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Calibration and Performance of the X-Ray Spectrometer on-board *Astro-E2*

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Abstract

The X-ray Spectrometer (XRS) is a non-dispersive X-ray spectrometer on-board the X-ray astronomy satellite, *Astro-E2*, which is scheduled to be launched in 2005. The detector system consists of a 31-pixel microcalorimeter array, and achieves an unprecedented energy resolution of ~ 6 eV over the energy band 0.3–12 keV. Here we present the results of our ground calibration and performance tests that we have carried out for the fully completed flight system of the XRS. Our latest results taken at ISAS with the XRS on the spacecraft show that the measured energy resolutions are about 5–6 eV FWHM at 6 keV for most of the pixels.

Keywords:

X-ray, calorimeter, astrophysic, spectroscopy, Astro-E2, XRS

1. Introduction

Astro-E2 is the fifth Japanese X-ray astronomy satellite developed under Japan-US international collaboration [1]. It is a rebuild of the Astro-E mission, which was lost during launch in 2000, and is scheduled for launch in 2005. Currently, two large X-ray observatories are operating in orbit: *Chandra* from NASA, which has a remarkable imaging capability (< 1″ spatial resolution), and *XMM-Newton* from ESA (European Space Agency), which is superior in effective area. Both carry X-ray CCD cameras and dispersive grating spectrometers which have delivered various impressive results. However, CCD cameras achieve an energy resolution of about 100 eV at 6 keV at the best performance, and grating spectrometers are chiefly usable for point-like sources in the soft energy band of less than 2 keV. *Astro-E2* is characterized by an extremely good energy resolution (ΔE ~ 6 eV at 6 keV) and wide energy coverage (0.3–700 keV) that will complement *Chandra* and *XMM-Newton*.

Astro-E2 has three co-aligned detectors: an X-ray microcalorimeter array (X-Ray Spectrometer; XRS)[2, 3], four X-ray CCD cameras (X-ray Imaging Spectrometer; XIS) [4], and well-type phoswitch scintillators in combination with silicon PIN diodes (Hard X-ray Detector; HXD)[5]. The XRS and each XIS are located in the focal planes of five dedicated X-ray telescopes (XRT) [6], and cover the soft energy band of 0.3–10 keV, while HXD extends the bandpass up to 700 keV. The spacecraft weighs approximately 1700 kg, and is about 5.0 m high as launched and 6.5 m high after deployment in orbit. It will be placed in a near-earth orbit with a nominal altitude of 550 km, and an inclination of 31°, using JAXA's M-V rocket. As of October 2004, final integration tests are in progress at ISAS. The left panel of Fig. 1 is a photograph of the *Astro-E2* spacecraft during a thermal-vacuum test phase. The detailed description of *Astro-E2* and its status are found at the web site[*1].

Since the XRS is a non-dispersive instrument, it is applicable to extended sources such as galaxy clusters and supernova remnants. Thus, it will provide a unique capability for studying physical state and chem-

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[*1] http://heasarc.gsfc.nasa.gov/docs/astroe/prop_tools/astroe2_td/

Fig. 1 A photograph of the *Astro-E2* spacecraft during the thermal-vacuum test at ISAS.

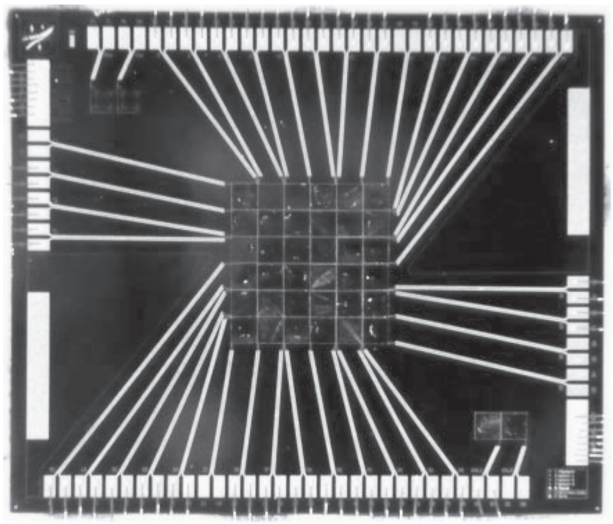

Fig. 2 View of the full 6 × 6, 3.8-mm-square XRS array.

