Hitomi (ASTRO-H) X-ray Astronomy Satellite

Kaastra, J.S.; et al.

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Abstract. The Hitomi (ASTRO-H) mission is the sixth Japanese x-ray astronomy satellite developed by a large international collaboration, including Japan, USA, Canada, and Europe. The mission aimed to provide the highest energy resolution ever achieved at $E > 2$ keV, using a microcalorimeter instrument, and to cover a wide energy range spanning four decades in energy from soft x-rays to gamma rays. After a successful launch on February 17, 2016, the spacecraft lost its function on March 26, 2016, but the commissioning phase for about a month provided valuable information on the onboard instruments and the spacecraft system, including astrophysical results obtained from first light observations. The paper describes the Hitomi (ASTRO-H) mission, its capabilities, the initial operation, and the instruments/spacecraft performances confirmed during the commissioning operations for about a month. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.JATIS.4.2.021402]

1 Introduction

The Hitomi (ASTRO-H) satellite was launched from Tanegashima Space Center of Japan Aerospace Exploration Agency (JAXA) at 17:45 JST on February 17, 2016 (Fig. 1). After successfully executing start-up operations, the satellite lost contact with the ground on March 26, with signatures of partial breakup of the spacecraft. On April 28, JAXA decided to discontinue the recovery operation of Hitomi. Even though the lifetime was short, the commissioning phase for about a month provided valuable information on the onboard instruments and the spacecraft system, including astrophysical results obtained from first light observations. This paper reports the mission purpose of Hitomi and the technologies achieved through the operations carried out in the commissioning phase.

Our image of the Universe has been dramatically changing from static to dynamic on many scales. X-ray measurements have efficiently detected dynamical and energetic properties of cosmic objects, based on significant improvements in the sensitivity for timing, imaging, and spectroscopic studies. High-resolution x-ray images provided by Chandra, in particular, show dynamical features in the form of shocks, cosmic jets, and outflows of hot gasses. Clusters of galaxies are the largest gravitationally bound objects in the Universe. Many of these systems are now recognized to be undergoing violent mergers characterized by shocks and cold fronts in x-ray and radio images. Supermassive black holes are found in many galaxies, surrounded by a dense gas in some cases, and their coevolution with the host galaxies over the cosmological timescale is an important issue still to be understood. Precise velocity and ionization state of the plasma within these objects, as well as heated component or emission from accelerated particles cannot be identified only by image. Breakthroughs in x-ray observation techniques would bring new views about the evolution of these objects.

High-resolution spectroscopy combined with a wideband energy coverage is a very powerful way of looking into the dynamical evolution of the Universe through x-ray observations. Energy resolution as high as $\Delta E < 7$ eV in full-width at half maximum (FWHM) would enable to measure Doppler motions with an accuracy of ~ 100 km s^{-1} at 6 keV and also can diagnose the detail of ionization state of metals. Sensitivity up to 600 keV, combined with imaging capability up to 80 keV, will show the highest energy regions in the spectrum and the spatial distribution of the accelerated particles. Our current knowledge on how much and in what form the nonthermal energy is produced and carried is still quite poor. The great improvements in the energy resolution and wideband coverage of Hitomi represent a substantial advance in our ability to probe all forms of energy in cosmic objects, such as clusters of galaxies and supermassive black holes. Such an improvement in x-ray astronomy also matches well with the recent progress occurring in radio and gamma-ray bands.

The Hitomi (ASTRO-H) mission has been designed to achieve these aims.[1–8] This is an international x-ray satellite, which was launched with the 30th H-IIA rocket. NASA selected U.S. participation on ASTRO-H as a Mission of Opportunity in the Explorer Program category. Under this program, the NASA/Goddard Space Flight Center collaborates with ISAS/JAXA on the implementation of the x-ray microcalorimeter and the Soft X-ray Telescopes (SXTs) (SXS Proposal NASA/GSFC, 2007).[9] Other institutional members of the collaboration are SRON (Netherlands Institute for Space Research), Geneva University, CEA/IRFU [French Alternative Energies and Atomic Energy Commission (CEA)/Institute of Research into the Fundamental Laws of the Universe (IRFU)], CSA (Canadian Space Agency), Stanford University, and European Space Agency. In early 2009, NASA, ESA, and JAXA selected 13 science advisors to provide scientific guidance to the ASTRO-H project. The ESA contribution to the ASTRO-H mission includes the procurement of payload hardware elements that enhance the scientific capability of the mission.

2 Spacecraft

There are four focusing telescopes mounted on the top of a fixed optical bench (FOB). Two of the four telescopes are SXTs and they have a 5.6-m focal length. They focus soft-energy x-rays ($E = 0.3$ to 12 keV) onto focal plane detectors mounted on the base plate of the spacecraft (see Fig. 2). One SXT points to a microcalorimeter spectrometer array in the Soft X-ray Spectrometer (SXS) with excellent energy resolution of <7 eV, and the other SXT points to a large-area CCD array in the Soft

