Long-Term monitoring of Sco X-1 with the Small X-ray Satellite NinjaSat

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Abstract

The X-ray emission of Sco X-1 consists of a soft component from the accretion disk described by a multi-color blackbody and a hard component where photons from the central region are up-scattered by hot electrons in the corona. Moreover, a hard X-ray tail produced by non-thermal high-energy electrons accelerated around the neutron star is observed with temporal variability, and understanding the mechanisms of this electron acceleration is the goal of this study.The 6U-class small X-ray satellite NinjaSat is equipped with a gas X-ray detector (GMC) with a total effective area of 16 cm² at 6 keV, covering an observational energy band of 2–50 keV.It is also the only satellite capable of continuously monitoring bright X-ray sources over timescales of months. In long-term observations of Sco X-1 with NinjaSat, temporal variations indicative of a hard X-ray tail have been observed.This presentation presents the results of long-term monitoring of Sco X-1 with NinjaSat.

1.Physical Insights of Sco X-1 Observations

- Sco X-1 is an ideal object for studying the mechanisms of X-ray emission produced in the vicinity of a neutron star accreting at nearly the Eddington luminosity(Fig1)
- X-rays from Sco X-1 consist of two blackbody components
  ①The accretion disk (kT ≈ 1–1.8 keV)
  ②The neutron star surface (kT ≈ 2.5–2.7 keV)
- Occasionally, a hard tail(③) is observed in the X-ray spectrum (Fig 2)
  → Suggests high-energy electrons with a non-thermal distribution around the neutron star
  →The origin of these accelerated electrons remains unknown.
- However, the extreme brightness of Sco X-1 poses challenges for observation with conventional X-ray instruments.

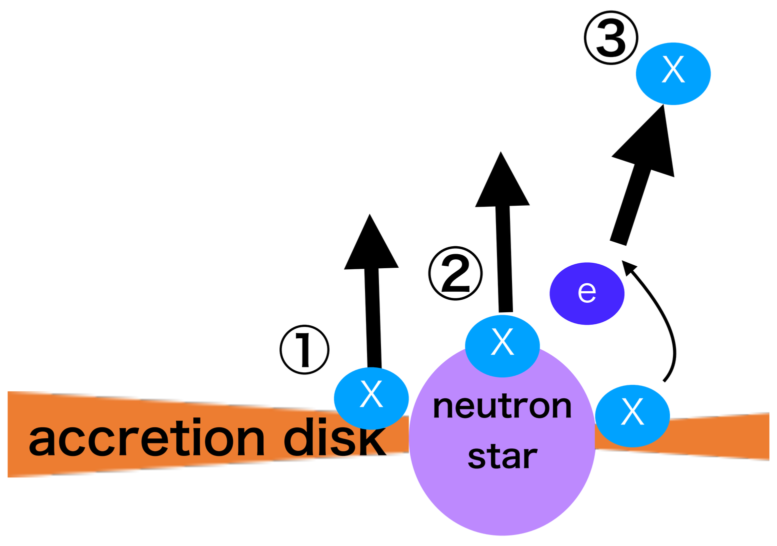

Fig 1

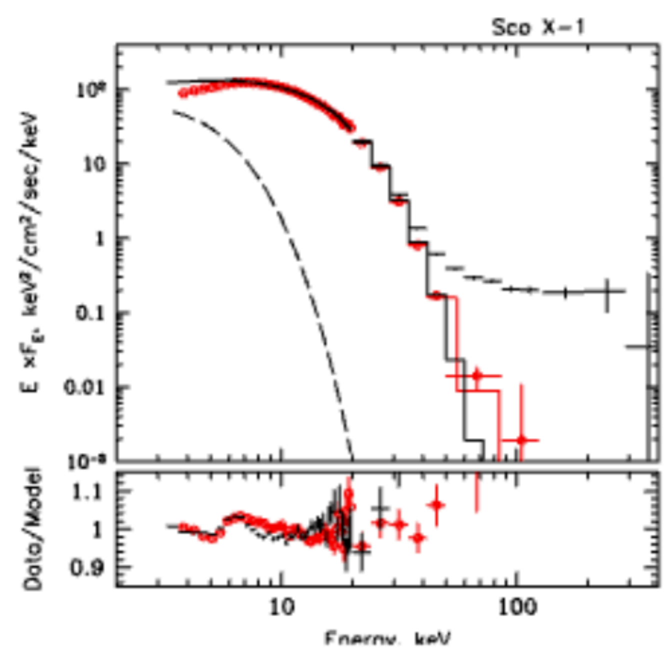

Fig 2 INTEGRAL and RXTE[2]

