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The ASTRO-H mission

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Abstract. ASTRO-H (the sixth X-ray mission in Japan) will investigate the physics of the high-energy universe via a suite of four instruments, covering a very wide energy range, from 0.3 keV to 600 keV. These instruments include a high-resolution, high-throughput spectrometer sensitive over 0.3-12 keV with high spectral resolution of 7 eV (FWHM), enabled by a micro-calorimeter array located in the focal plane of thin-foil X-ray optics; hard X-ray imaging spectrometers covering 5-80 keV, located in the focal plane of multilayer-coated, focusing hard X-ray mirrors; a wide-field imaging spectrometer sensitive over 0.4-12 keV, with an X-ray CCD camera in the focal plane of a soft X-ray telescope; and a non-focusing Compton-camera type soft gamma-ray detector, sensitive in the 40-600 keV band. The simultaneous broad bandpass, coupled with high spectral resolution, will enable the pursuit of a wide variety of important science themes.

Key words. Stars: abundances – Telescopes – Space vehicles – Space vehicles: instruments – X-rays: galaxies: clusters– Cosmology: observations

1. Introduction

The X-ray band is capable of probing extreme environments of the Universe such as those near black holes or the surface of neutron stars, as well as observing exclusively the emission from high-temperature gas and selectively the emission from accelerated electrons. In recent years, Chandra, XMM/Newton, Suzaku and other X-ray missions have made great advances in X-ray Astronomy. We have obtained knowledge that has revolutionized our understanding of the high energy Universe and we have learned that phenomena observed in the X-ray band are deeply connected to those observed in other wavelengths from radio to Gamma-rays.

ASTRO-H is an international X-ray satellite that Japan plans to launch with the H-II A rocket in 2015 (Fig. 1). In order to revolutionize X-ray astronomy even further, the ASTRO-H mission is equipped with a suite of sensitive instruments with the highest energy resolution ever achieved at E > 3 keV and a wide energy range spanning four decades in energy from soft X-rays to gamma-rays (Takahashi et al. 2012). This instrumental suite will provide the best sensitivity ever achieved for spectroscopy in the 1-600 keV band (Table 1). The mission aims to understand the dynamics of the Universe in general, and study compact regions of high matter and energy concentration allowing probe of production of energetic particles, which are far from the thermal equilibrium.

2. Spacecraft and instruments

The ASTRO-H X-ray observatory consists of four focusing telescopes mounted on a fixed

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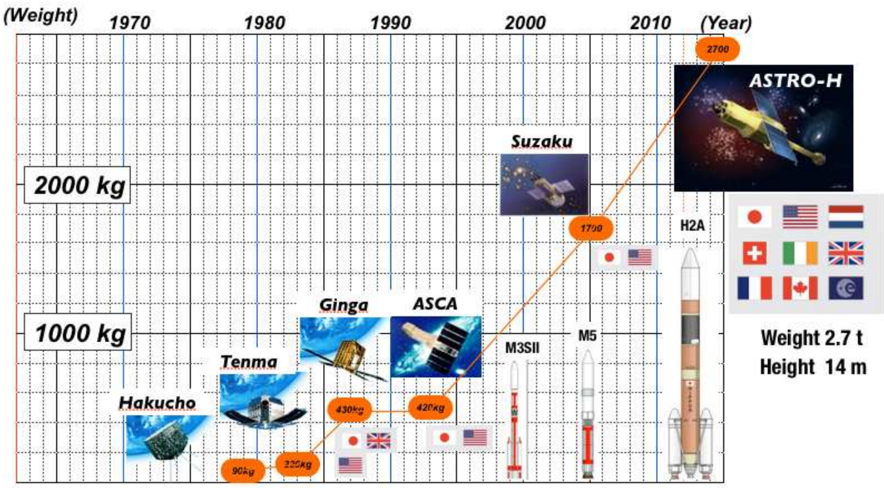

Fig. 1. History of Japanese X-ray satellites based on various international collaborations. The size and weight of satellites increase with the increase of launch capability of Japanese rockets.

optical bench (FOB). Two of the four telescopes are Soft X-ray Telescopes (SXTs) and they have a 5.6 m focal length. They will focus medium-energy X-rays (E 0.3-12 keV) onto focal plane detectors mounted on the base plate of the FOB (Fig. 2).

One SXT will point to a micro-calorimeter spectrometer array and the other SXT will point to a large-area CCD array. The other two telescopes are Hard X-ray Telescopes (HXTs) capable of focusing high-energy X-rays (E = 5-80 keV). The focal length of the HXTs is 12 m. The Hard X-ray Imaging detectors (HXIs) are mounted at the end of a 6 m extendable optical bench (EOB) that is stowed to fit in the launch fairing and deployed once in orbit.