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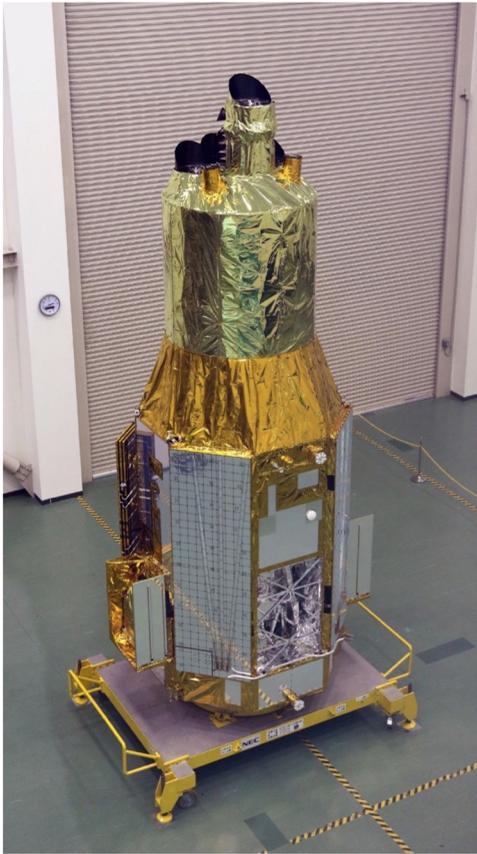
Table 1 Key parameters of the payload.

Parameter	HXI	SXS	SXI	SGD
Detector technology	Si/CdTe cross-strips	Microcalorimeter	X-ray CCD	Si/CdTe Compton Camera
Focal length	12 m	5.6 m	5.6 m	—
Effective area	300 cm^2 at 30 keV	300 cm^2 at 6 keV	350 cm^2 at 6 keV	>20 cm^2 at 100 keV
		250 cm^2 at 1 keV	370 cm^2 at 1 keV	Compton mode
Number of pixels	128 strips orthogonally	6×6	$(640 \times 640) \times 4$ chips	—
Energy range	5 to 80 keV	0.3 to 12 keV	0.4 to 12 keV	60 to 600 keV
Energy resolution (FWHM)	<2 keV (at 60 keV)	<7 eV (at 6 keV)	<200 eV (at 6 keV)	<4 keV (at 60 keV)
Angular resolution	1.7 arc min (at 30 keV)	~1.2 arc min	~1.3 arc min	—
Effective field of view	~9×9 arc min^2	~3×3 arc min^2	~38×38 arc min^2	<0.6×0.6 deg^2 (<150 keV)
Time resolution	25.6 μs	5 μs	4/2/0.5/0.1 s	25.6 μs
Operating temperature	−25°C	50 mK	−120°C	−20°C

Table 2 Hitomi mission.

Launch site	Tanegashima Space Center, Japan
Launch vehicle	JAXA H-IIA rocket
Orbit altitude (apogee)	576.5 km
Orbit altitude (perigee)	574.4 km
Orbit type	Approximate circular orbit
Orbit inclination	31 deg
Total length	14 m
Mass	2.7 metric ton
Power	<3500 W

HXI plate since the mast is composed of multiple joints and hence has some mechanical looseness. Accordingly, lateral angular velocity sometimes approached a software limit, so we carried out the deployment intermittently. We achieved the final full extension configuration of the EOB using four orbits. All operations were performed when the satellite was in contact with the ground station in Japan.

In Fig. 3(a), we show the time history of the center position of the EOB (EOB-X and EOB-Y), its rotation around the spacecraft Z-axis from the nominal orientation, and an apparent unbiased distance (EOB-r12p) throughout Hitomi's life from the start of the EOB extension. EOB-r12p is a difference between measured and actual distance between two corner cubes. The times of satellite-attitude maneuvers are drawn with the vertical lines. The time of the EOB extension is clearly marked by a jump of the center positions of the HXI plate measured by CAMS. After that, however, the location of the HXI plate is mostly within 0.5 mm in peak-to-bottom (note that

10 arc sec at a distance of 12 m is 0.582 mm). Within a single observation (during time interval of two adjacent maneuvers), jitter of the HXI plate is as small as ~0.2 mm. This is comparable or smaller than the pixel size of the HXI (0.25 mm). The stability of the image at the focal plane was monitored with CAMS. As shown in Fig. 3(b), the movement of the focal plane image is <400 μm corresponding to about 7 arc sec. We conclude that we achieved a highly stable EOB.

The microcalorimeter array of SXS has a linear size of 5 mm and is located at the focal plane of the telescope SXT-S. This gives the angular size covered by SXS to be 3 arc min. For the HXT, with focal length 12 m, the effective area at 1 arc min offset from the optical axis is about 80% at 50 to 60 keV. Therefore, the vignetting at 1 arc min off-axis is about 20%. The mutual alignment to enable both SXS and HXI to observe an object right at the optical axes of the telescopes took a lot of effort. As a result, the pointing of an object at the center of the SXS instrument gave images right at the expected positions for the SXI, HXI1, and HXI2 instruments.

Since Hitomi was in an LEO, with the attitude pointed to a direction in the inertial frame, the satellite conditions change throughout one orbit. The temperature gradient changes depending on the day and night phases, and the albedo from the earth and also gravity gradient on the spacecraft change largely in the orbit. To fulfill the requirement of the pointing control accuracy of ~60 arc sec, the thermal design needs to be very precise.[12] The temperatures measured by Heater Control Electronics sensors at various spacecraft positions were all within the acceptable range. Also, temperature data after the start-up of mission instruments, after March 20, were mostly within 5°C of the predicted values.[18] There are differences of 7°C in some instruments, but no data show deviations larger than 10°C.

