma-ray astronomy, and led to the GLAST mission. Our 3-DTI technology, with true photon imaging, enables the widest range of science goals by optimizing the sensitivity to both line and continuum emissions, to both point-like and extended objects, and to both steady state and transient sources. In addition to resolving the medium-energy emission, the 3-DTI technology is sensitive to polarization, adding further constraints to our understanding of many of the astrophysical objects mentioned above [13].

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