ical composition (from oxygen to nickel) of diffuse hot cosmic plasma. In addition, the XRS has superior energy resolution at high energies compared to any instruments so far in orbit, including grating spectrometers. A detailed spectroscopy of Fe K lines (6–7 keV) will enable us to perform plasma diagnostics as well as to reveal the dynamical motion on the order of $\sim 100\ \mathrm{km\,s^{-1}}$ from the Doppler shifts and line broadening.

To make the maximum use of its capability, it is very important to understand the nature of the instrument and to calibrate its performance on ground. In this paper, we briefly describe the design, performance, and calibration results obtained during ground testing.

2. Design of XRS

The sensor of the XRS is a 6 × 6 array of microcalorimeter pixels*2 with HgTe absorbers attached on silicon thermistors (Fig. 2) [3, 7]. The detector is operated at 60 mK. The XRS precisely measures the energy of an incoming X-ray photon by detecting the temperature rise of a few mK resulting from the absorption of the photon. To maintain the sensor at a precisely regulated cryogenic temperature, the XRS incorporates four stages of cooling system inside a dewar: an adiabatic demagnetization refrigerator (ADR); superfluid liquid helium; solid neon; and a Stirling cycle mechanical cooler. The total weight of the XRS dewar is about 400 kg, including the cryogens, and the expected lifetime is about 2.5–3.0 years. To reduce the incident X-ray flux from bright sources, there is a filter wheel located about 400 mm above the sensor [8]. ^{55}Fe and ^{41}Ca sources are attached to the filter wheel, and can be taken in and out of the field of view for the drift monitoring in orbit. The Helium Insert, which includes the microcalorimeter array, the ADR, and a helium cryostat, and the signal processing electronics were developed by NASA/Goddard Space Flight Center (GSFC), while the neon dewar and the mechanical cooler were developed by ISAS and Sumitomo Heavy Industries, Ltd. (SHI).

Since the beginning of the *Astro-E2* program, enormous efforts were put into improving the performance of the XRS based on our understanding of the original XRS. The most significant improvement is the higher energy resolving power of $E/\Delta E = 1000$ at 6 keV (Full Width at Half Maximum; FWHM), which is a factor of 2 better than the original [9]. The high spectral resolution enables us to resolve Mn-$K_{\alpha 1}$ and $K_{\alpha 2}$ lines (11 eV apart) much more clearly. With the newly added mechanical cooler, a longer lifetime of the cryogens is expected. A lower background should be achieved by using the more collimated in-flight calibration source which illuminates only one pixel. The XRS performance for both Astro-E and Astro-E2 is summarized in Table 1.

*2 31 pixels are connected to readout electronics, including one calibration pixel with an ^{55}Fe source dedicated for gain drift monitoring.

Table 1 Performance of the original XRS of Astro-E and the new XRS of Astro-E2

	Astro-E	Astro-E2
Energy resolution (FWHM at 6 keV)	12 eV	6 eV
Field of view	$1.9' \times 4.1'$	$2.9' \times 2.9'$
Array format	2×16	6×6
Number of pixels	32	31 +1(for calibration only)
Pixel size	1.23×0.318 mm	0.624×0.624 mm
Lifetime	< 2 years	2.5–3 years

3. Ground calibration

We have performed ground calibrations to measure the energy resolution, energy scale, line spread function, quantum efficiency, filter transmittance, etc. The characterizatiion and calibration of the sensor array were performed at NASA/GSFC in early 2003 [10] and from December 2003 to February 2004. In March 2004, the He Insert, which contains the detector and the ADR, was shipped from US to Japan, and installed it into the flight dewar at SHI. Performance verification and calibration tests were carried out at SHI for four weeks in July and August, with the neon tank filled with about 10 % solid neon. After the environment test of the XRS dewar at ISAS, it was mounted onto the spacecraft in September, and the neon tank was filled to 100 % with solid neon. We then verified its performance through a one-week spacecraft running test in the end of September. The results presented here are mainly from the data taken at SHI and ISAS.