Along with the parameter tuning operation for the satellite bus and the attitude system, we observed several x-ray sources. The main purpose of the observations was the calibration of x-ray instruments, but the sources also provided interesting scientific data. The observed sources are the Perseus cluster (February 25 to 27, March 4 to 8), N132D (March 8 to 11),
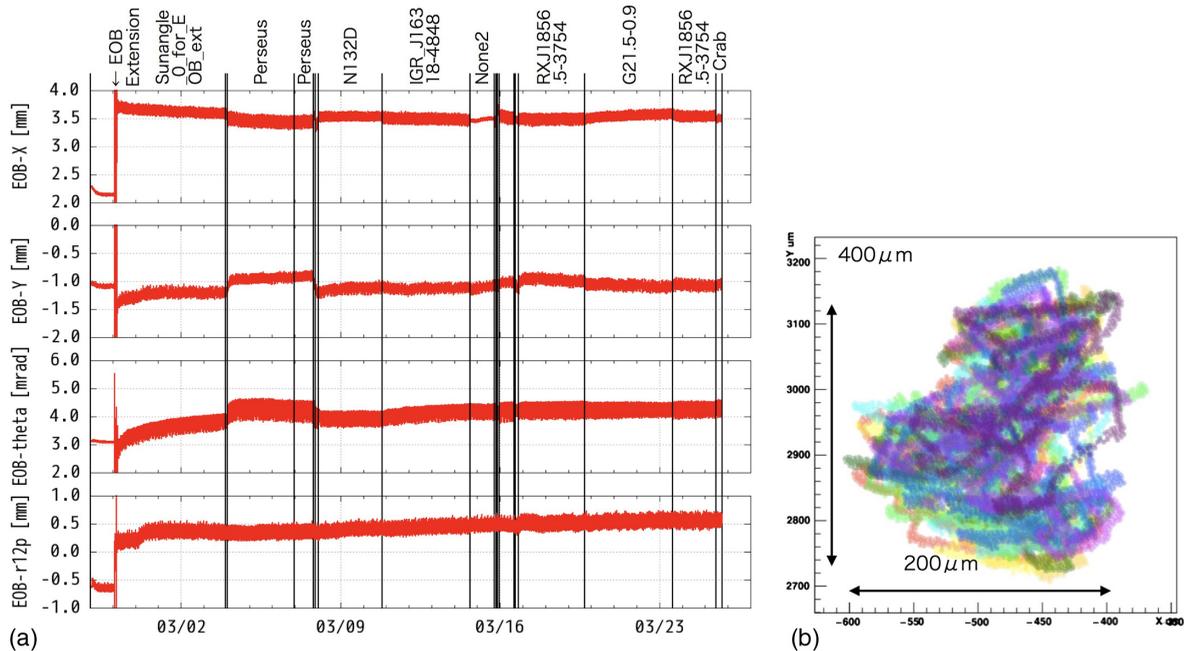
Fig. 3 (a) The time history of the center position of the EOB (EOB-X and EOB-Y), its rotation around the spacecraft Z-axis (the launch direction) from the nominal orientation, and changes of the distance between the two corner cubes. (b) Stability of the focal plane alignment measured in about a day with CAMS after the EOB extension.

IGR J16318-4848 (March 11 to 15), RX J1856-3754 (March 17 to 19, 23 to 25), G21.5-0.9 (March 19 to 23), and the Crab Nebula (March 25). The SXS was operational before the Perseus cluster observation, and SXI started observation during the pointing to Perseus. The HXI1 and HXI2 were started on March 8 to 15 and SGD on March 16 to 25. All the instruments finished their start-up operations on the day before the loss of contact. The Hitomi data will be archived in the public archive at the DARTS (JAXA/ISAS) and HEASARC (NASA/GSFC) after 1-year propriety period that starts when the final data processing is completed.[19]

The first light observation of the Perseus cluster unequivocally showed the superb spectroscopic performance of the SXS by revealing the narrow line complex of He-like ion of iron around 6.7 keV from the core of the Perseus cluster.[20]

4 Science Instruments

Instruments onboard the Hitomi Satellite include a high-resolution, high-throughput spectrometer (SXS) sensitive over 0.3 to 12 keV with high spectral resolution of $\Delta E < 7$ eV (FWHM), enabled by a microcalorimeter array located in the focal plane of thin-foil x-ray optics; hard x-ray imaging spectrometers (HXI) covering 5 to 80 keV, located in the focal plane of multilayer-coated, focusing hard x-ray mirrors (HXT); a wide-field imaging spectrometer sensitive over 0.4 to 12 keV, with an x-ray CCD camera (SXI) in the focal plane of a SXT; and a nonfocusing Compton camera-type SGD, sensitive in the 60- to 600-keV band.

In the following sections, these instruments are briefly described. Detailed descriptions of the instruments and their current status are available in other papers.

4.1 Soft X-ray Telescopes

The SXT[21–25] is very similar to the Suzaku X-ray Telescope[26] but with a longer focal length of 5.6 m and a larger outer diameter of 45 cm. The SXT consists of three parts: an x-ray mirror, a stray light baffle called the pre-collimator, and a thermal shield to keep the mirror temperature at around 20°C. The mirror is a conically approximated Wolter I grazing incidence optic with 203 nested shells. Each shell is segmented into four quadrants.

