The ASTRO-H Mission

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on behalf of the ASTRO-H team
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Abstract

The joint JAXA/NASA ASTRO-H mission is the sixth in a series of highly successful X-ray missions initiated by the Institute of Space and Astronautical Science (ISAS) The planned launch date is 2014. ASTRO-H will investigate the physics of the high-energy universe by performing high-resolution, high-throughput spectroscopy with moderate spatial resolution over the 0.3–600 keV energy range. ASTRO-H is a combination of wide band X-ray spectroscopy (3–80 keV) provided by multi-layer coating, focusing hard X-ray mirrors and hard X-ray imaging detectors, and high energy-resolution soft X-ray spectroscopy (0.3–10 keV) provided by thin-foil X-ray optics and a micro-calorimeter array. The mission will also carry an X-ray CCD camera as a focal plane detector for a soft X-ray telescope and a non-focusing soft gamma-ray detector. With these instruments, ASTRO-H covers very wide energy range from 0.3 keV to 600 keV. The micro-calorimeter system is developed by international collaboration lead by ISAS/JAXA and NASA. The simultaneous broad bandpass, coupled with high spectral resolution of $\Delta E \sim$7 eV by the micro-calorimeter will enable a wide variety of important science themes to be pursued.

Key words: X-ray, Hard X-ray, gamma-ray, X-ray Astronomy, Gamma-ray Astronomy

1. Introduction

ASTRO-H, which was formerly called as NeXT, is an international X-ray satellite that Japan plans to launch with the H-II A rocket in 2014 (Takahashi et al. 2008). It has completed the phase A study in 2008 and entered into Phase B since Oct. 2008. NASA has selected the US participation in ASTRO-H as a mission of opportunity. Under this program, the NASA/Goddard Space Flight Center collaborates with ISAS/JAXA on the implementation of an X-ray micro-calorimeter spectrometer (SXS Proposal NASA/GSFC, 2007). Other international members are from SRON, Geneva University and CEA/DSM/IRFU. In addition, in early 2009, NASA, ESA and JAXA have selected science working group members to provide scientific guidance to the ASTRO-H project relative to the design/development and operation phases of the mission.

The ASTRO-H mission objectives are to study the evolution of yet-unknown obscured super massive Black Holes (SMBHs) in Active Galactic Nuclei (AGN); trace the growth history of the largest structures in the Universe; provide insights into the behavior of material in extreme gravitational fields; determine the spin of black holes and the equation of state of neutron stars; trace particle acceleration structures in clusters of galaxies and SNRs; and investigate the detailed physics of jets.

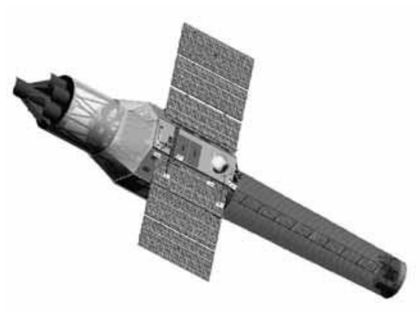

Fig. 1. Artist's drawing of the ASTRO-H satellite. The focal length of the Hard X-ray Telescope (HXT) is 12m, whereas the Soft X-ray Spectrometer (SXS) and Soft X-ray Imager (SXI) will have a focal length of 5.6 meters.

In this paper, we will summarize the scientific requirements, the mission concept and the current baseline configuration of instruments of ASTRO-H.

2. Science Requirements

ASTRO-H aims to achieve the following objectives by inheriting the tradition and advancing the technology of highly successful X-ray missions initiated by the Institute of Space and Astronautical Science (ISAS) beginning with the launch of the Hakucho mission in 1979 through to the currently operating Suzaku mission.

1. For "revealing the large-scale structure of the universe and its evolution,"
   - ASTRO-H observes galaxy clusters, the largest structure of the universe, and uncovers their entire pictures of thermal energy, kinetic energy of intracluster medium, and non-thermal energy, and directly trace the dynamic evolutions of galaxy clusters.
   - ASTRO-H observes distant (past) super massive black holes hidden by thick surrounding materials with 100 times higher sensitivity than Suzaku, and studies the evolution and the role in galaxy formation of such black holes.
2. For "understanding the extreme conditions in the universe, "
   - ASTRO-H measures the motion of matter governed by gravitational distortion at extreme proximity of black holes, and reveal the structure of relativistic space-time.
3. For "exploring the diverse phenomena of the non-thermal universe, "
   - ASTRO-H probes the physical condition of the sites where high energy particles (cosmic rays) gain energy, which leads to a better understanding of the process in which gravity, collisions, and explosions give rise to cosmic rays.
4. For "elucidating dark matter and dark energy, "
   - ASTRO-H maps the distribution of dark matter in galaxy clusters and the total mass of galaxy clusters at different distances (ages), and studies the roles of dark matter and dark energy in the evolution of galaxy clusters.