2. The Small X-ray Satellite NinjaSat[1]

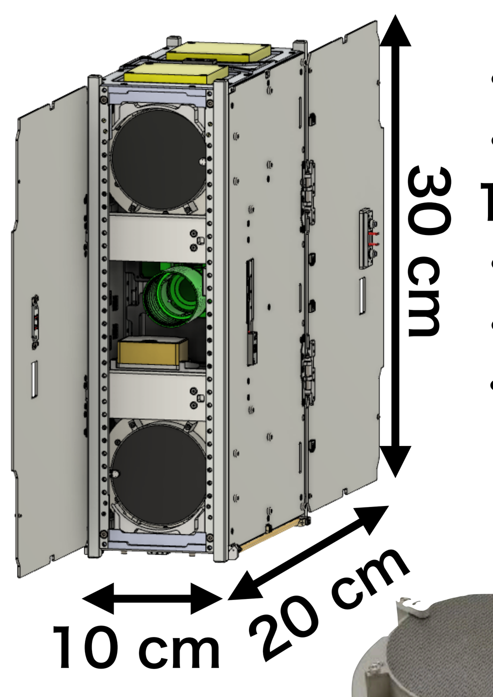

Fig.3

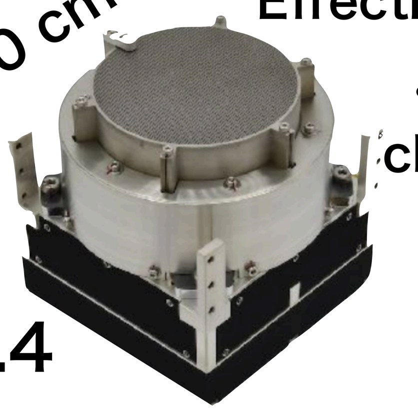

Fig.4

- Launched on November 11, 2023
- Re-entered Earth's atmosphere on September 17, 2025
- Dimensions: 10 × 20 × 30 cm³
- Mass: approximately 9 kg
- Detector: GMC (Gas Multiplier Counter)(Fig 4)
  Fill gas：XeArDME(75%/24%/1%)@1.2 atm
  Energy band：2~50 keV
  Effective area：16 cm³ @6 keV
- Even with NinjaSat, observing Sco X-1 is challenging
  →To enable observation, the low-energy threshold was adjusted from 2 keV to 5 keV, reducing the data volume.

3.Long-term Monitoring of Sco X-1 with NinjaSat

- Observation Period ：2025 4/9 (MJD 60774) ~ 2025 5/7 (MJD 60803)
- Total Observation Time：223 ksec
- Constructed a Color–Color Diagram (CCD) based on the total observation time
  →confirming the characteristic ν-shaped track consistent with previous studies
- Following previous studies, the black and red regions in the figure were assigned as NB and FB, respectively

