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The X-Ray Observatory Suzaku

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Abstract

High-sensitivity wide-band X-ray spectroscopy is the key feature of the Suzaku X-ray observatory, launched on 2005 July 10. This paper summarizes the spacecraft, in-orbit performance, operations, and data processing that are related to observations. The scientific instruments, the high-throughput X-ray telescopes, X-ray CCD cameras, non-imaging hard X-ray detector are also described.

Key words: instrumentation — space vehicles — space vehicles: instruments — X-rays: general

1. Introduction

Astro-E2, the fifth in a series of Japanese X-ray astronomy satellites devoted to observations of celestial X-ray sources, was launched by Japan Aerospace Exploration Agency (JAXA) with the M-V launch vehicle from JAXA's Uchinoura Space Center (USC) on 2005 July 10, and was renamed Suzaku. Suzaku is a red bird in Asian mythology, one of the four guardian animals, protecting the southern skies. Like ASCA (a flying bird, Tanaka et al. 1994), Suzaku is a joint Japanese–US mission, developed by the Institute of Space and Astronautical Science of JAXA (ISAS/JAXA) in collaboration with the National Aeronautics and Space Administration's Goddard Space Flight Center (NASA/GSFC) and many other institutions.

After launch, Suzaku first deployed its solar paddles and an extensible optical bench (EOB), and performed ~ 10 days of a perigee-up orbit maneuver to get into a near circular orbit at 570 km altitude with an inclination angle of 31°. The orbital period was about 96 minutes. It then underwent an initial checkout phase lasting for approximately three weeks, including instrument turn-on and an initial calibration. Despite the initial success of the X-Ray Spectrometer (XRS) to obtain a cryogenic temperature of 60 mK with a cooling system consisting of a Stirling-cycle mechanical cooler (100 K), solid neon (17 K), liquid helium (1.3 K), and an adiabatic demagnetization refrigerator (60 mK), and an energy resolution of 7 eV (Kelley et al. 2007), on 2005 August 8, a thermal short between the helium and neon tanks resulted in the liquid helium coolant venting to space, leaving that system inoperable. The remaining instruments are working well, and Suzaku retains its excellent X-ray sensitivity, with high throughput over a broad-band energy range from 0.2 to 600 keV. Suzaku's broad bandpass, low background, and good CCD energy resolution make it a unique tool capable of addressing a variety of outstanding problems in astrophysics.

2. Spacecraft

Suzaku is in many ways similar to ASCA in terms of orbit, pointing, and tracking capabilities, although the mass is about four-times larger; the total mass at launch was 1706 kg. Five sets of X-ray mirrors are mounted on top of the EOB and five focal-plane detectors and a hard X-ray detector are mounted on the base panel of the spacecraft (figures 1 and 2). The spececraft length is 6.5 m along the telescope axis after deployment of the EOB. The electronics boxes of both the spacecraft bus and the scientific instruments are mounted on the side panels of the spacecraft. The spacecraft attitude is stabilized by four sets of reaction wheels with one redundancy, while the attitude is measured by three gyroscopes and two star trackers. There are two gyroscopes mounted in skew directions, which provide redundancy. The accumulated angular momentum is removed by magnetic torquers that interact with the Earth's magnetic field. The spececraft pointing accuracy is approximately $0\overset{\prime}{.}24$ with a stability of better than $0\overset{\prime}{.}022$ per 4 s (a half of typical exposure time of CCDs). The pointing direction of the X-ray telescope presently has additional uncertainty and temporal variations due to thermal distortion of the spacecraft structure. Please see Serlemitsos et al. (2007) for details. The pointing direction of the telescope is limited by the power constraint of the solar paddle. The area of the sky accessible at a time is