3. Spacecraft and Instruments

ASTRO-H is in many ways similar to Suzaku in terms of orbit, pointing, and tracking capabilities (Table.1), although the mass is larger; the total mass at launch will be 2400 kg, and the length is longer, the total length in the orbit will be $\sim$ 14 m. ASTRO-H will be launched into a circular orbit with altitude 500–600 km, and inclination 30 degrees or less. Science operations will be similar to that 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 40–100 ksec integrated observing time, which corresponds to 1–2.5 days of clock time. All instruments operate simultaneously.

Table 1. ASTRO-H Mission

Launch date	2014 (planned)
Launch site	Tanegashima Space Center, Japan
Launch vehicle	JAXA H-IIA rocket
Mass	$\sim$2.4 metric tons
Orbit altitutude	550 km circular
Orbit Inclination	Approximate circular orbit
Orbit type	$\sim$31 degree
Orbit Period	96 minutes
Mission length	longer than 3 years (target 5 years)

To achieve the scientific goals, the ASTRO-H satellite must collect X-rays from celestial objects ranging from 0.2 keV to 80 keV with X-ray telescopes and carry out imaging and spectroscopy observations using three types of focal-plane detectors. It must also be able to detect X-rays from 10 keV to 600 keV with a non-imaging device. The properties (i.e. the arrival time, position, and energy) of detected signals must be recorded in the stored data system of the satellite after being digitized, which are transmitted to ground stations.

ASTRO-H will carry two hard X-ray telescopes (HXTs) for the hard X-ray imager (HXI), and two soft X-ray telescopes (SXT), one with a micro-calorimeter spectrometer array with excellent energy resolution of $\sim$7 eV, and the other with a large area CCD. Both soft and hard X-ray mirrors are mounted on top of the fixed optical bench. Two focal-plane detectors for soft X-ray mirrors are mounted on the base plate of the spacecraft, while two hard X-ray detectors are mounted on the extensible optical bench to attain 12 m focal length. In order to extend the energy coverage to soft γ-ray region, a Soft Gamma-ray Detector (SGD) will be implemented as a non-focusing detector.

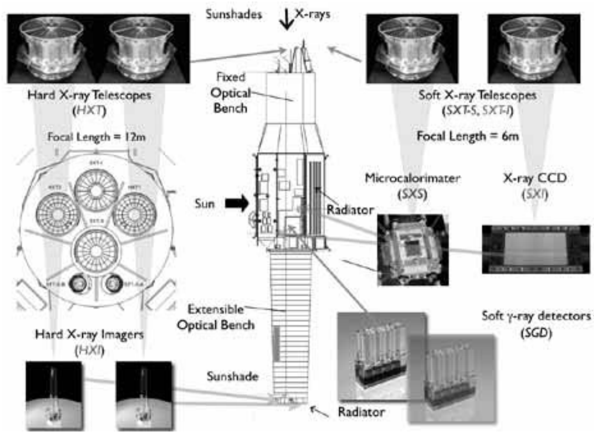

Fig. 2. Configuration of the ASTRO-H satellite

3.1. Hard X-ray Imaging System

The hard X-ray imaging system onboard ASTRO-H consists of two identical mirror-detector pairs (Hard X-ray Telescope (HXT) and Hard X-ray Imager (HXI)). The HXT has conical-foil mirrors with graded multilayer reflecting surfaces that provide a 5–80 keV energy range (Ogasaka et al. 2008). The effective area of the HXT is maximized for a long focal length, with current design value of 12 m giving an effective area of $\sim$300 cm^2 at 30 keV. A depth-graded multi-layer mirror reflects X-rays not only by total external reflection but also by Bragg reflection. In order to obtain high reflectivity up to 80 keV, the HXT's consist of a stack of multi-layers with different sets of periodic length and number of layer pairs with a carbon/platinum coating.