In order to extend the energy coverage to the soft Gamma-ray region up to 600 keV, the Soft Gamma-ray Detector (SGD) will be implemented as a non-focusing detector. Two SGD detectors, each consisting of three units will be mounted separately on two sides of the satellite. With these instruments, ASTRO-H will cover the entire bandpass between 0.3 keV and 600 keV. Detailed descriptions of the instruments and their current status are available in other papers listed in Takahashi et al. (2012).

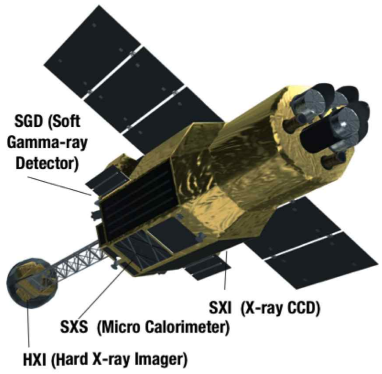

Fig. 2. Schematic view of the ASTRO-H satellite. The total mass at launch will be ~ 2700 kg. ASTRO-H will be launched into a circular orbit with altitude of 500 − 600 km, and inclination of ~ 31 degrees.

In combination with a high throughput X-ray telescope, the SXS improves on the Chandra and XMM-Newton grating spectrometers in two important ways. At E > 2 keV, SXS is both more sensitive and has higher res-

Table 1. Key parameters of the ASTRO-H payload (Takahashi et al. 2012)

Parameter	Hard X-ray Imager (HXI)	Soft X-ray Spectrometer (SXS)	Soft X-ray Imager (SXI)	Soft γ-ray Detector (SGD)
Detector technology	Si/CdTe cross-strips	micro calorimeter	X-ray CCD	Si/CdTe Compton Camera
Focal length	12 m	5.6 m	5.6 m	–
Effective area	300 cm^2@30 keV	210 cm^2@6 keV 160 cm^2 @ 1 keV	360 cm^2@6 keV	>20 cm^2@100 keV Compton Mode
Energy range	5 –80 keV	0.3 – 12 keV	0.5 – 12 keV	40 – 600 keV
Energy resolution (FWHM)	2 keV (@60 keV)	< 7 eV (@6 keV)	< 200 eV (@6 keV)	< 4 keV (@60 keV)
Angular resolution	<1.7 arcmin	<1.3 arcmin	<1.3 arcmin	–
Effective Field of View	$\sim 9 \times 9$ arcmin^2	$\sim 3 \times 3$ arcmin^2	$\sim 38 \times 38$ arcmin^2	0.6×0.6 deg^2 (< 150 keV)
Time resolution	25.6 μs	5 μs	4 sec/0.1 sec	25.6 μs
Operating temperature	−20°C	50 mK	−120°C	−20°C

olution), especially in the Fe K band where SXS has 10 times larger the collecting area and much better energy resolution, giving a net improvement in sensitivity by a factor of 30 over Chandra (Mitsuda et al. 2010; Porter et al. 2010). The broad bandpass of the SXS encompasses the critical inner-shell emission and absorption lines of Fe I-XXVI between 6.4 and 9.1 keV. Fe K lines provide particularly useful diagnostics because of their (1) strength, due to the high abundance and large fluorescent yield (30%), (2) spectral isolation from other lines, and (3) relative simplicity of the atomic physics. Fe K emission lines reveal conditions in plasmas with temperatures between 10^7 and 10^8 K, which are typical values for stellar accretion disks, SNRs, clusters of galaxies, and many stellar coronae. In cooler plasmas, Si, S, and Fe fluorescence and recombination occurs when an X-ray source illuminates nearby neutral material. Fe emission lines provide powerful diagnostics of non-equilibrium ionization due to inner shell K-shell transitions from Fe XVII–XXIV (Decaux et al. 1997).

The SXS uniquely performs high-resolution spectroscopy of extended sources. In contrast to a grating, the spectral resolution of the calorimeter is unaffected by source's angular size because it is non-dispersive. For all sources with angular extent larger than 30 arcsec, Chandra MEG energy resolution is degraded compared with that of a CCD; the energy resolution of the XMM-Newton RGS is similarly degraded for sources with angular extent ≥25 arcsec. SXS therefore makes possible high-resolution spectroscopy of sources inaccessible to current grating instruments.

3. Science operation

ASTRO-H is in many ways similar to Suzaku in terms of orbit, pointing, and tracking capabilities, although the mass is considerably larger (the total mass at launch will be 2700 kg, nearly double Suzaku's 1700 kg). ASTRO-H will be launched into a circular orbit with altitude of 500–600 km, and inclination of 31 degrees. Science operations will be similar to those of Suzaku, with pointed observation of each target until the integrated observing time is accumulated, and then slewing to the next target. A typical observation will require a few

Fig. 3. The TTM model of the ASTRO-H satellite. Structures such as FOB, side panels and base plates are flight parts.