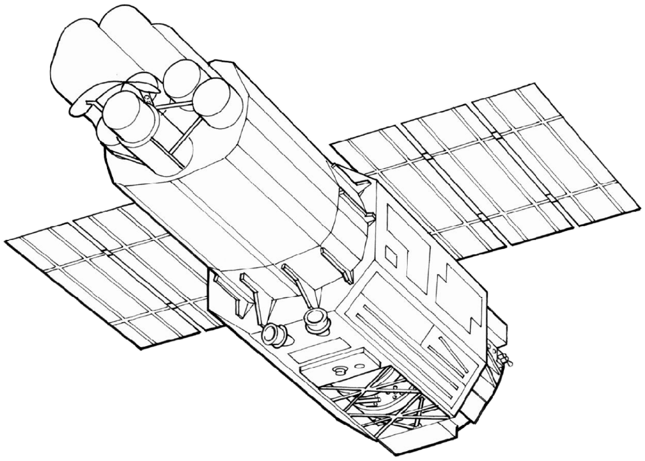

Fig. 1. Schematic view of the Suzaku satellite in orbit. Both solar paddles and the extensible optical bench (EOB) are deployed. On the top, the X-ray telescope (XRT-S) for the X-ray spectrometer (XRS), and the four X-ray telescopes (XRT-Is) for the X-ray CCD camera (XIS) can be seen.

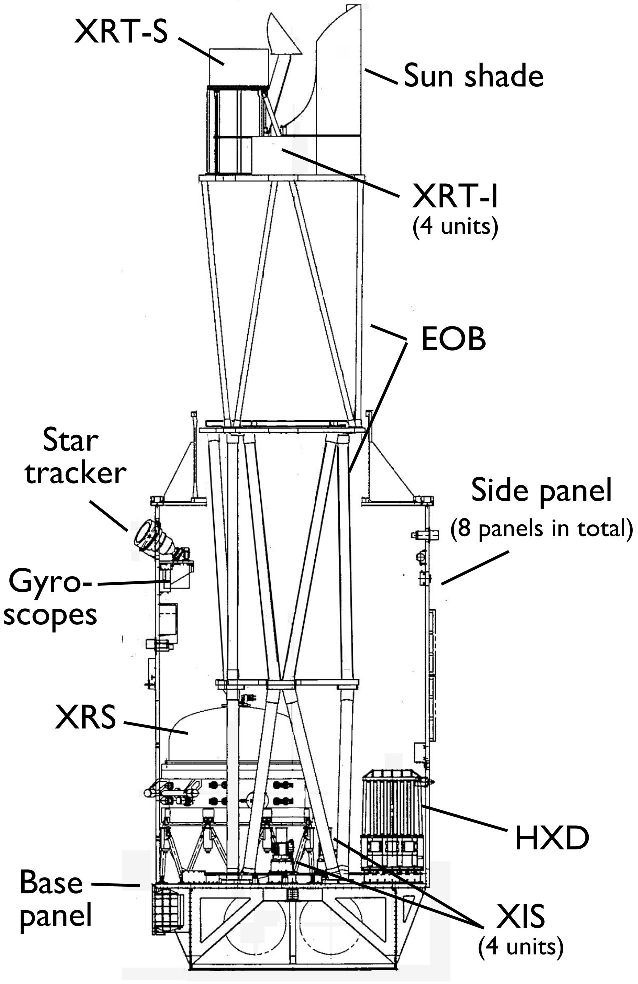

Fig. 2. Side view of Suzaku with the internal structures after EOB deployment.

a belt within which the Sun angle is between 65° and 115°. Any part of the sky is accessible at least twice a year. The maximum slew rate of the spacecraft is 6°/min, and settling to the final attitude takes $\sim$ 10 min, using star trackers. The normal mode of operations will have the spacecraft pointing in a single direction for at least 1/4 day (10 ks). With this constraint, most targets will be occulted by the Earth for about one third of each orbit, but some objects near the orbital poles can be observed nearly continuously. Observation is also interrupted by passages of the South Atlantic Anomaly. The current projection is that the observing efficiency of the satellite will be about 43%.