The HXI consists of four-layers of 0.5 mm thick Double-sided Silicon Strip Detectors (DSSD) and one layer of 0.5–1 mm thick CdTe imaging detector (Kokubun et al. 2008). In this configuration, soft X-ray photons will be absorbed in the Si part (DSSD), while hard X-ray photons go through the Si part and are detected by the newly developed CdTe double strip detector.The DSSDs cover the energy below 30 keV while the CdTe strip detector covers the 20-80 keV band. The DSSD has a size of 3$\times$3 cm^2 and a thickness of 0.5 mm, resulting in 2 mm in total. A CdTe strip detector has a size of $\sim$3$\times$3 cm^2 and a thickness of 0.75 mm. In addition to the increase of efficiency by keeping non X-ray background low, the stack configuration and individual readout provide information on the interaction depth.

3.2. Soft X-ray Spectrometer System

The Soft X-ray Spectrometer (SXS) is based on Suzaku-XRS (X-Ray Spectrometer) technology, which is the lowest risk option for implementing the capabilities needed for the SXS. The SXS consists of the Soft X-ray Telescope (SXT-S), the X-ray Calorimeter Spectrometer (XCS) and the cooling system (Mitsuda et al. 2008).

The XCS is a 32 channel system with an energy resolution of $\leq$7 eV between 0.3–12 keV. Micromachined, ion-implanted silicon is the basis of the thermistor array, and 800-micron-thick HgTe absorbers provide high quantum efficiency across the 0.3–12 keV band. The effective area of the instrument will be 225 cm^2 at 6 keV, by a factor of about 1.5 larger than that of Suzaku XRS. The detector is a 6x6 format array which covers a 3$\times$3 arcmin^2 filed of view, with a focal length of 5.6 m.

The XCS cooling system must cool the array to 50 mK with sufficient duty cycle to complete the SXS scientific objectives, requiring 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 for at least 24 hours per cycle. As with Suzaku, the array will be cooled using an Adiabatic Demagnetization Refrigerator (ADR). The ADR and detector assembly will be developed, integrated, and tested together at GSFC, prior to installation into a dewar system developed by ISAS. The ADR Controller (ADRC) electronics control and monitor the ADR performance. The design of the dewar system is based on coolers developed for space-flight missions in Japan (Suzaku, Akari, and the SMILES instrument to be deployed on the ISS) that have achieved excellent performance with respect to cooling power, efficiency and mass. The lifetime is designed to be longer than 5 years.

3.3. Soft X-ray Imaging System

X-ray sensitive silicon charge-coupled devices (CCDs) are a key device for the X-ray astronomy. The low background and high energy resolution achieved with the XIS/Suzaku clearly show that the X-ray CCD will also play very important role in the ASTRO-H mission. Soft X-ray imaging system consists of an imaging mirror and a CCD camera (Soft X-ray Telescope (SXT-I) and Soft X-ray Imager (SXI)) (Tsunemi et al. 2008).

In order to cover the soft X-ray band below 10 keV, the SXI will use next generation Hamamatsu CCD chips with a thick depletion layer, low noise, and almost no cosmetic defects. The SXI features a large FOV and covers 38$\times$38 arcmin^2 region on the sky, complementing the smaller FOV / lower angular resolution but much higher spectral resolution of the SXS calorimeter. A mechanical cooler ensures a long operational life at -120 °C. The overall quantum efficiency and spectral resolution is better than the Suzaku XIS. The imaging mirror has a 5.6-m focal length, and a diameter no larger than 45 cm.

3.4. Soft Gamma-ray Detector (SGD)

Highly sensitive observations in the energy range above the HXT/WXI bandpass are crucial to study the spectrum of accelerated particles. The SGD is a non-focusing soft gamma-ray detector with a 10–600 keV energy range and sensitivity at 300 keV, more than 10 times better than the Suzaku HXD (Hard X-ray Detector). It outperforms previous soft-γ-ray instruments in background rejection capability by adopting a new concept of narrow-FOV Compton telescope (Takahashi et al. 2003).