The flight SXT mirror assemblies [Fig. 4(a)], SXT-I for the SXI and SXT-S for the SXS, were fabricated at NASA/GSFC and delivered to JAXA. According to calibration at GSFC and ISAS, the angular resolution [half-power diameter (HPD)] is 1.3 and 1.2 arc min for the SXT-I and SXT-S, respectively. The result obtained with SXT-S exceeds the desired goal. Effective areas were measured to be ~590 cm² at 1 keV and ~430 cm² at 6 keV. The system net effective area at 1 and 6 keV is about 250 and 300 cm² for the SXS and 370 and 350 cm² for the SXI, respectively. However, since the SXS gate valve (GV) was closed during observations, the SXS effective area was reduced by the Be window transmission and the GV obscuration. The SXS net effective area with the GV closed was about 160 cm² at 6 keV with almost no area below 2 keV.

According to the in-flight data, the SXT-I and SXT-S were clearly focusing x-rays onto the corresponding detectors and they seemed to be working as expected. The overall effective area (flux) was examined using the Crab and the G21.5-0.9 data. Model fittings for both spectra produced a power-law photon index consistent with the previous measurements,[27,28] which indicates that the effective area response was consistent with the ground calibration results.[29] The measured HPD was 1.3 and 1.2 arc min for SXT-I and SXT-S, respectively. Detailed in-flight performance of the SXT is presented in other publications.[30]
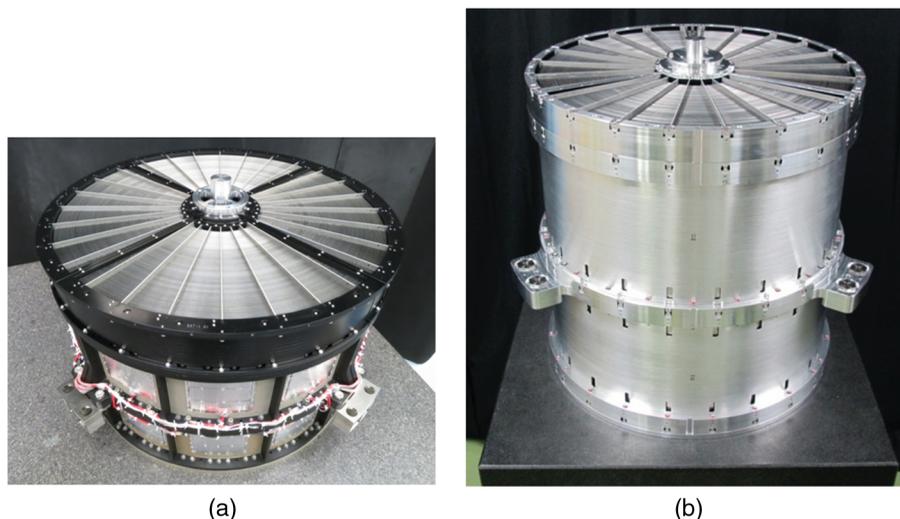
Fig. 4 Photographs of flight models of (a) Soft X-ray Telescope, SXT-S, and (b) Hard X-ray Telescope, HXT-1.

4.2 Hard X-ray Telescopes

A depth-graded multilayer mirror reflects x-rays not only by total external reflection but also by Bragg reflection. To obtain a high reflectivity up to 80 keV, the HXT consists of a stack of multilayers with different sets of periodic length and number of layer pairs with a platinum/carbon coating. The technology of a hard x-ray focusing mirror has already been proven by the balloon programs InFOCμS (2001, 2004),[31,32] HEFT (2004),[33] SUMIT (2006),[31] and recently with the NuSTAR satellite.[34]

The HXT[35–40] consists of three parts: an x-ray mirror, a stray light baffle (pre-collimator), and a thermal shield [Fig. 4(b)]. The mirror is based on conically approximated Wolter I grazing incidence optics.[37,38] The diameters of the innermost and the outermost reflectors are 120 and 450 mm, respectively. The total number of nested shells is 213. Since a telescope module is made up from three segments with an azimuthal opening angle of 120 deg each, it requires 1278 reflectors in total. Production of two flight-ready HXT mirror assemblies, HXT-1 and HXT-2, was completed in 2014. According to calibration performed using the beam line BL20B2 of the synchrotron radiation facility SPring-8, the characteristics of HXT-1 and HXT-2 are quite similar. Based on the ground calibration at the SPring-8, a collecting area of 174 cm^2 at 30 keV for one telescope has been achieved, resulting in a total effective area of 348 cm^2. The HPD of the HXTs is ~1.9 arc min at 30 keV.[40,41] After the launch, the characteristics of HXTs were evaluated using observational data of the Crab Nebula. The HPDs of HXT-1 and HXT-2 in the 5- to 80-keV band were 1.59 and 1.65 arc min, respectively. Note, however, that the encircled energy function (EEF) was normalized at $r = 6$ arc min on the ground whereas, due to the limitation of the HXI field of view, the in-flight EEF was normalized at $r = 4$ arc min and the data in the area $r > 4$ arc min were subtracted as background. We, therefore, reprocessed the ground calibration data in the same way as the in-flight data. The reanalyzed HPDs at 30 keV were 1.77 and 1.84 arc min for HXT-1 and HXT-2, respectively. The in-flight HPDs seem to be slightly smaller than the ground ones. However, both the in-flight and ground HPDs can have an uncertainty of 0.1 arc min. Thus, they are consistent with each other within the uncertainty. The unabsorbed flux of the Crab nebula in the 3- to 50-keV band was measured to be 3.59×10^{-8} erg s^{-1} cm^{-2} with HXT-1 and 3.55×10^{-8} erg s^{-1} cm^{-2} with HXT-2. These values are slightly (~5%) larger than that measured with NuSTAR. Detailed in-flight performance of the HXT is presented in other publications.[42]