3. Scientific Instrumentation

The scientific payload of Suzaku (figure 2) initially consisted of three distinct co-aligned scientific instruments. There are four X-ray sensitive imaging CCD cameras (X-ray Imaging Spectrometer, XIS, Koyama et al. 2007), three front-illuminated (FI: energy range 0.4–12 keV) and one back-illuminated (BI: energy range 0.2–12 keV), capable of moderate energy resolution. Each XIS is located in the focal plane of a dedicated X-ray telescope (XRT, Serlemitsos et al. 2007). The second instrument is a non-imaging, collimated Hard X-ray Detector (HXD, Takahashi et al. 2007), which extends the bandpass of the observatory to much higher energies with its 10–600 keV bandpass (Kokubun et al. 2007). The last instrument, XRS, is no longer operational and will not be discussed further.

3.1. XRT

Five sets of the X-Ray Telescope (XRT) were developed jointly by NASA/GSFC, Nagoya University, Tokyo Metropolitan University, and ISAS/JAXA. These are grazing-incidence reflective optics consisting of tightly nested, thin-foil conical mirror shells. Because of the reflectors' small thickness, they permit high-density nesting, and thus provide a large aperture efficiency with a moderate imaging capability in the energy range of 0.2–12 keV, all accomplished in telescope units under 20 kg each, including pre-collimators for the rejection of stray light. Four sets of XRT onboard Suzaku (XRT-I0 to XRT-I3) are used for the XIS.

The angular resolutions of the XRTs range from $1'\!.8$ to $2'\!.3$, expressed in terms of the half-power diameter, which is the diameter within which half of the focused X-ray is enclosed. The angular resolution does not significantly depend on the energy of the incident X-rays in the energy range of Suzaku, 0.2–12 keV. The effective areas are typically 440 cm^2 at 1.5 keV and 250 cm^2 at 8 keV per telescope. The focal lengths are 4.75 m for the XRT-Is. Individual XRT quadrants have their own focal lengths deviated from the design values by a few centimeters. The optical axes of the quadrants of each XRT are aligned within $2'$ from each other. The field of view for XRT-Is is about $17'$ at 1.5 keV and $13'$ at 8 keV (see also table 1).

3.2. XIS

The X-ray Imaging Spectrometer (XIS) employs X-ray sensitive silicon charge-coupled devices (CCD), which are operated in a photon-counting mode, similar to that used in

Table 1. Overview of Suzaku capabilities.

S/C	Orbit apogee	568 km
	Orbital period	96 min
	Observing efficiency	$\sim 43\%$
XRT	Focal length	4.75 m
	Field of view	$17'$ at 1.5 keV
		$13'$ at 8 keV
	Plate scale	$0\overset{\prime}{.}724\,\mathrm{mm}^{-1}$
	Effective area	$440\,\mathrm{cm}^2$ at 1.5 keV
		$250\,\mathrm{cm}^2$ at 8 keV
	Angular resolution	$2'$ (HPD)
XIS	Field of view	$17\overset{\prime}{.}8 \times 17\overset{\prime}{.}8$
	Bandpass	0.2–12 keV
	Pixel grid	1024×1024
	Pixel size	$24\,\mu\mathrm{m} \times 24\,\mu\mathrm{m}$
	Energy resolution	~ 130 eV at 6 keV (FWHM)
	Effective area	$330\,\mathrm{cm}^2$ (FI), $370\,\mathrm{cm}^2$ (BI) at 1.5 keV
	(incl XRT-I)	$160\,\mathrm{cm}^2$ (FI), $110\,\mathrm{cm}^2$ (BI) at 8 keV
	Time resolution	8 s (normal mode), 7.8 ms (P-sum mode)
HXD	Field of view	$4\overset{\circ}{.}5 \times 4\overset{\circ}{.}5$ ($\gtrsim 100$ keV)
	Field of view	$34' \times 34'$ ($\lesssim 100$ keV)
	Bandpass	10–600 keV
	– PIN	10–70 keV
	– GSO	40–600 keV
	Energy resolution (PIN)	~ 3.0 keV (FWHM)
	Energy resolution (GSO)	$7.6/\sqrt{E_{\mathrm{MeV}}}\,\%$ (FWHM)
	Effective area	$\sim 160\,\mathrm{cm}^2$ at 20 keV, $\sim 260\,\mathrm{cm}^2$ at 100 keV
	Time resolution	$61\,\mu\mathrm{s}$
HXD-WAM	Field of view	2π (non-pointing)
	Bandpass	50 keV–5 MeV
	Effective area	$800\,\mathrm{cm}^2$ at 100 keV / $400\,\mathrm{cm}^2$ at 1 MeV
	Time resolution	31.25 ms for GRB, 1 s for All-Sky-Monitor

