PROCEEDINGS OF SCIENCE

Performance of the XL-Calibur flight in July 2022

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X-ray polarimeters for astrophysical use have been enthusiastically developed in recent years. X-ray polarization reveals magnetic field structures and/or geometry structures from celestial objects such as a neutron star and a corona surrounding a black hole. The XL-Calibur is a balloon-borne mission to observe the polarization of hard X-rays, 15–80 keV. This mission equips a Compton scattering polarimeter which is placed at the focal point 12 m away from the hard X-ray telescope. The design of our polarimeter has a capability to detect a few % polarization degrees for a 1 Crab-flux source with observing it for 6 hours each day during a week-long flight. The XL-Calibur was launched in July 2022 and flown for about one week from Esrange Space Center in Sweden to the Canadian Northwest Territories.

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1. Introduction

X-ray polarization is an essential aspect of light and the fourth prove to investigate astrophysical objects. X-ray polarization observation has been started from 1975 by OSO-8[1]. It has been expected that the X-ray polarization reveal the structure of astrophysical objects such as a magnetic field structure of a pulsar wind nebula, a corona structure surrounding a black hole and so on. There are a lot of studies for soft X-ray (below 10 keV) observations because the IXPE satellite[2] was launched in 2021. However, examples of hard X-ray polarization observation are a few since difficulty to observe it.

Hard X-ray polarization detection technique is mainly to use Compton scattering. The main interaction of hard X-ray with a medium is Compton scattering rather than photo-absorption. A Compton scattering type detector has two parts, scatterer and absorber. A scatter is desirable for sensitivity for Compton scattering. On the other hand, an absorber is good for photo-absorption sensitivity. We can detect polarized photons of hard X-ray to evaluate a distribution of the scattered photons. The photons make an anisotropy distribution.

X-ray is absorbed by atmosphere on ground, but hard X-ray over 15 keV can observe at an altitude of around 40 km. Some balloon-born hard X-ray polarimeters have been succeeded to observe astrophysical objects, but the number of targets is a few[3–5]. We developed a more sensitive detector system to observe more objects with hard X-ray polarization.

2. XL-Calibur – balloon-borne hard X-ray polarimeter

The XL-Calibur (PI: H. Krawczynski, Washington University in St. Louis) is the 2nd generation hard X-ray polarimeter mission next to the X-Calibur[5]. It is international mission among US-Sweden-Japan.

The detection system of the XL-Calibur is constructed of the hard X-ray telescope (HXT) and the hard X-ray polarimeter. The HXT focus hard X-rays with 15-80 keV at the polarimeter 12 m away. The HXT and polarimeter are mounted both ends of a lightweight truss. The computers that control the systems and the controller of attitude are in the central part of the truss.

2.1 Hard X-ray Telescope

The Hard X-ray telescope is an X-ray super mirror of Wolter-I optics. It is the same model of ASTRO-H (Hitomi) X-ray Satellite[6]. In our mission, the telescope did not equip pre-collimator for avoiding stray light from off-axis, which is differ from ASTRO-H one. This telescope capability was designed up to five times for the effective area and twice for the band width from X-Calibur's telescope.

We carried out calibration of the effective area and optical axis at SPring-8, a synchrotron facility in Japan[7]. The calibrated effective area was 175 cm^2 and 73 cm^2 at 30 keV and 50 keV, respectively. The half power diameter is around 2.1 arcmin for entire energy band, which means that a half of focused photons will be concentrated within $\sim$ 7.3 mm in diameter at 12 m away. These results showed that the designed performances were achieved.

2.2 Hard X-ray Polarimeter

The polarimeter is comprised of two parts, main detector and active shield. The main detector consists of a Be rod as scatterer and surrounded 17 CdZnTe detectors as absorber. Incident photons focused by HXT pass through a tungsten collimator and are scattered at a Be rod with 12 mm in diameter and 80 mm long. The CdZnTe is one side with four pieces, and the rest are placed directly below the Be rod. The $Bi_4Ge_3O_{12}$ (BGO) scintillation detector with photo multiplier surround the main detector. In order to avoid systematic anisotropy in the main detector, the polarimeter was rotated with 3 rpm.

The each CdZnTe size is $0.8^t \times 20 \times 20$ mm^3 with 64 pixels. Each CdZnTe detector signal is read by two front-end application specific integrated circuits (ASIC) with 32-channel readout. The CdZnTe energy resolution is 5.9 keV at 40 keV. We adopted the 0.8 mm thickness CdZnTe semiconductor detector because of reducing background. The operation voltage of the CdZnTe is set to -41 V. Estimated background count rates is less than 1 Hz with anti-coincidence detector as an active shield.

The origin of background is energetic particle from cosmic ray and 2nd particles in atmosphere. When a high energy particle invades to the main detector, the shield constructed of BGO generate veto signal. The shield is divided into two parts: *top* mounted on the upper side of the mounting panel and *bottom* mounted on the lower side facing the ground. Each part is configured separately with its own thresholds and settings. The scintillation light is amplified by four photo multiplier (PMT) for each part. The operational voltage is $\sim$ 1 kV, the threshold of veto signal is set to 100 keV.