4.3 Soft X-ray Spectrometer System

The SXS system consists of the SXT, the filter wheel (FW) assembly,[43] and the SXS.[44–47] The SXS is a 36-pixel system with an energy resolution of better than 7 eV between 0.3 and 12 keV. The array design for the SXS is basically the same as that for the Suzaku XRS[48] but has larger pixel pitch and absorber size. HgTe absorbers are attached to ion-implanted Si thermistors formed on suspended Si microbeams.[49–51] The 6×6 array of silicon thermistors on an 832-μm pitch was manufactured during the Suzaku/XRS program along with arrays with smaller pitch as an option for a larger field of view [Fig. 5(a)]. For SXS, improved heat sinking was added to the frame of the array, and HgTe absorbers with very low specific heat were attached to the pixels. The width of the individual absorbers was 819 μm.[51] A square-cm anticoincidence detector was installed behind the microcalorimeter array in the detector assembly. The detector assembly consisted of the detector enclosure and its mechanical, thermal, and electrical interfaces, including the first stage of amplification.

The SXS detector assembly and low-temperature coolers were installed in the dewar [Fig. 5(b)]. The cooling system was required to cool the array to 50 mK with sufficient duty cycle to fulfill the SXS scientific objectives. This restriction requires extremely low heat loads. To achieve the necessary gain stability and energy resolution, the cooling system must regulate the detector temperature, to within 2-μK rms over intervals of about half an hour, for at least 24 h/cycle.[52] From the detector stage to room temperature, the cooling chain is composed of a three-stage adiabatic demagnetization refrigerator (ADR),[53] superfluid liquid ^{4}He (hereafter LHe), a ^{4}He Joule–Thomson (JT) cryocooler, and two-stage Stirling cryocoolers.

To obtain a good performance for bright sources, an FW assembly, which includes a wheel with selectable filters and a set of modulated x-ray sources, were provided by SRON
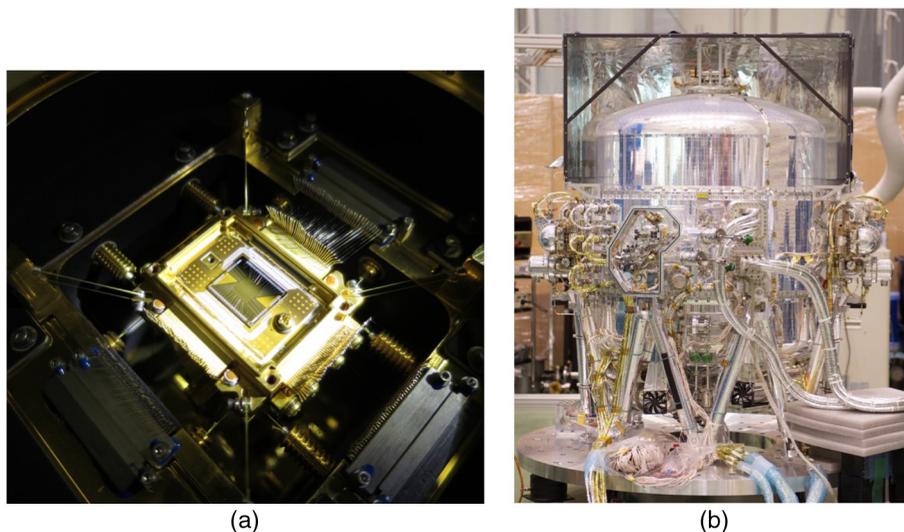
Fig. 5 Photographs of (a) SXS sensor and (b) SXS dewar. The sensor was suspended from the outer structure using Kevlar, and electrical connections to the housing were made using tensioned wires to reduce the sensitivity to microphonics. The outer shell of the dewar is 950 mm in diameter.

and the University of Geneva. This was placed at a distance of 90 cm from the detector. The FW is able to rotate a suitable filter into the beam to optimize the quality of the data, depending on the source characteristics.[43] In addition to the filters, a set of on–off-switchable x-ray calibration sources, using a light-sensitive photocathode, were available. With these calibration sources, the energy scale could be calibrated with a typical 1- to 2-eV accuracy, allowing proper gain and linearity calibration of the detector in-flight.

All SXS components except for the SXS power distributor (SXS-DIST) were powered off at launch (cold launch). The first critical operation was to re-establish the He plumbing in space.[54] Quickly after the fairing opened, the He vent valve was opened, which was confirmed by the telemetry during the first contact 50 min after the launch. We next focused on starting the cooling chain. On day 0, we started two shield coolers at the full wattage and two precoolers (PC) at a low wattage. On day 1, the PCs were also ramped up to the full wattage. By day 4, the JT cooler was also ramped up step by step. On day 5, the ADR cool down was started and the sensor was cooled to 50 mK. After that, the cooling chain worked without any problem until the end of the mission by repeating ADR recycles periodically and continuously operating the cryocoolers.

The signal chain was also started within the first week. On day 2, both the analog and digital signal processors were started (called XBOX and PSP, respectively). After the initial check and the parameter setting, the first noise measurement was performed on day 2 at a warm detector temperature and on day 5 at the 50-mK temperature.

The SXS was ready for observations by as early as day 6. On day 7, the spacecraft was pointed to the Perseus cluster, and we observed x-rays from an astronomical target for the first time. Although the pointing was offset from the cluster core by a few arc minutes, we obtained sufficient counts to make an offset correction based on our own count rate map within a few cycles. On day 8, an adjustment maneuver was made toward the core of the cluster for a longer exposure time. The detector NXB level measured during the Earth occultation was very low ($<1.0 \times 10^{-3}$ cts s^{-1} keV^{-1}).