the ASCA SIS (Burke et al. 1994; Yamashita et al. 1997), Chandra ACIS (Garmire et al. 1992; Bautz et al. 1998), and XMM-Newton EPIC (Strüder et al. 2001; Turner et al. 2001). In general, an X-ray CCD converts an incident X-ray photon into a charge cloud, with the magnitude of charge proportional to the energy of the absorbed X-ray. This charge is then shifted out onto the gate of an output transistor via an application of a time-varying electrical potential. This results in a voltage level (often referred to as "pulse height") proportional to the energy of the X-ray photon.

The four sets of Suzaku XIS are designated XIS 0, XIS 1, XIS 2, and XIS 3, each located in the focal plane of an X-ray Telescope; XRT-I0, XRT-I1, XRT-I2, and XRT-I3. Each CCD camera has a single CCD chip with an array of 1024×1024 picture elements ("pixels"), and covers an $17\overset{\prime}{.}8 \times 17\overset{\prime}{.}8$ region on the sky. Each pixel is $24\,\mu$m square, and the size of the CCD is 25 mm × 25 mm. Effective area is shown in figure 3. One set of the XIS, XIS 1, uses a back-illuminated CCD, while the other three use front-illuminated CCDs. The XIS has been partially developed at MIT (CCD sensors, analog electronics, thermoelectric coolers, and temperature

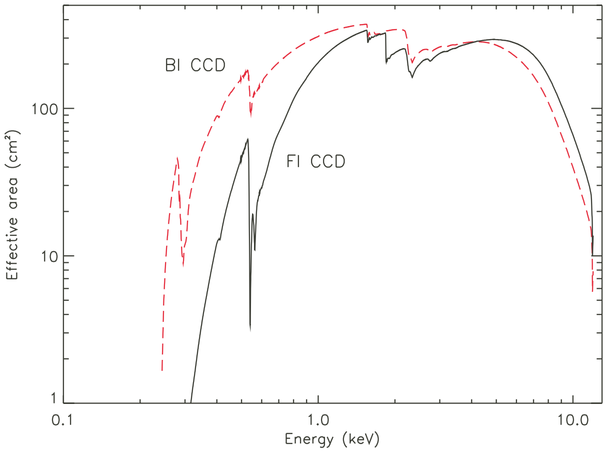

Fig. 3. Effective area of one XRT + XIS system, for both the FI (XIS 0, 2, 3) and BI (XIS 1) CCDs.

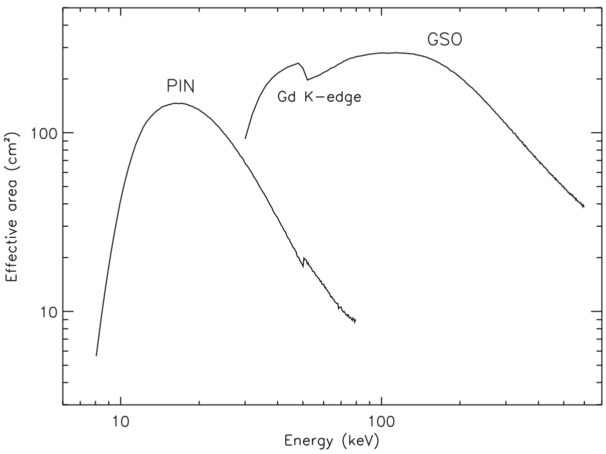

Fig. 4. Total effective area of the HXD detectors, PIN and GSO, as a function of energy.

control electronics), while the digital electronics and a part of the sensor housing were developed in Japan, jointly by Kyoto University, Osaka University, Rikkyo University, Ehime University, and ISAS/JAXA.

