# The X-ray Observatory *Suzaku*

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(Received 2006 August 10; accepted 2006 0)

## Abstract

The 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 which 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:** Instrumentations — Spacecrafts — X-rays:general

## 1. Introduction

*Astro-E2*, the fifth in the 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 July 10, 2005, 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 the solar paddles and the extensible optical bench (EOB), and performed $\sim$ 10 days of the perigee-up orbit maneuver to get into a near circular orbit of a 570 km altitude with an inclination angle of 31°. The orbital period is about 96 minutes. Then it underwent an initial checkout phase lasting approximately three weeks, including instrument turn-on and initial calibration. Despite 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 (100K), solid neon (17K), liquid helium (1.3K), and an adiabatic demagnetization refrigerator (60mK), and an energy resolution of 7 eV (Kelley et al. 2006), on August 8, 2005 a thermal short between the helium and neon tanks resulted in the liquid helium coolant venting to space, leaving 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 makes 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. The 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 the 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 which interact with the Earth's magnetic field. The spececraft pointing accuracy is approximately $0.24'$ with a stability better than $0.022'$ per 4 sec (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 Serlemitosos et al. (2006) for details. 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 a belt within which the sun angle is between 65 ° and 115 °. Any part of 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 $\sim 10$ minutes, using the star trackers. The normal mode of operations will have the spacecraft pointing in a single direction for at least 1/4 day (10 ksec). 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%.

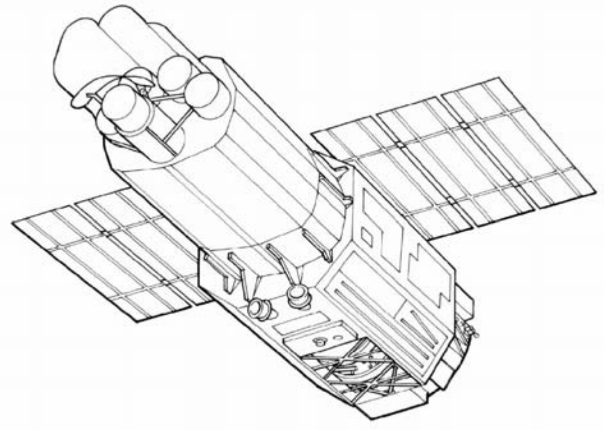

**Fig. 1.** Schematic view of the *Suzaku* satellite in orbit. Both solar paddles and the extensible optical bench (EOB) are deployed. On the top, the X-ray telescope (XRT-S) for the X-ray spectrometer (XRS), and the four X-ray telescopes (XRT-Is) for the X-ray CCD camera (XISs) can be seen.

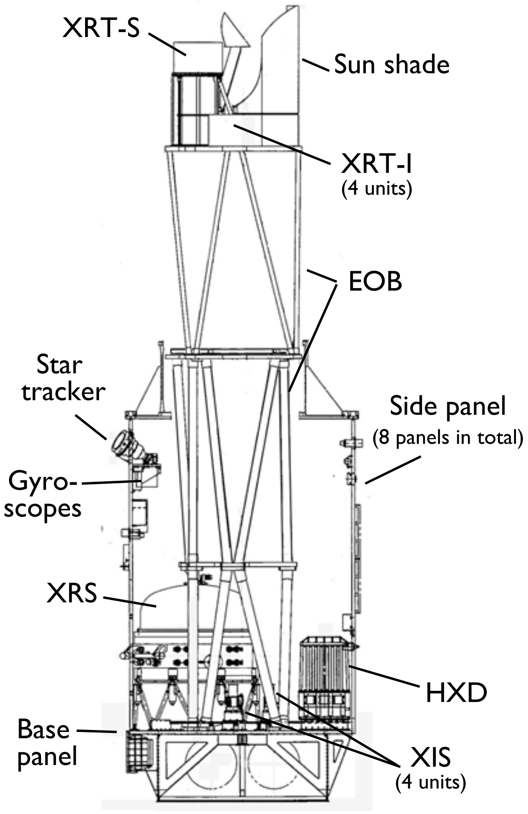

**Fig. 2.** A side view of *Suzaku* with the internal structures after the EOB deployment.

## 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 Spectrometers, XISs, Koyama et al. 2006), 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, Serlemitosos et al. 2006) . The second instrument is the non-imaging, collimated Hard X–ray Detector (HXD, Takahashi et al. 2006), which extends the bandpass of the observatory to much higher energies with its 10–600 keV bandpass (Kokubun et al. 2006). The last instrument, XRS, is no longer operational and will not be discussed further.