After the EOB extension, we started commissioning the FW electronics, which was the last SXS subsystem to be powered. The FW was rotated on day 30 to provide x-ray illumination of the whole array by ^{55}Fe sources. The resulting calibration data set was used to refine the gain scales and measure the energy resolutions of the individual pixels. Figure 6(a) is a histogram of the distribution of resolutions measured across the array. The composite resolution of the whole array was 4.9 eV (FWHM) [Fig. 6(b)].[51,55,56]

What remained to be done during the commissioning phase but was not completed were: (i) the start-up of the modulated x-ray source, (ii) opening of the GV and the start of the temperature control of the dewar main shell filter, and (iii) the final setting of the event threshold. The cryogen-free operation using the third stage ADR, which was planned in later phase of the mission,[57] was also not carried out.

4.4 Soft X-ray Imager

X-ray sensitive silicon CCDs are key detectors for x-ray astronomy. The low background and high-energy resolution combined with wide field of view achieved with the Suzaku XIS clearly shows that the x-ray CCD can also play a very important role in the mission. The soft x-ray imaging system consists of an x-ray mirror, the SXT-I, and a CCD camera, the SXI.[58–63,64] Figure 7(a) shows a photograph of the SXI detector. The SXI camera contains a cold plate on which four CCDs are placed. The cold plate is connected to two identical single-stage Stirling coolers.

Start-up operation of SXI began from March 2, 2016. The CCD temperature reached the nominal value, −110°C, on March 7, and we started data acquisition in the event mode. One of the Stirling coolers was used to cool down the CCDs. Fine control of the temperature was performed with heaters attached to the cold plate, and we confirmed the same level of temperature stability as that during the ground tests. We employed a charge injection technique from the beginning of the operation to cope with the decrease of the charge transfer efficiency due to radiation damage. Artificial charge was injected from the top of columns of the CCDs at every 160 rows
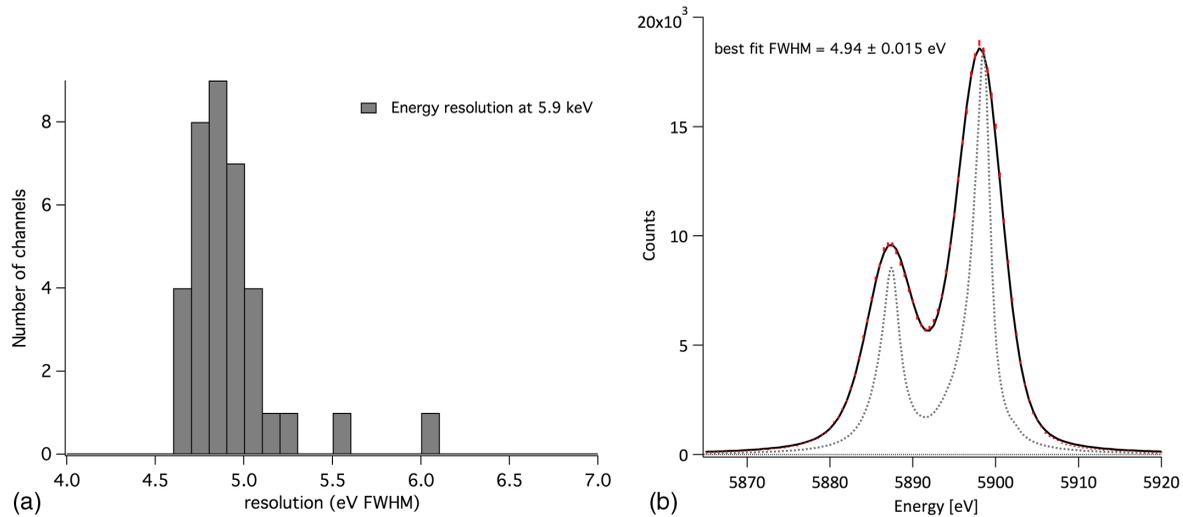
Fig. 6 (a) A histogram of the distribution of resolutions measured across the array. (b) The whole-array spectrum around 5.9 keV. The points are the data, with sqrt(N) error bars on the counts barely visible. The dark line is the best fit to a model of the natural line shape convolved with Gaussian broadening, and the dashed gray line is the natural line shape.
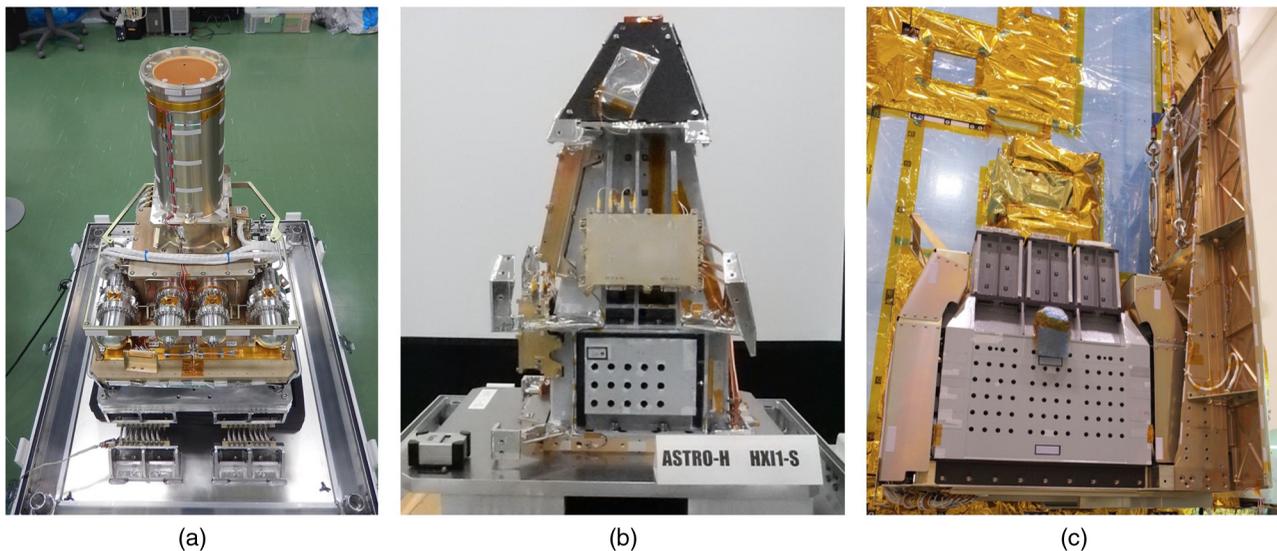