In order to lower the background dramatically and thus to improve the sensitivity as compared to the HXD of Suzaku, we combine a stack of Si pad detectors and CdTe pad detectors to form a semiconductor Compton imager. In order to detector scattered photon at large angle, the side part of the Si stack is also surrounded by CdTe detectors. The Si stack consists of 32 layers of 0.5 mm thick Si detectors. Eight layers of CdTe detectors with a thickess of 0.75 mm will be placed underneath the Si stack and two CdTe layers will surround the Si Stack. The imager is then mounted inside the bottom of a well-type active shield. Above $\sim$50 keV, we can require each event to interact twice in the stacked detector, once by

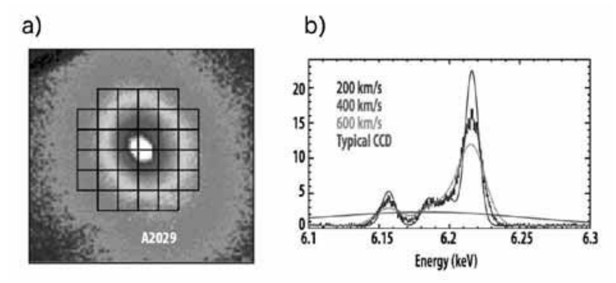

Fig. 3. A portion of a simulated spectrum from the cluster A2029, assuming 400 km/s turbulence, and models assuming 200, 400, and 600 km/s, clearly showing the capability of SXS to measure cluster dynamics. The simulation is for 100 ksec.

Compton scattering in a stack of Si detectors, and then by photo-absorption in the CdTe part (Compton mode). Once the locations and energies of the two interactions are measured, the Compton kinematics allows us to calculate the energy and direction (as a cone in the sky) of the incident γ-ray by following the Compton equation,

4. Expected Performance

The key properties of SXS are its high spectral resolution for both point and diffuse sources over a broad bandpass, high sensitivity, and low non-X-ray background. These properties open up the 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 and Swift.

SXS spectroscopy of extended sources can reveal line broadening and Doppler shifts due to turbulent or bulk velocities (Fig. 3). This capability enables the spectral identification of cluster mergers, SNR ejecta dispersal patterns, the structure of AGN and starburst winds, and the spatially dependent abundance pattern in clusters and elliptical galaxies. SXS can also measure the optical depths of resonance absorption lines, from which the degree and spatial extent of turbulence can be inferred. Additionally, 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.

Fig. 4 shows Detection limits of the SXT-I/SXI and HXT/HXI for point sources and for sources with of 60' × 60' extension. By assuming a background level of $\sim 1{\times}10^{-4}$ counts/s/cm^2/keV, in which the non X-ray background is dominant, the source detection limit in 1000 ksec would be roughly $10^{-14}\,\mathrm{erg\,cm^2\,s^{-1}}$ in terms of the 10–80 keV flux for a power-law spectrum with a photon index of 2. This is about two orders of magnitude better than present instrumentation, so will give a breakthrough in our understanding of hard X-ray spectra. With this sensitivity, 30-50 % of hard X-ray Cosmic Background would be be resolved.

In addition to the imaging observations below 80 keV, the SGD will provide a high sensitivity in the soft γ-ray region to match the sensitivity of the HXT/HXI combination. The extremely low background brought by a narrow-FOV Compton telescope adopted for the SGD will provide sensitive γ-ray spectra up to 600 keV, with moderate sensitivity for polarization measurements.

XMM-Newton and Suzaku spectra frequently show time-variable absorption and emission features in the 5–10 keV band. If these features are due to Fe, they represent gas moving at very high velocities with both red and blue shifted components from material presumably near the event horizon. CCD resolution is too low and the required grating exposures are too long to properly characterize the velocity field and ionization of this gas and determine whether it is from close to the black hole or from high velocity winds. SXS, in combination with HXI, provides a dramatic increase in sensitivity over Suzaku, enabling measurements that probe the geometry of the central regions of ~50 AGNs on the orbital timescale of the Fe producing region (for an AGN with a $3{\times}10^7 M_\odot$ black hole, this is ~60 $GM_\odot/c^2 = 10$ ksec).

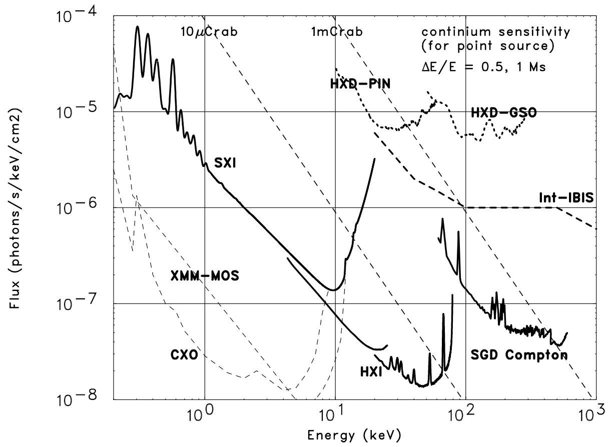

Fig. 4. Detection limits of the SXT-I/SXI and HXT/HXI for point sources.

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