3.3. HXD

The Hard X-ray Detector (HXD) is a non-imaging, collimated hard X-ray scintillating instrument sensitive in the $\sim 10\,\mathrm{keV}$ to $\sim 600\,\mathrm{keV}$ band. It has been developed jointly by the University of Tokyo, Aoyama Gakuin University, Hiroshima University, ISAS/JAXA, Kanazawa University, Osaka University, Saitama University, SLAC, and RIKEN. Its main purpose is to extend the bandpass of the Suzaku observatory to the highest feasible energies, thus allowing broad-band studies of celestial objects.

The HXD sensor (HXD-S) is a compound-eye detector instrument, consisting of 16 main detectors (arranged as a 4×4 array) and the surrounding 20 crystal scintillators for active shielding. Each unit actually consists of two types of detectors: a GSO/BGO phoswich counter, and 2 mm-thick PIN silicon diodes located inside the well, but in front of the GSO scintillator. The PIN diodes are mainly sensitive below $\sim 60\,\mathrm{keV}$, while the GSO/BGO phoswich counter (scintillator) is sensitive above $\sim 30\,\mathrm{keV}$. The scintillator signals are read out by photomultiplier tubes. The HXD features an effective area of $\sim 160\,\mathrm{m}^2$ at $20\,\mathrm{keV}$, and $\sim 260\,\mathrm{cm}^2$ at $100\,\mathrm{keV}$ (see figure 4). The energy resolution is $\sim 3.0\,\mathrm{keV}$ (FWHM) for the PIN diodes, and $7.6/\sqrt{E}\,\%$ (FWHM) for the scintillators, where E is energy in MeV. The HXD time resolution is $61\,\mu$s.

The outer anti-coincidence scintillators can be used as a wide-field hard X-ray detector, which is referred as the Wide-band All-sky Monitor (WAM). This can be used to detect bright X-ray transients, γ-ray bursts, and solar flares.

4. Spacecraft Operation and Data Processing

The spacecraft is operated by duty scientists at Sagamihara Space Operation Center (SSOC) of ISAS/JAXA and at USC, supported by technicians and engineers at these two centers. There are also contact scientists at ISAS/JAXA and NASA/GSFC who work as an interface to guest observers. The duty scientists at SSOC create a series of spacecraft commands according to the operation requirements compiled by the contact scientists. Then the duty scientists at USC actually send them to the spacecraft, receive data, and check the housekeeping data of the spacecraft and the science instruments. The long-term schedule of the spacecraft operation is taken care of by the operation team, which consists of scientists and a technician at ISAS/JAXA. The telemetry data downlinked from the spacecraft are first converted to the FITS format. The spacecraft attitude and orbit data are added at the same time. This initial processing was done by a data-processing team consisting of scientists and technicians at ISAS/JAXA. Further data processing is being done at ISAS/JAXA and NASA/GSFC in parallel.

The science working group (SWG) members used data processed by Version 0.x processing software to analyze the performance-and-verification (PV) data. The Version 1.0 processing software for guest observer data was developed based on the Version 0.6 software. The final version of the processing software of the 0.x series is version 0.7, which is almost identical to Version 1.2 of guest observer data. The limitations of the Suzaku data processing can be found on the Suzaku web pages.[1]