Fig. 7 Photographs of (a) SXI, (b) HXI, and (c) SGD.

(before the on-chip 2×2 binning). We confirmed that the noise level of CCDs was about 5 to 7 e⁻rms, the same as that of the ground tests. We also confirmed that the amount of the injected charge was not changed from the ground test.

The first target was the Perseus cluster of galaxies. As shown in Fig. 8(a), the cluster image is offset from the SXI center, because the CCDs were placed to have an offset relative to the aim point of SXT-I by 5 arc min to avoid the CCD gaps. Two calibration sources of ^{55}Fe are also seen as semicircular shapes on top and bottom centers. Initial performance of the SXI was checked using these calibration source data and the Perseus data. The gain and the energy resolution of the CCDs were found to be roughly consistent with the ground data.[65] Thus, we confirmed that the SXI functioned properly on orbit. We accumulated background data from the source-free regions of the SXI field of view. In the case of Suzaku

XIS(BI),[66] non-x-ray background NXB increased rapidly above 6 keV. Such an increase of NXB almost disappeared for the SXI due to the thick depletion layer (200 μm) compared to that of the XIS(BI) ($\sim$42 μm). Furthermore, the Ni K lines in the NXB spectrum became much weaker while the Au L lines became more prominent.

4.5 Hard X-ray Imager

There are two HXI sensor modules: HXI1-S and HXI2-S [Fig. 7(b)]. The imager part of the HXI[67–74] consisted of four layers of 0.5-mm-thick double-sided silicon strip detectors (DSSD) and one layer of newly developed 0.75-mm-thick CdTe double-sided cross-strip detector (CdTe-DSD). In this configuration, soft x-ray photons below $\sim$30 keV are absorbed in the Si part, and hard x-ray photons above $\sim$30 keV go through the Si
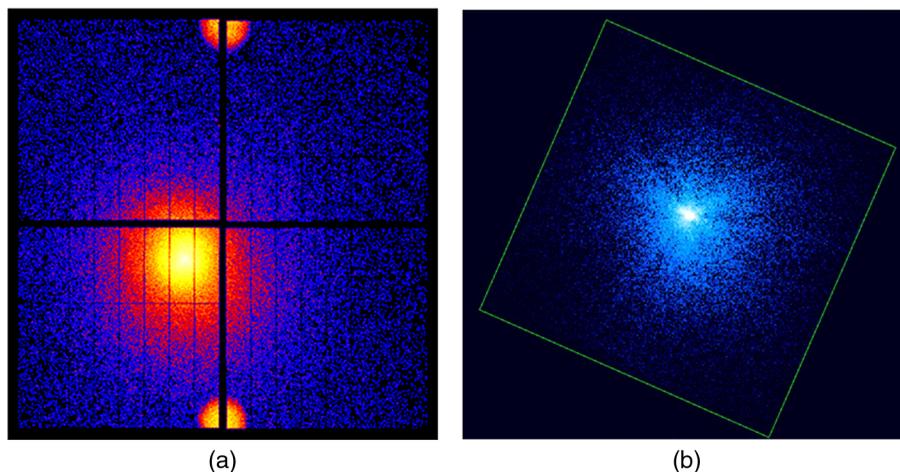
Fig. 8 (a) Logarithmically scaled image of the Perseus cluster. Its core is just on the aim point of the SXI. Two calibration areas are seen as bright regions on top and bottom center. The size of the image is 38×38 arc min^2.[63] (b) A logarithmically scaled image of the Crab Pulsar for 10- to 50-keV energy band, extracted from the HXI1 data of the Crab observation. The square in the image corresponds to the 9.1×9.1 arc min^2 FOV of the HXI. Note that the correction of the satellite attitude is preliminary and vignetting correction is not applied.[67]

part and are detected by the CdTe part. To reduce the background, the sensor part is surrounded by a thick active shield and collimator made of bismuth germanate (BGO) scintillator coupled to avalanche photodiodes (APDs). In addition to the increase in efficiency, the stack configuration and individual readouts per each layer provide information on the interaction depth. This depth information is very useful for reducing the background in space applications, because we can expect that low-energy x-rays interact in the upper layers and, therefore, it is possible to reject the low-energy events, mainly due to the NXB, detected in lower layers. The $E < 30$ keV spectrum, obtained with the Si DSSD, has a much lower background due to the absence of activation in heavy material, such as Cd and Te. The DSSDs cover the energy below 30 keV while the CdTe strip detector covers the 30- to 80-keV band.