### *3.1. XRT*

The X–Ray Telescopes (XRTs) have been 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 large aperture efficiency with a moderate imaging capability in the energy range of 0.2-12 keV, all accomplished in telescope

**Table 1.** Overview of *Suzaku* capabilities

| | | |
|---|---|---|
| S/C | Orbit Apogee | 568 km |
| | Orbital Period | 96 minutes |
| | Observing Efficiency | $\sim$ 43% |
| XRT | Focal length | 4.75 m |
| | Field of View | $17'$ at 1.5 keV |
| | | $13'$ at 8 keV |
| | Plate scale | 0.724 arcmin/mm |
| | 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 | $17.8' \times 17.8'$ |
| | Bandpass | 0.2–12 keV |
| | Pixel grid | 1024$\times$1024 |
| | Pixel size | 24 $\mu$m$\times$ 24 $\mu$m |
| | Energy Resolution | $\sim$ 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 | $4.5^\circ \times 4.5^\circ$ ($\gtrsim$ 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) | $\sim$ 3.0 keV (FWHM) |
| | Energy Resolution (GSO) | $7.6/\sqrt{E_{MeV}}$ % (FWHM) |
| | Effective area | $\sim$ 160 $\mathrm{cm}^2$ at 20 keV, $\sim$ 260 $\mathrm{cm}^2$ at 100 keV |
| | Time Resolution | 61 $\mu$s |
| HXD-WAM | Field of View | $2\pi$ (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 |

units under 20 kg each, including the pre-collimators for rejection of stray lights. Four XRTs 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 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–ray in the energy range of *Suzaku* , 0.2-12 keV. The effective areas are typically 440 $\mathrm{cm}^2$ at 1.5 keV and 250 $\mathrm{cm}^2$ 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 cm. 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 Spectrometers (XISs) employ X–ray sensitive silicon charge-coupled devices (CCDs), which are operated in a photon-counting mode, similar to that used in 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 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 *Suzaku* XISs are designated XIS0, XIS1, XIS2 and XIS3, 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 $17.8' \times 17.8'$ region on the sky. Each pixel is 24 $\mu$m square, and the size of the CCD is 25 mm × 25 mm. One of the XISs, XIS1, 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, thermo-electric coolers, and temperature 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 $\sim 10$ keV to $\sim 600$ 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

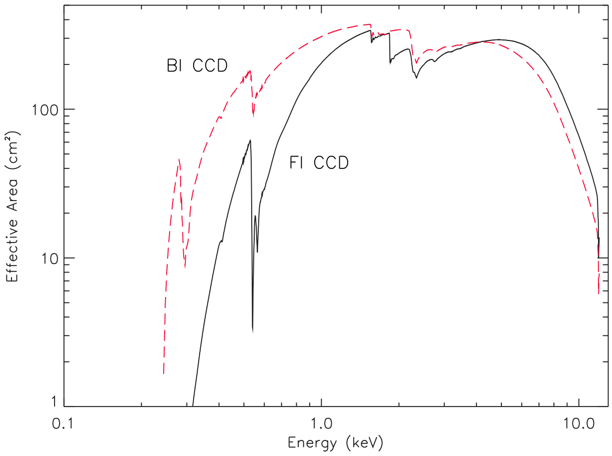

**Fig. 3.** Effective area of one XRT + XIS system, for both the FI (XIS-0, 2, 3) and BI (XIS-1) CCDs.

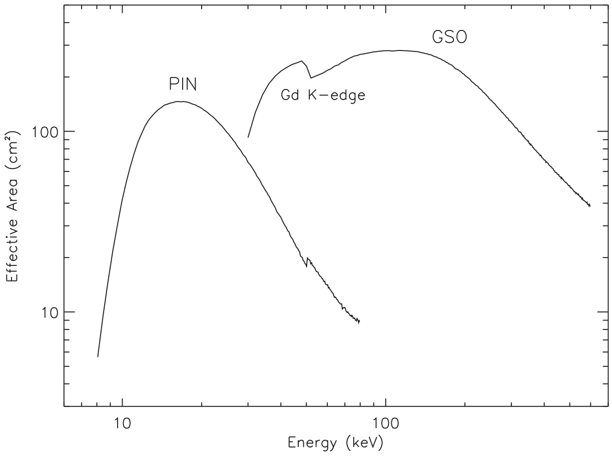

**Fig. 4.** Total effective area of the HXD detectors, PIN and GSO, as a function of energy.

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 $\sim 60$ keV, while the GSO/BGO phoswich counter (scintillator) is sensitive above $\sim 30$ keV. The scintillator signals are read out by photomultiplier tubes. The HXD features an effective area of $\sim 160$ cm$^2$ at 20 keV, and $\sim 260$ cm$^2$ at 100 keV (see figure 4). The energy resolution is $\sim$ 3.0 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, and is referred as the Wide-band All-sky Monitor (WAM). This can be used to detect bright X-ray transients, $\gamma$-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 in 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 the data processing team consisting of scientists and technicians at ISAS/JAXA. The 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 processing software of 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 in the *Suzaku* web pages[1].