5. Scientific Capabilities

Suzaku was designed to be highly complementary to the two large X-ray observatories that were already in orbit at launch, XMM-Newton (Jansen et al. 2001) and Chandra (Weisskopf et al. 2002). The key feature of Suzaku, the high-sensitivity wide-band X-ray spectroscopy all in one observatory, has been confirmed through $\sim$ 8 months of PV observations. It is characterized by low background and good energy resolution, in particular a good line spread function in the low-energy range. In figure 5, we show the background counting rate as a function of energy in the 0.5–10 keV range. Here, the background is normalized by the effective area and the field of view. This is a reasonable measure of sensitivity determined by the background for spatially extended sources. Among the instrument listed here, the ASCA SIS had the lowest background, and Suzaku XIS (BI and FI CCD) has a low background comparable to ASCA SIS. Figure 6 shows the background counting rate as a function of energy for the 10–400 keV region. The sensitivity in this energy region is essentially limited by the accuracy of background estimation. The background rate of Suzaku is the lowest among the existing missions for most X-ray energies. At present we can reproduce the background spectrum with an accuracy of 5% of the background level. In the near future, after accumulating more data, we expect to reach the 1% accuracy level. In figure 7, we show an example of the power of Suzaku for obtaining a very wide band spectrum of the radio galaxy Cen A.

Another significant advantage of using Suzaku is the good energy response of the CCD's below 1 keV. The line-spread function of Suzaku CCD is very symmetric in shape, even

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[1] ⟨http://www.astro.isas.jaxa.jp/suzaku/⟩.

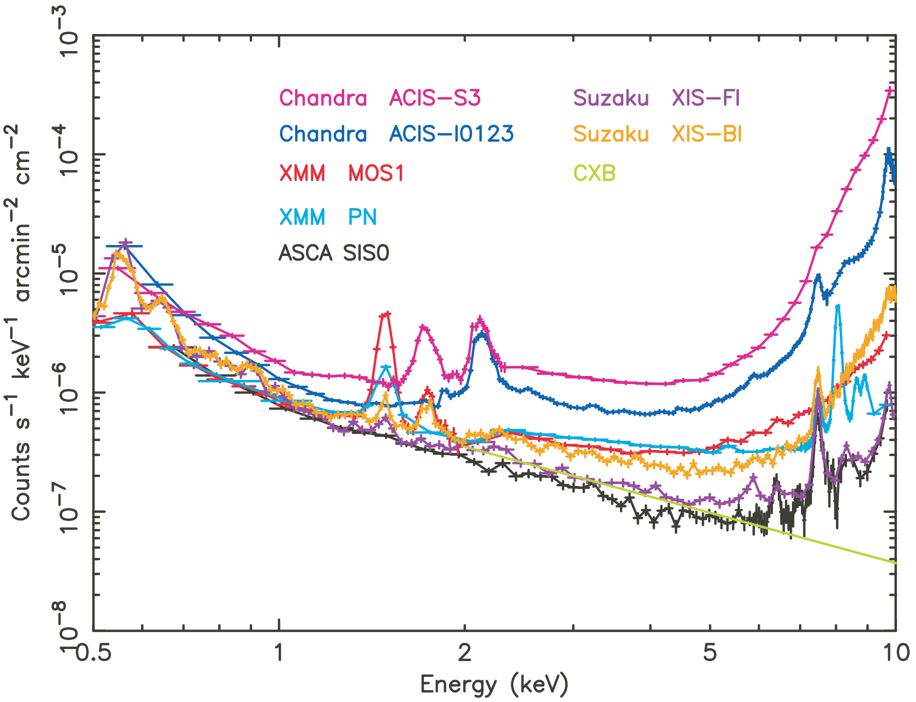

Fig. 5. XIS background counting rate as a function of energy. The background rate was normalized with the effective area and the field of view, which is a good measure of the sensitivity determined by the background for spatially extended sources. The background rate of ASCA, Chandra, and XMM-Newton adopted from Katayama et al. (2004) are shown for comparisons.