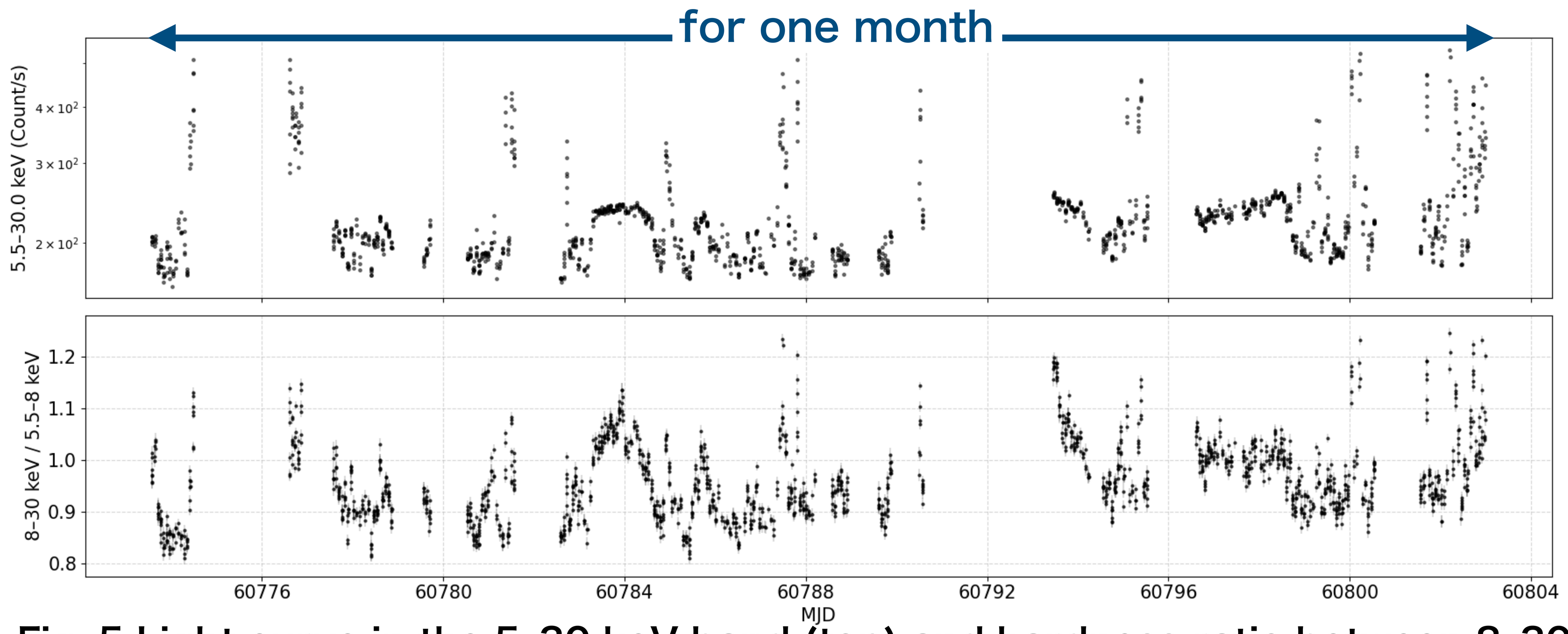

Fig. 5 Light curve in the 5–30 keV band (top) and hardness ratio between 8–30 keV and 5.5–8 keV (bottom)