$\times$ 100 ksec integrated exposure time (see Table 2).

All instruments are co-aligned and will operate simultaneously. The current plan is to use the first three months for check-out and start the PV phase with observations proprietary to the ASTRO-H team. Guest observing time will start from 10 months after the launch. About 75% of the satellite time will be devoted to GO observations after the PV phase is completed. We are planning to implement key-project type observations in conjunction with the GO observation time.

4. Expected scientific performance

ASTRO-H is expected to revolutionize high energy science on all astronomical scales. These include: 1) the very compact scales around black holes, 2) high-temperature plasmas around stars at all stages of their lives, 3) the diffuse hot media around supernova remnants, 4) the interstellar media of galaxies, 5) clusters of galaxies and 6) the large scale diffuse inter galactic medium. Opening up new parameter space in i) energy range, ii) sensitivity, iii) spectral resolution and iv) polarimetry, will allow detailed study of the dynamics, composition, morphology and evolution of matter across these cosmic scales.

The spectroscopic capability of X-ray micro-calorimeters is unique in X-ray astronomy, since no other previously or currently operating spectrometers could achieve comparable high energy resolution, high quantum efficiency, and spectroscopy for spatially extended sources at the same time. Imaging spectroscopy with the Soft X-ray Spectrometer (SXS) of extended sources can reveal line broadening and Doppler shifts due to turbulent or bulk velocities. This capability enables the determination of the level of turbulent pressure support in clusters, SNR ejecta dispersal patterns, the structure of AGN and starburst winds, and the spatially dependent abundance pattern in clusters and elliptical galaxies. The SXS can also measure the optical depths of resonance absorption lines, from which the degree and spatial extent of turbulence can be inferred. Additionally, the SXS can reveal the presence of relatively rare elements in SNRs and other sources through its high sensitivity to low equivalent width emission lines. The low SXS background ensures that the observations of almost all line-rich objects will be photon limited rather than background limited.

The imaging capabilities at high X-ray energies will open a new era in high spatial-resolution studies of astrophysical sources of non-thermal emission above 10 keV, probed simultaneously with lower energy imaging spectroscopy. This will enable us to track the evolution of active galaxies with accretion flows which are heavily obscured, in order to accurately assess their contribution to black hole growth over cosmological time scale. It will also uniquely allow mapping of the spatial extent of the hard X-ray emission in diffuse sources,thus tracing the sites of cosmic ray acceleration in structures ranging in size from megaparsecs, such as clusters of galaxies, down to parsecs, such as young supernova remnants. Those studies will be complementary to the SXS measurements: observing the hard X-ray synchrotron emission will allow a study of the most energetic particles, thus revealing the details of particle acceleration mechanisms in supernova remnants, while the high resolution SXS data on the gas kinematics of the remnant

Table 2. ASTRO-H Mission

Launch site	Tanegashima Space Center, Japan
Launch vehicle	JAXA H-IIA rocket
Orbit Altitude	~550 km
Orbit Type	Approximate circular orbit
Orbit Inclination	~ 31 degrees
Orbit Period	96 minutes
Total Length	14 m
Mass	~ 2.7 metric ton
Power	< 3500 W
Telemetry Rate	8 Mbps (X-band QPSK)
Recording Capacity	12 Gbits at EOL
Mission life	> 3 years

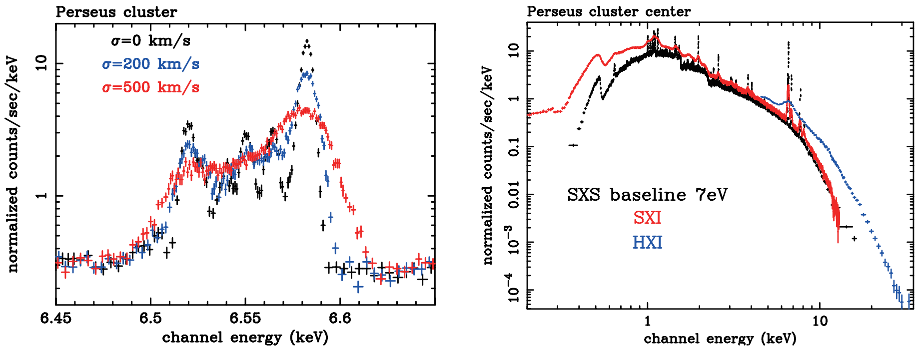

Fig. 4. Simulated spectra for 100 ks ASTRO-H observations of Perseus Cluster. **(left)** SXS spectra around the iron K line complex. Line profiles assuming σ = 0, 200 and 500 km s^{-1} turbulence. **(right)** SXS (black), SXI (red), and HXI (blue) spectra for hot plasma with a mixture of three different temperatures of 0.6, 2.6 and 6.1 keV (r < 2′) (Takahashi et al. 2010).

will constrain the energy input into the accelerators.