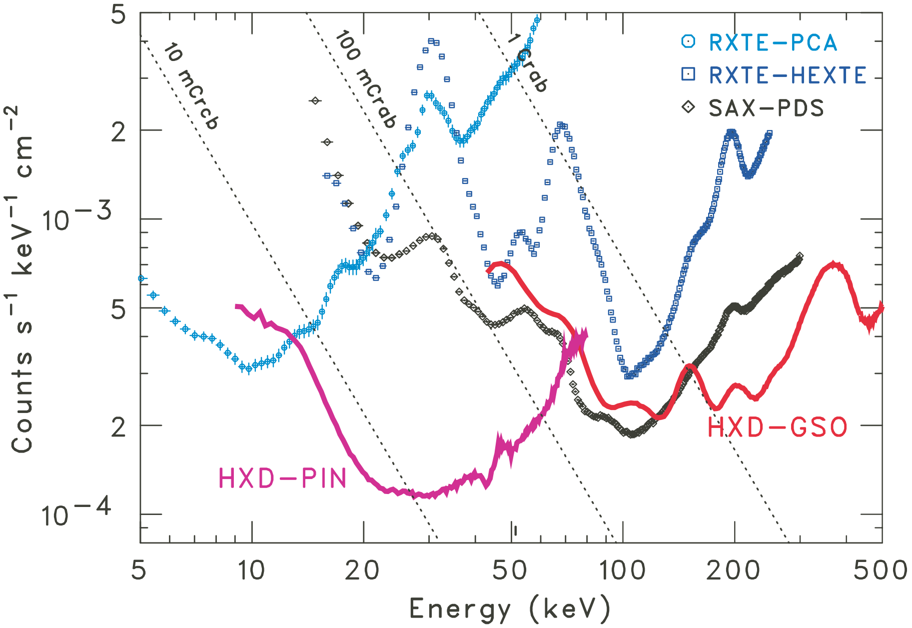

Fig. 6. Background counting rate of Suzaku HXD as a function of energy. The background rate was normalized by the effective area. Background spectra of Beppo-SAX and RXTE were taken from documents for cycle 5 and cycle 11 guest observer programs[2], respectively, and are shown for comparison. The intensity of the Crab nebula is also shown.

in the low-energy range below 1 keV. In other words, the pulse-height distribution to monochromatic X-rays has a much smaller low-pulse-height tail compared to the CCDs on previous missions. This makes it possible to clearly recognize low-energy lines, e.g. K-shell emission lines of C, N, O.

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[2] ⟨http://heasarc.gsfc.nasa.gov/docs/sax/shp_proposal.html⟩, ⟨http://heasarc.gsfc.nasa.gov/docs/xte/cycle11_stage1.html⟩.

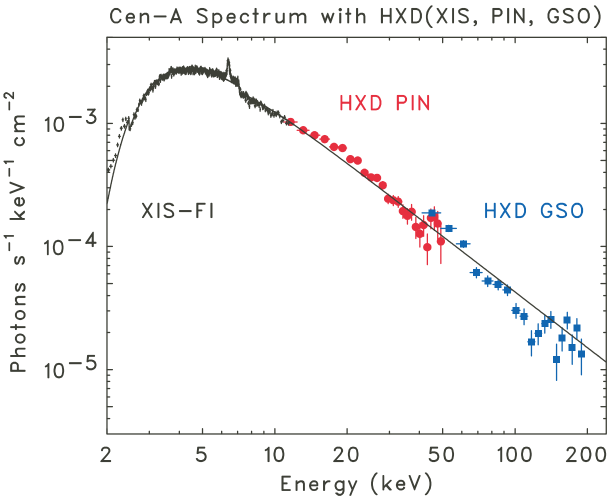

Fig. 7. Energy spectrum of Cen A radio galaxy obtained with Suzaku. The spectrum was obtained with XIS FI CCD (XIS 0, 2, 3) and HXD and deconvolved using an absorbed power-law model.

We owe the success of the Suzaku observatory to the dedication and high capability of many people who have worked on this project for many years; many since the time of ASTRO-E (1994–2000). Here, we list those people who contributed to the spacecraft design, development, and tests in order to express our gratitude. We also express our thanks to those who may have been inadvertently missing in the list. We also would like to thank the M-V team lead by Morita, Y., and Mito, T., for successfully putting the spacecraft into the orbit.

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