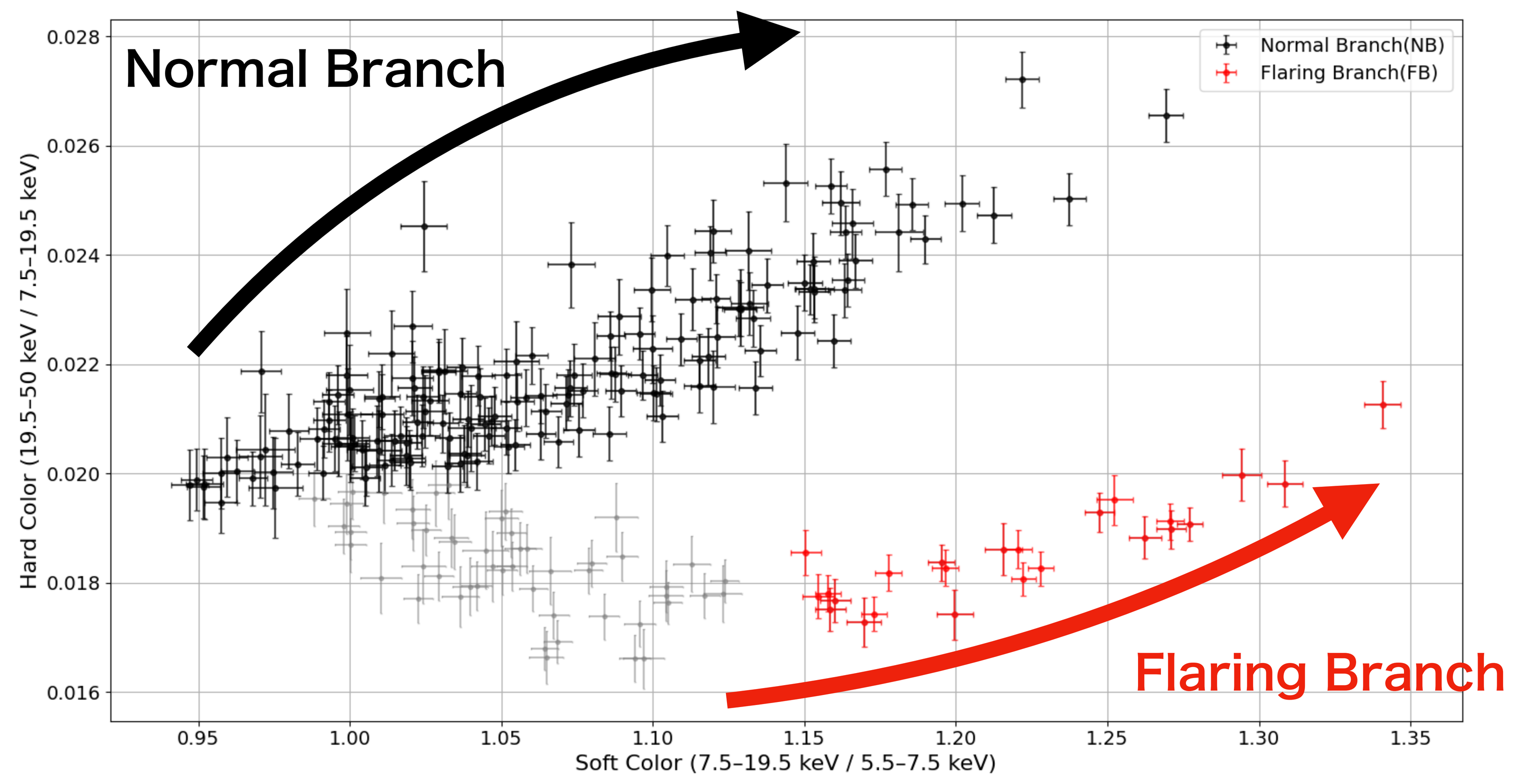

Fig 6 Color–Color Diagram(CCD)

4.Time-resolved spectra of Sco X-1

- In Section 3, the NB (black) and FB (red) time intervals were defined, and spectral analysis was performed using these intervals (solid lines in Fig. 7)
- A bbody + bbody model was adopted based on 1.① and 1.② (dashed lines in Fig. 7)
- Figs. 8 and 9 show data/ model ratios; at high energies, the data for NB lie above the simple blackbody model compared to FB, indicating a deviation that could be a hint of a hard component.
  - To verify whether a hard tail truly exists, the detector's systematic errors and response functions need to be characterized in more detail.

