HARD X-RAY AND GAMMA-RAY IMAGING SYSTEMS UTILIZING GERMANIUM STRIP DETECTORS

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Abstract. We investigate the characteristics of imaging systems in the 20 keV – 10 MeV energy band which incorporate the high spatial and spectral resolution of planar germanium strip detectors. A Compton scatter telescope provides sensitivity above approximately 250 keV; a coded aperture positioned above the top germanium detector plane of the Compton telescope forms a coded-aperture telescope with sensitivity in the 20 – 250 keV band. The high spectral resolution and spatial resolution of germanium strip detectors provides a Compton telescope with dramatically improved energy resolution, angular resolution, and sensitivity compared with previous Compton instruments. Such a system has excellent angular response for point source identification and spectroscopy and also provides response to high energy diffuse emissions such as the Galactic 511 keV line emission and ^{26}Al emission. Monte Carlo simulations of the concept and estimates of the sensitivity shall be presented.

Key words: Ge detectors, Strip detectors, Gamma-rays

1. Introduction

Astrophysical observations in the hard X-ray and soft gamma ray energy range have made slow but steady progress from the pioneering balloon instruments of the 1960's and the early satellite experiments of the OSO and HEAO missions. Recent satellite experiments on Gamma Ray Observatory (BATSE, OSSE and COMPTEL), GRANAT (SIGMA) and the planned INTEGRAL provide line γ-ray sensitivities approaching 10^{-5} cm^{-2} s^{-1}. High resolution γ-ray spectroscopy, as planned for INTEGRAL, is clearly important in understanding the sites and mechanisms producing the gamma ray emission, but improved sensitivity to 10^{-6} cm^{-2} s^{-1} or better is required to open up the field of γ-ray spectroscopy in astrophysics. As the sensitivity improves and the number of sources detected increases, imaging with $\sim$ arc-minute resolution also becomes a requirement to avoid source confusion for both galactic and extragalactic observations. We are investigating detector technologies and instrument concepts which will provide both high resolution spectroscopy and good angular resolution imaging and can be scaled to instruments with interesting sensitivity. The objective is an instrument

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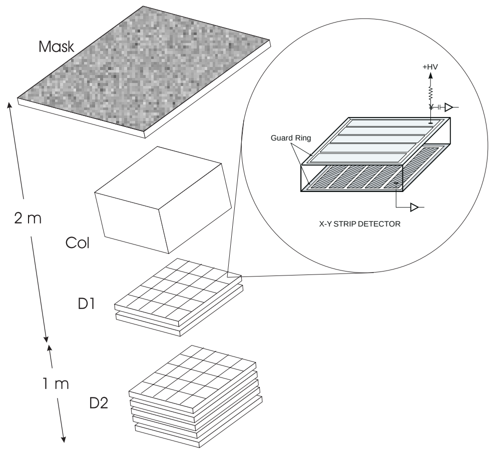

Fig. 1. Conceptual diagram of the combined coded-aperture imager and Compton telescope. The Compton telescope consists of two detector planes (D1 and D2) ~1 m apart. A coded mask is mounted ~ 2 m above the top detector plane, which forms the coded-aperture imager using the top layer of D1. A coarse collimator just above the D1 layer restricts the field of view for the imager.

which provides arc-minute imaging, a line sensitivity of 10^{-6} γ cm^{-2}s^{-1} in the 20 keV – 10 MeV region, and an energy resolution approaching that provided by germanium spectrometers.

2. Instrument Concept

Our investigations are currently centered on germanium planar strip detectors which can provide 2 – 3 keV spectral resolution and spatial resolution of ~ 2 mm (see associated contribution by Kroeger et al.). These detectors, which are ~ 5cm × 5cm × 1cm thick, are excellent hard x-ray detectors and can be layered to provide good sensitivity to 10 MeV. When used with a coded aperture, a single array of Ge strip detectors can provide arc-minute imaging in hard x-rays. Compton scatter telescopes using multiple layers of these detector arrays could achieve imaging resolution of a few tenths of a degree in the soft gamma ray range. We investigate the characteristics of these two configurations separately, but an intriguing instrument concept, shown in Fig. 1, uses the top detector plane of the Compton telescope as the detector plane of a coded-aperture hard x-ray imager, thus providing a system with good spectral and imaging resolution from ~20 keV to 10 MeV.