The electronics boxes of the HXIs (HXI-DE, DPU, and AE) were powered on February 28 to 29. Then, the HXI sensor (HXI-S) parts temperature was gradually decreased from 5°C to −25°C followed by the bias voltage operation of HXI1-S starting on March 8. The APD bias, Si DSSD bias, and CdTe DSD bias were raised to their operational voltage step by step, and the HXI1-S became operational on March 12. The HXI2-S followed on March 14. All 1280 readout channels for each of the HXI1-S and HXI2-S imager performed well, showing noise performance consistent with the prelaunch on-ground measurements. An image of the Crab Pulsar taken with HXI1 is shown in Fig. 8(b).[67,75]

In addition to the thick BGO active shield and the concept of multilayer configuration of the imager, CXB baffling within the detector and inside the spacecraft worked well to reduce the background. The HXI achieved a low background level of $1 − 3 \times 10^{-4}$ cnt s^{-1} cm^{-2} throughout their energy band of 5 to 80 keV, except for at a few energy region of activation lines in CdTe (here, the flux is normalized by the geometrical size of the detector, 10 cm^2), which is the lowest level ever achieved in orbit. Due to the optimum design of the HXT and the long focal length of 12 m, the effective area was also the largest among the hard x-ray imaging spectroscopy instruments, flown to date. The HXI showed the potential to

provide the highest sensitivity in this energy band, especially for diffuse sources.

4.6 Soft Gamma-Ray Detector

Figure 7(c) shows a photograph of the SGD detector module. The SGD[76–81] measures soft γ-rays via reconstruction of Compton scattering in the semiconductor Compton camera, covering an energy range of 60 to 600 keV with a sensitivity at 300 keV, being 10 times better than that of the Suzaku Hard X-ray Detector,[82,83] by adopting a new concept of a narrow-FOV Compton telescope, combining Compton cameras and active well-type shields. There are two SGD sensor modules: SGD1 and SGD2. The Compton camera is made of 32 layers of 0.625-mm-thick Si pad detectors and 8 layers of 0.75-mm-thick CdTe pad detectors. The side of Si detectors is also surrounded by two layers of CdTe detectors. In the Si/CdTe Compton camera, events involving the incident γ-ray being scattered in the Si detectors and fully absorbed in the CdTe detectors are used for Compton imaging. The direction of the γ-ray is calculated by solving the Compton kinematics with information concerning deposit energies and interaction positions recorded in the detectors. In principle, each layer could act not only as a scattering part but also as an absorber part. A very compact, high-angular resolution (fineness of image) camera is realized by fabricating semiconductor imaging elements made of Si and CdTe, which have excellent performance in position resolution, high-energy resolution, and high-temporal resolution.

The camera was then mounted inside the bottom of a well-type active shield, made of BGO scintillators. The major advantage of employing a narrow FOV is that the direction of incident γ-rays is constrained to be inside the FOV. If the Compton cone, which corresponds to the direction of incident gamma rays, does not intercept the FOV, we can reject the event as background. Most of the background can be rejected by requiring this condition. The opening angle provided by the BGO shield is ~ 10 deg at 500 keV. An additional PCuSn collimator restricts the field of view of the telescope to 33′ for photons below

100 keV, to minimize the flux due to the cosmic x-ray background in the FOV.

The power-on operation of SGD-DE, SGD-DPU, and SGD-AE was performed on March 1, 2016.[81,84] After this operation, SGD HK telemetries, including temperature monitors of SGD-S, were generated. Then, the SGD-S was gradually cooled down to −25°C from March 3 to 13 by changing the SGD heater settings. Start-up operation of SGD-S began on March 15, 2016. First, Compton cameras, APD CSAs for BGO readout, and HV modules for Compton cameras and APDs were powered on, and then we applied the high-voltage step by step and set up detectors into the nominal observation mode. From March 21, SGD1-S had been operated in the nominal observation mode, and SGD2-S was shifted into the nominal observation on March 24, 2016. Basic performance of the SGD was confirmed in the Crab observation, albeit with very short exposure.

5 Summary

Carrying onboard the two types of x-ray optics and the four types of detectors, Hitomi (ASTRO-H) was designed to provide exciting wideband and high-energy-resolution data on various high-energy astrophysical objects. Its one month of operation in orbit demonstrated that many of the technologies introduced to the Hitomi mission worked well. In fact, all instruments produced data with satisfactory quality, though for a short period, until the loss of spacecraft capability. In particular, the acquired data clearly verified the key properties of the SXS, i.e., the high spectral resolution (4.9-eV FWHM) for both point and diffuse sources over a broad 0.3- to 12-keV bandpass, with the low non-x-ray background ($<1.0 \times 10^{-3}$ cts s^{-1} keV^{-1}). Although the GV was not opened, the effective area was consistent with the designed value, indicating that an effective area of 250 cm^2 at 1 keV and 300 cm^2 at 6 keV would be achieved if the GV was open. Hitomi has, thus, opened the door to a generation of x-ray astronomy; forthcoming scientific papers based on the limited amount of data will clearly show the power of this challenging mission.

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Biographies for the authors are not available.