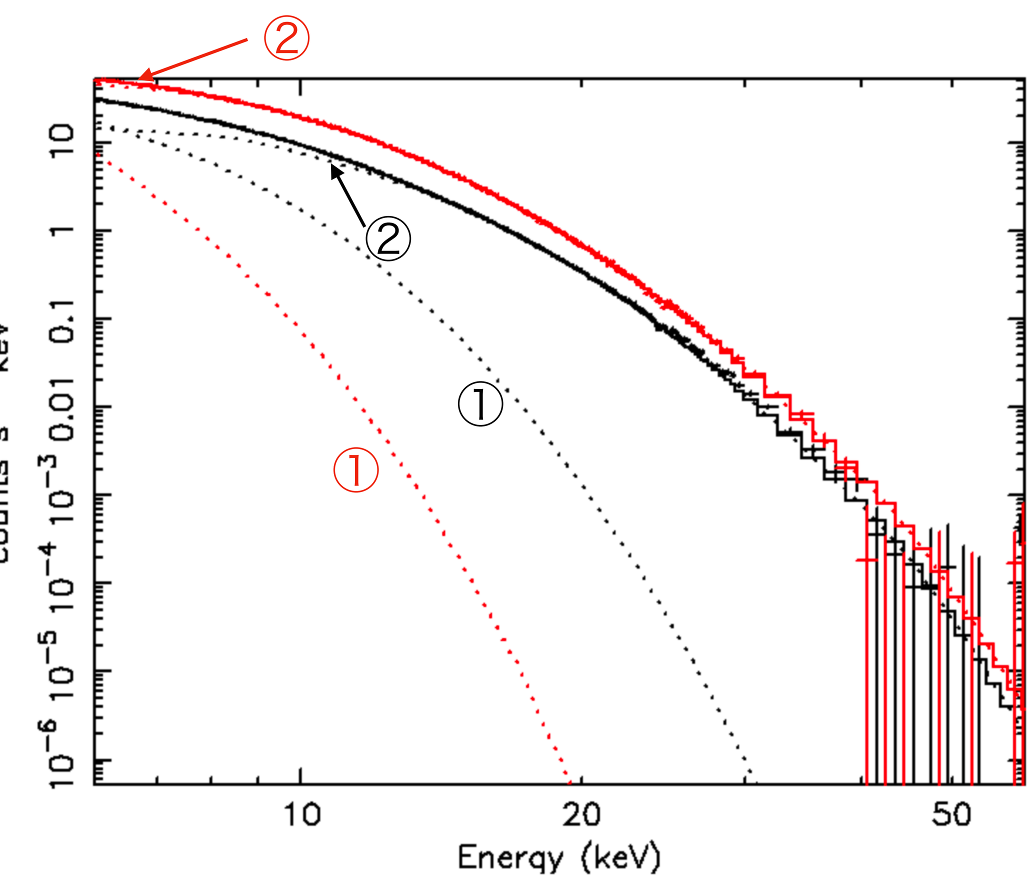

Fig 7 Spectrum

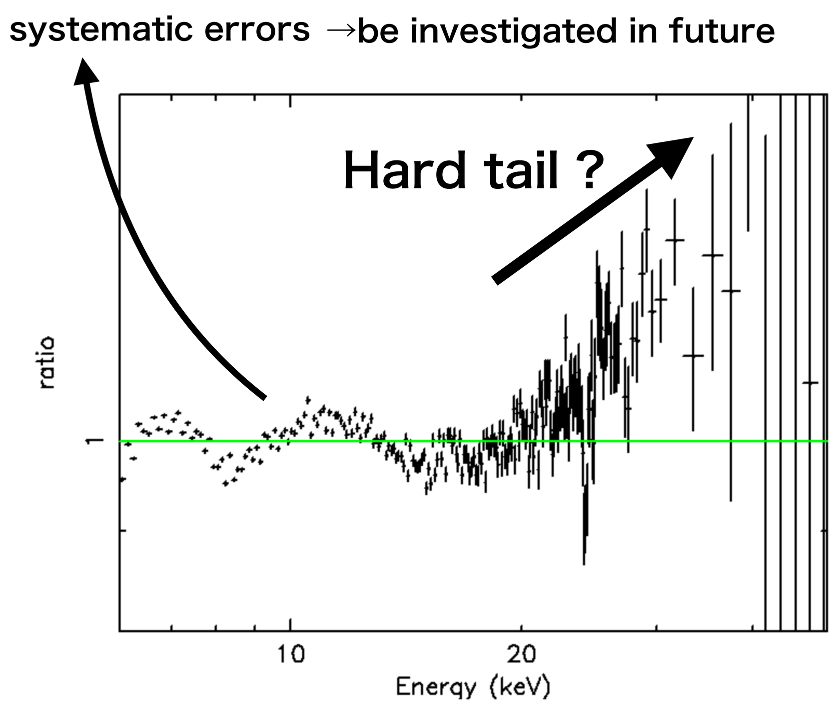

Fig. 8 Data/model ratio for NB or HB

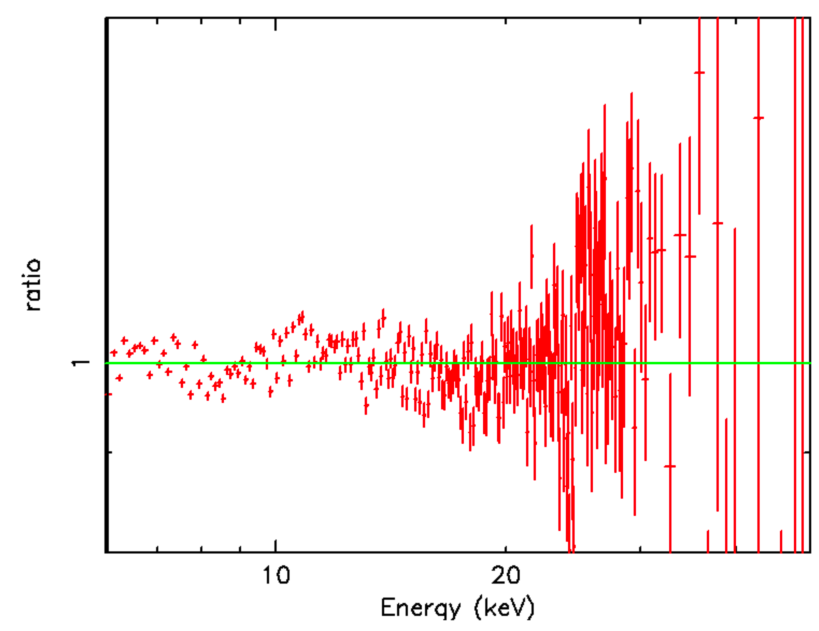

Fig. 9 Data/model ratio for FB

5. Summary

- NinjaSat data were used to investigate the hard tail of Sco X-1, aiming to understand the origin of these accelerated electrons, which remains unknown.
- Conducted long-term monitoring of Sco X-1 with NinjaSat
- Constructed a Color–Color diagram (CCD), confirming the characteristic ν-shaped track as reported in previous studies
- Observed that at high energies, NB data deviate above the simple blackbody model compared to FB, suggesting a potential hard component
- Further investigation of the detector's systematic errors and response functions is needed to verify the existence of the hard tail

6.Reference

[1]T. Tamagawa et al. 2024, arXiv:2412.03016
[2]Mikhail G. Revnivtsev et al. 2014, arXiv:1409.1679v2