## 5. Scientific Capabilities

*Suzaku* was designed to be highly complementary to the two large X-ray observatories which 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 the $\sim 8$ 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 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 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

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

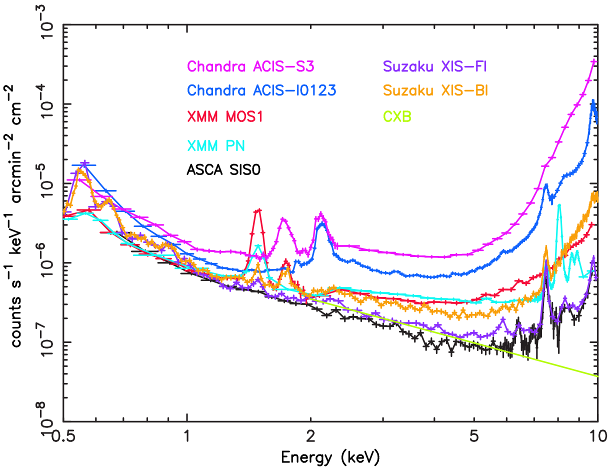

**Fig. 5.** XIS background counting rate as a function of energy. The background rate was normalized with the effective area and the field of view, which is a good measure of sensitivity determined by the background for spatially extended sources. The background rate of *ASCA*, *Chandra*, and *XMM-Newton*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

an accuracy of 5% of the background level. In the near future, after accumulating more data, we expect to reach 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 in the low energy range below 1 keV. In other words, the pulse height distribution to a monochromatic X-rays has much less 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.

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). Here we list those people contributed on 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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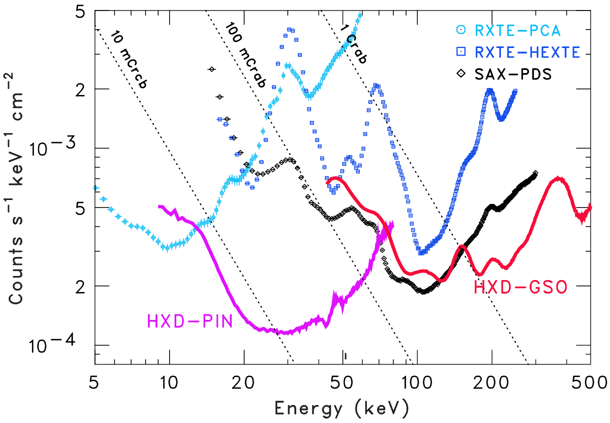

**Fig. 6.** Background counting rate of *Suzaku* HXD as a function of energy. The background rate was normalized by the effective area. Background spectra of *Beppo-SAX* and *RXTE* were taken from documents for cycle 5 and cycle 11 guest observer programs[a], respectively, and are shown for comparison.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

[a] http://heasarc.gsfc.nasa.gov/docs/sax/shp_proposal.html
http://heasarc.gsfc.nasa.gov/docs/xte/cycle11_stage1.html

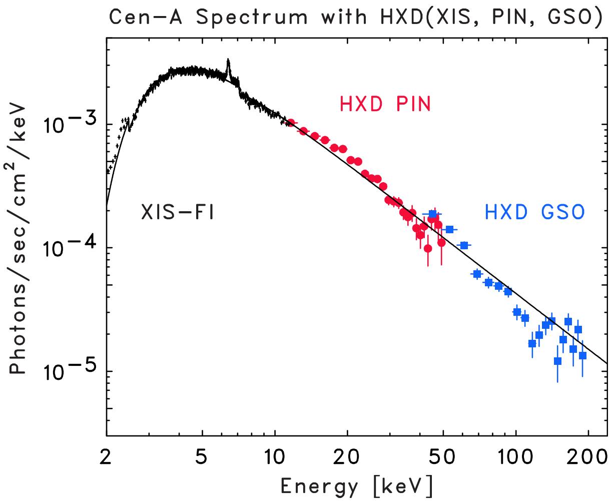

**Fig. 7.** Energy spectrum of Cen A radio galaxy obtained with *Suzaku*. The spectrum was obtained with XIS FI CCDs (XIS-0, 2, 3) and HXD and deconvolved using an absorbed power-law model.

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