As shown in Figure 5, the sensitivity to be achieved by ASTRO-H (and similarly NuSTAR) is about two orders of magnitude improved compared to previous collimated or coded mask instruments that have operated in this energy band. This will bring a breakthrough in our understanding of hard X-ray spectra of celestial sources in general. With this sensitivity, 30 – 50 % of the hard X-ray Cosmic Background will be resolved. It will enable us to track the evolution of active galaxies with accretion flows that are heavily obscured, in order to accurately assess their contribution to the Cosmic X-ray Background (i.e., black hole growth) over cosmic time. n addition, simultaneous observations of blazar-type active galaxies with Fermi-LAT and the TeV γ-ray telescopes are of vital importance to study particle acceleration in relativistic jets. n exciting and unique possibility is the detection of the polarization in hard X-rays by SGD during particularly strong flaring states of the brightest BL Lacs, like that of Mrk 501 in 1997 when the synchrotron continuum of the source extended up to the $\gtrsim$ 100 keV photon energy range.

5. Conclusions

The ASTRO-H mission objectives are: to determine the evolution of yet-unknown obscured supermassive black holes (SMBHs) in Active Galactic Nuclei (AGN); to trace the

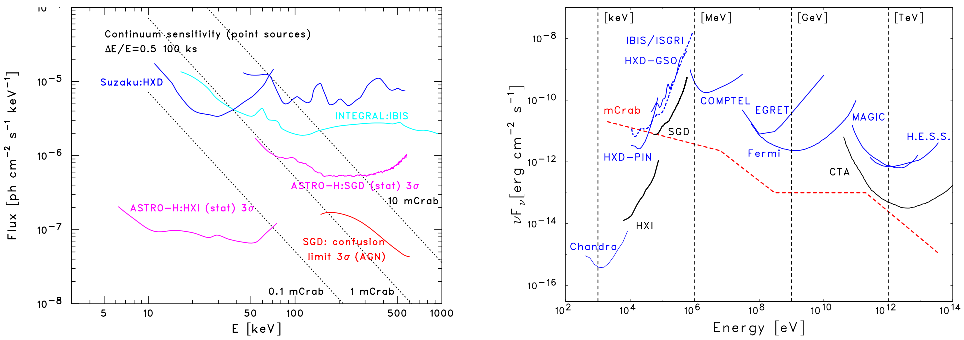

Fig. 5. (left) The 3σ sensitivity curves for the HXI and SGD onboard ASTRO-H for an isolated point source. (100 ks exposures and $\Delta E/E = 0.5$) (right) Differential sensitivities of different X-ray and γ-ray instruments for an isolated point source (Takahashi et al. 2013). Lines for the Chandra/ACIS-S, the Suzaku/HXD (PIN and GSO), the INTEGRAL/IBIS (from the 2009 IBIS Observer's Manual), and the ASTRO-H/HXI,SGD are the 3σ sensitivity curves for 100 ks exposures. A spectral bin with $\Delta E/E = 1$ is assumed for Chandra and $\Delta E/E = 0.5$ for the other instruments.

growth history of the largest structures in the Universe; to trace the chemical evolution of the universe; to probe feedback from the growth of supermassive black holes onto their galaxy and cluster environments; to provide insights into the behavior of material in extreme gravitational fields; to determine the spin of black holes and the equation of state of neutron stars; to trace particle acceleration structures in clusters of galaxies and SNRs; and to investigate the detailed physics of astrophysical jets.

ASTRO-H will open a completely new field of spatial studies of non-thermal emission across a broad range of energies extending well above 10 keV with hard X-ray telescopes and enable us to track the evolution of active galaxies with accretion flows that are heavily obscured. It will also uniquely allow mapping of the spatial extent of the hard X-ray emission in diffuse sources, thus tracing the sites of particle acceleration in structures ranging in size from clusters of galaxies down to supernova remnants.

The key properties of SXS onboard ASTRO-H are its high spectral resolution for both point and diffuse sources over a broad bandpass, high sensitivity (effective area of 160 cm^2 at 1 keV and 210 cm^2 at 7 keV), and low non-X-ray background (1.5×10^{-3} cts $\mathrm{s}^{-1}\mathrm{keV}^{-1}$). These properties open up a full range of plasma diagnostics and kinematic studies of X-ray emitting gas for thousands of targets, both Galactic and extragalactic. SXS improves upon and complements the current generation of X-ray missions, including Chandra, XMM-Newton, Suzaku, Swift and NuSTAR.

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