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The Si/CdTe semiconductor Compton camera of the ASTRO-H Soft Gamma-ray Detector (SGD)

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ABSTRACT

The Soft Gamma-ray Detector (SGD) is one of the instrument payloads onboard ASTRO-H, and will cover a wide energy band (60–600 keV) at a background level 10 times better than instruments currently in orbit. The SGD achieves low background by combining a Compton camera scheme with a narrow field-of-view active shield. The Compton camera in the SGD is realized as a hybrid semiconductor detector system which consists of silicon and cadmium telluride (CdTe) sensors. The design of the SGD Compton camera has been finalized and the final prototype, which has the same configuration as the flight model, has been fabricated for performance evaluation. The Compton camera has overall dimensions of 12 cm × 12 cm × 12 cm, consisting of 32 layers of Si pixel sensors and 8 layers of CdTe pixel sensors surrounded by 2 layers of CdTe pixel sensors. The detection efficiency of the Compton camera reaches about 15% and 3% for 100 keV and 511 keV gamma rays, respectively. The pixel pitch of the Si and CdTe sensors is 3.2 mm, and the signals from all 13,312 pixels are processed by 208 ASICs developed for the SGD. Good energy resolution is afforded by semiconductor sensors and low noise ASICs, and the obtained energy resolutions with the prototype Si and CdTe pixel sensors are 1.0–2.0 keV (FWHM) at 60 keV and 1.6–2.5 keV (FWHM) at 122 keV, respectively. This results in good background rejection capability due to better constraints on Compton kinematics. Compton camera energy resolutions achieved with the final prototype are 6.3 keV (FWHM) at 356 keV and 10.5 keV (FWHM) at 662 keV, which satisfy the instrument requirements for the SGD Compton camera (better than 2%). Moreover, a low intrinsic background has been confirmed by the background measurement with the final prototype.

1. ASTRO-H SGD

ASTRO-H, the new Japanese X-ray Astronomy Satellite [1–3] following the currently operational Suzaku satellite, aims to fulfill the following scientific goals:

- Revealing the large-scale structure of the universe and its evolution.
- Understanding the extreme conditions of the universe.
- Exploring the diverse phenomena of the non-thermal universe.
- Elucidating dark matter and dark energy.

In order to fulfill the above objectives, the ASTRO-H satellite hosts the following four types of instruments: SXT (Soft X-ray Telescope)+SXS (Soft X-ray Spectrometer), SXT+SXI (Soft X-ray Imager), HXT (Hard X-ray Telescope)+HXI (Hard X-ray Imager) [4–11] and SGD (Soft Gamma-ray Detector) [4–7,9,12–14].

The SGD will cover the energy range of 60–600 keV with a high sensitivity. The SGD utilizes semiconductor detectors using Si and

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CdTe pixel sensors with good energy resolution (≲2 keV) for the Compton camera, which were made possible by recent progress on the development of low noise Si gamma-ray sensors [15–18] and high quality CdTe sensors [19–25]. The BGO active shield provides a low background environment by rejecting the majority of external backgrounds. Internal backgrounds are rejected based on the inconsistency between the constraint on the incident angle of gamma rays from Compton kinematics and that from the narrow FOV (field of view) of the collimator. This additional background rejection by Compton kinematics will improve the sensitivity by an order of magnitude in the 60–600 keV band compared with the currently operating space-based instruments.

In this paper, we will present the detailed configuration and the data acquisition system of the SGD Compton camera. We will also present the performance evaluated for the final prototype, which is equivalent to the flight model.

2. SGD concept and Si/CdTe semiconductor Compton camera

The SGD is based on the concept of narrow FOV Compton telescopes [5], combining Compton cameras and active well-type shields. The active well-type shield concept originates from the Hard X-ray Detector (HXD) [26] onboard the Suzaku satellite. The HXD achieves the best sensitivities in the hard X-ray band, consisting of Si photodiodes and GSO scintillators with BGO active shield and copper passive collimator. The SGD, however, replaces the Si photodiodes and GSO scintillators with the Compton camera, which provides additional information for the background rejection. Fig. 1 shows a conceptual drawing of an SGD unit. A BGO collimator defines a field of view of ~10° for high energy photons while a fine collimator restricts the FOV to ≲0.6° for low energy photons (≲150 keV), which is essential to minimize the CXB (cosmic X-ray background) and source confusion. Scintillation light from the BGO crystals is detected by avalanche photo-diodes (APDs) allowing for a compact design compared to phototubes.