Compton scatter telescopes utilize two detector planes designed to scatter the incident radiation in the top plane and capture the scattered photon in the lower plane. Measurements of the energy losses and positions of the interactions in the two detector planes permits the reconstruction of the incident photon direction. In telescopes such as this and COMPTEL on GRO [4], it is not possible to measure the direction of the Compton electron in the top detector and the possible directions, when projected onto the sky, produce a small circle of the half-angle specified by the scatter angle and centered on the direction of the scattered photon. A point source of gamma rays is detected at the intersection of many such circles. Uncertainties in the energy loss measurements and in the interaction positions change the circle to an annulus and ultimately determine the angular resolution of Compton telescopes. Simultaneous improvements in spectral resolution and detector spatial resolution, as available in Ge planar strip detectors, are required to affect good angular resolution in these systems. We have modeled a Compton telescope system constructed from Ge planar strip detectors with 2 mm strips and 2 keV energy resolution. As discussed by Kroeger et al.[3], orthogonal strips on the two surfaces of the detector provide 2-dimensional spatial information with 2 mm resolution. The Compton telescope we have studied is shown in the bottom portion of Fig. 1. The top detector plane (D1) is formed from an array of strip detectors in two layers to provide $\sim$1 m^2 active area. The bottom plane (D2) is $\sim$1 m below D1 and comprised of five layers of strip detectors. Each layer is $\sim$ 1 m square and constructed from $\sim$ 400 detector elements of the type shown in the figure inset. The coincidence requirement for energy losses in the D1 and D2 planes produces systems with relatively low efficiency, generally 1 – 3%, but also reduces the detector background. Monte Carlo simulation of the on-axis efficiency for this configuration as a function of incident photon energy indicates $\sim$ 2% efficiency at 250 keV peaking at $\sim$ 3% in the 400 keV to 1 MeV range, and down to $\sim$ 1% by 10 MeV. For incident angles of 30° off-axis, the response is $\sim$ 80% of the on-axis response.

Below 300 keV, the coded aperture telescope using the D1 plane of detectors provides good response down to $\sim$ 20 keV. As displayed in Fig. 1, a coded mask formed from $\sim$ 1 mm-thick lead or tungsten is placed 2 m above the D1 layer. The thickness is selected to provide good modulation of hard X rays but thin enough to be reasonably transparent to higher energy photons. The figure also shows a coarse collimator which could be useful in restricting the hard x-ray field of view.

3. Discussion

The Ge-Ge Compton telescope offers significant capabilities compared to the instruments on GRO and the INTEGRAL study instruments [1]. As with COMPTEL on GRO, it has a large field of view ($\sim$ 60°) and has the ability to image diffuse emission such as the ^{26}Al emission from the Galaxy. Its excellent spectral resolution and 2 mm spatial resolution provide significant improvements over COMPTEL in spectroscopy, point source imaging and sensitivity. Improvements in sensitivity to continuum emissions by $\times 10$ appear to be achievable. The Ge spectroscopy and low background of the Compton configuration will provide significant sensitivity to narrow line emissions. Fig. 2 shows the narrow line and continuum sensitivity of the Ge Compton telescope relative to current capabilities (OSSE [2], COMP-

TEL [4], INTEGRAL [1]). The sensitivity is determined by Monte Carlo response to the cosmic diffuse background as a limiting background to the detection of point sources. Other sources of background, such as local gamma ray production, spallation products and neutron interactions, which may be important have not been included at this time. The dashed line in the figure is an estimate of the Ge coded-aperture telescope sensitivity.

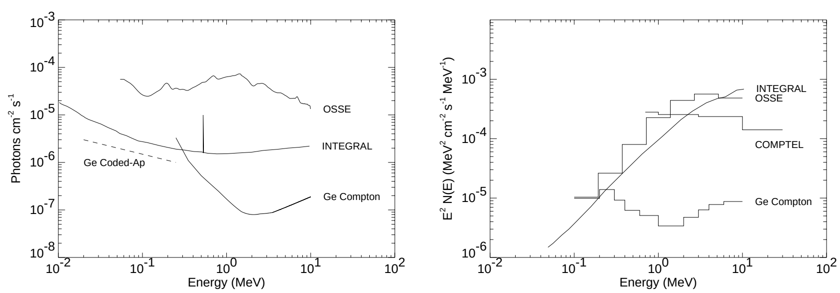

Fig. 2. Sensitivity (3σ) of the Ge-Ge Compton telescope to narrow emission lines (left panel) and continuum emissions (right panel) compared with current or planned instruments (10^6-sec observations). Sensitivity is based on diffuse background limiting sensitivity.

The studies to date indicate that imaging systems utilizing planar germanium stip detectors can provide significant improvements over the current GRO and GRANAT instruments and the planned capabilities of the INTEGRAL mission. These systems appear to be the best approach for simultaneously achieving good sensitivity to point and diffuse emissions and perhaps may also permit investigation of the diffuse γ-ray background. There are, however, many technical challenges and investigations which remain to be addressed. Some of these challenges are cryogenic support for the array of planar detectors, low-power and high-density electronics for the strip detectors, the ability to perform time-of-flight background rejection between the two detector planes, and local gamma ray production and other background issues affecting sensitivity. We will continue to investigate these issues in preparation for the next major gamma ray astronomy mission opportunity.

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