2.3 Pointing system and optical axis compensation for high elevation

The pointing accuracy of the XL-Calibur reaches arc seconds by using Wallops Arc Second Pointer (WASP)[8]. X-Calibur, the former mission, also equipped the system, and its control was successful. For the purpose of precise pointing, the system is equipped with two star cameras: one that is oriented towards celestial objects and another that is offset by 25° from this direction.

We need to focus incident photons on the surface of a 12 mm diameter bar at 12 m away. A lengthy truss undergoes deformation due to the influence of gravity, and this deformation varies with elevation angles. As a result, the imaging position of the telescope shifts slightly when comparing it to the position when it is horizontal to the ground. Since gravity deflects of the truss structure, we use two optical cameras, forward looking camera (FLC) and back looking camera (BLC) to compensate the optical axis of the mirror besides star cameras and sun sensor to evaluate the object position. During ground tests, we estimated that the magnitude of deformation would be around 2 mm at an elevation angle of 60°. Taking the deflection change with the elevation, we mounted HXT to truss.

3. Flight logs

The XL-Calibur was launched from Esrange Space Center in Sweden at 23:45 UTC on 2023-7-11. The balloon flown to Canadian northwest territory, and touchdown at 7:40 UTC on 2023-7-18. We planned some observations such as Crab and Cyg. X-1, but the observations

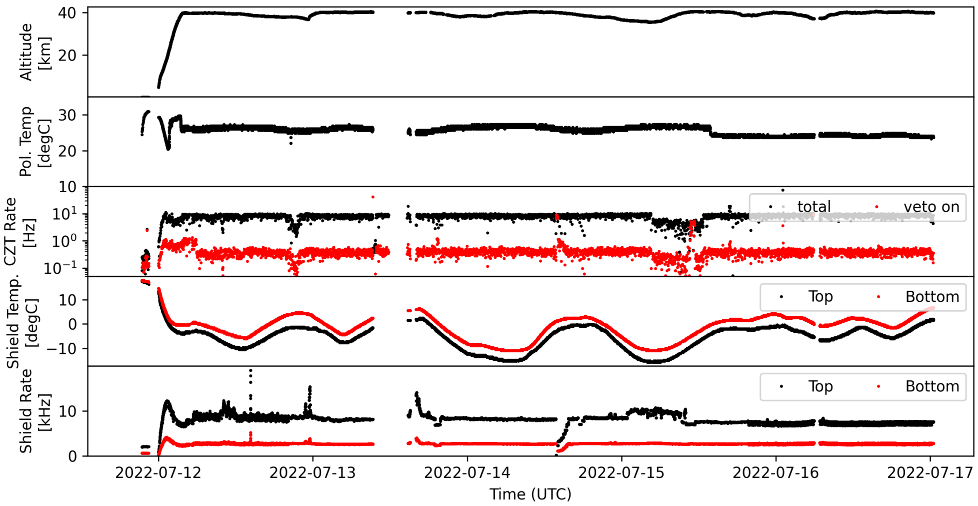

Figure 1: Trends in the flight. *Top* panel is the altitude. *The 2nd* panel is the polarimeter temperature. *The 3rd* panel is the CdZnTe count rates with 20-40 keV, black and red show veto signal off and on, respectively. *The 4th* panel is the shield temperature, black and red show top and bottom ones, respectively. *Bottom* panel is the shield count rates, the colors is same before.

could not carry out due to technical problem. However, we verified and confirmed that the main detector and shield were operated as expected[9].

Figure 1 shows the trends of some components in the flight. During certain periods within the trend, there are time intervals where telemetry is not recorded due to reasons such as CPU resets. We can see that we could control the altitude ~ 38 km during 6 days. Polarimeter temperature is stable in below 30 degree. The count rate of CdZnTe with 20-40 keV occasionally experiences short-term fluctuations but remains stable overall. The rate with veto signal is below 1 Hz, which is in line with the design. The temperature of both top and bottom shields varies around 0 degree, varying by approximately ±10 degree due to the direction of sun. The count rates differ between the top and bottom shields, but they remain stable during the flight. The top shield facing upward registers around 10 kHz, while the bottom shield facing the ground records a few kHz. These results are consistent with our design values and show no contradictions.

4. Conclusion

The XL-Calibur is a mission for observing hard X-ray polarization It equips a Compton scatter like polarimeter with active shield The XL-Calibur was launched on July 11th 2022 at Esrange Space Center in Sweden, and cruised to northeast Canada in about 6 days. Unfortunately, Crab and Cyg. X-1 were not observed, but we confirmed our detectors performed as expected. In 2024, we have planed to launch the XL-Calibur from Sweden again.

5. Acknowledgments

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