The hybrid design of the Compton camera module incorporates both Si and CdTe imaging detectors. The Si sensors are used as detectors for Compton scattering since Compton scattering is the dominant process in Si above ~50 keV compared with ~300 keV for CdTe. The Si sensors also provide better constraints on the Compton kinematics because of smaller effect of Doppler broadening [27,28]. The CdTe sensors are used to absorb gamma rays following Compton scattering in the Si sensors.

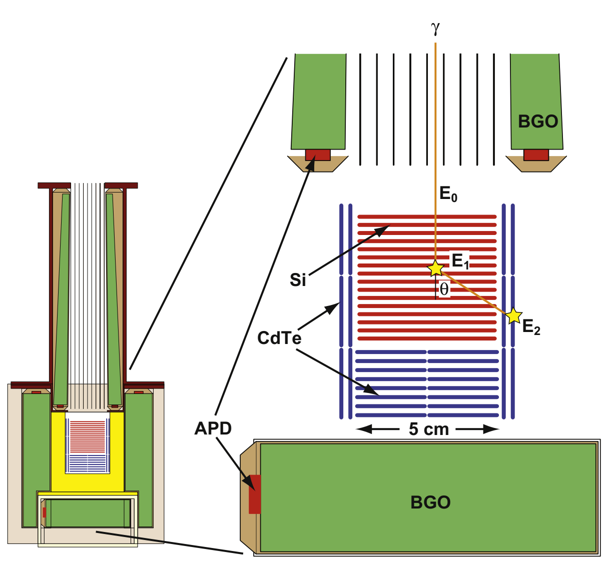

Fig. 1. Conceptual drawing of an SGD Compton camera unit.

3. Instrument-level requirements for SGD Compton cameras

The ASTRO-H mission-level science objectives described above require the SGD to provide spectroscopy up to 600 keV for over 10 accreting supermassive black holes with fluxes equivalent to 1/1000 of the Crab Nebula (as measured over the 2–10 keV band, assuming the spectrum to be a power-law with spectral index of 1.7). This mission-level science requirement defines the following instrument-level requirements for the SGD Compton camera:

- Effective area for the detector must be greater than 20 cm^2 at 100 keV to obtain a sufficient number of photons in a reasonable observation time (typically 100 ks).
- Observation energy range must be from 60 keV to 600 keV.
- Energy resolution must be better than 2 keV (FWHM) or better than 2% (FWHM).

These are the following design constraints on the SGD Compton camera from mounting the ASTRO-H:

- The size of one camera must be 12 cm × 12 cm × 12 cm to minimize the size of BGO active shield, since the BGO is the dominant contributor to the total weight of the SGD.
- The number of Compton cameras must be six in total ASTRO-H.
- Power consumption must be lower than 6 W for one camera.

The instrument-level requirements and the design constraints described above guide the designs of the Si sensor, the CdTe sensor and the readout Application Specific Integrated Circuit (ASIC) for both. The detection area of the Si sensor must be larger than 5 cm × 5 cm. The total thickness of the Si sensor must be about 2 cm, which corresponds to the 50% interaction efficiency for 100 keV photons. Therefore, 32 layers of Si sensors are needed when 0.6 mm thick Si devices are used. In order to satisfy the effective area requirement, CdTe sensors must cover 50% of the solid angle covered by the Si sensors. The readout ASICs for the Si and CdTe sensors must have an internal analog-to-digital converter (ADC) and must be controllable with digital signals because space in the Compton camera is limited. Moreover, the ASIC must consume less than 0.5 mW/channel and have good noise performance of 100–200 e$^-$ (ENC) under the condition that the input capacitance is several pF.

4. SGD Compton camera design

4.1. Overall design

Based on the design guide described in the last section, the Compton camera consists of 32 layers of Si sensors and 8 layers of CdTe sensors surrounded by 2 layers of CdTe sensors. Fig. 2 shows a 3D model of the Compton camera structure. This arrangement allows a placement of the CdTe sensor on the side very close to the stacked Si and CdTe sensors, maximizing the coverage of the photons scattered by the Si sensors. In addition to sensor modules, the Compton camera holds an ASIC controller board (ACB) and four ASIC driver boards (ADBs). The ACB holds a field programmable gate array (FPGA) that controls the ASICs. The ADB buffers control signals from the ACB, sends control signals to 52 ASICs, and also provides a current limiter to power the ASICs.

The mechanical structure of the Compton camera needs to hold all components described above within a volume of 12 × 12 × 12 cm^3. Another important requirement for the mechanical structure is sensor cooling. All sensors need to have a temperature that is within 5 °C of the cold plate interface at the bottom of the Compton camera.