3.1 Energy scale

To determine X-ray energies of the incident photons from the universe, it is necessary to know an energy scale function to convert the measured pulse heights into their X-ray energies. Hence, the energy scale is one of the most important properties of the XRS, and an accuracy of 1–2 eV is required.

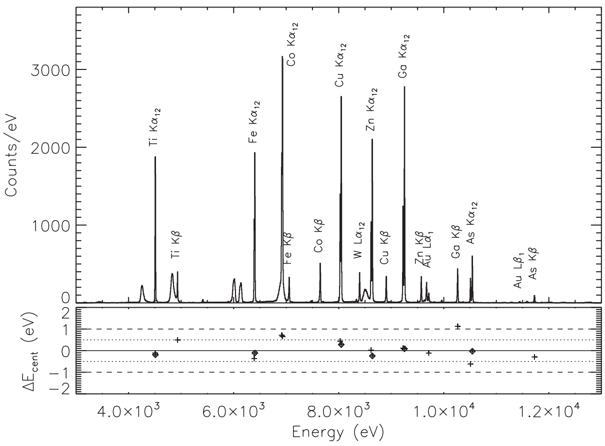

Fig. 3 Composite energy spectra of Rotating Target Source and residuals to the line fits.

An electron impact X-ray source (Rotating Target Source; RTS) with a target wheel including Ti, V, Fe, Co, Cu, Zn, GaAs and Au was used to produce fluorescence emission lines from 4.5 keV to 12 keV. We generate the empirical enegy scale by fitting the measured pulse heights for the K_α lines in the RTS spectra to a fourth order polynominal function. Figure 3 shows the energy-corrected RTS spectrum and residuals to the line fits. Using only the simplest centroiding for the complex K_β and L_α lines, the accuracy of the energy scale has been achieved to be better than 1 eV in the 4.5–12 keV energy band.

3.2 Energy resolution and line spread function

The energy resolution and the line spread function (LSF; response to monocromatic X-ray photons) are two other key parameters of the XRS. At NASA/GSFC, we used a monochromator to measure the LSF, and at SHI and at ISAS, we used a radioactive source of ^{55}Fe to verify it. Figure 4 shows a spectrum of Mn $K_{\alpha 1}$ and $K_{\alpha 2}$ from the ^{55}Fe source attached on the filter wheel during the final spacecraft integration tests in the full flight configuration at ISAS in the end of September, 2004. The spectra of all the pixels except for two pixels whose characteristics are slightly worse than other pixels in the

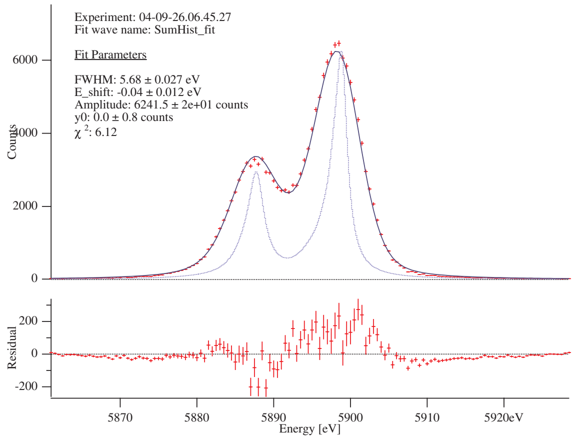

Fig. 4 Spectrum of Mn$K\alpha_1$ and $K\alpha_2$ from an ^{55}Fe source with a fitting to the instrinsic line shape and a Gaussian instrumental function. The spectra of all pixels except for two were combined together. The resolution was 5.68 ± 0.03 eV (FWHM).

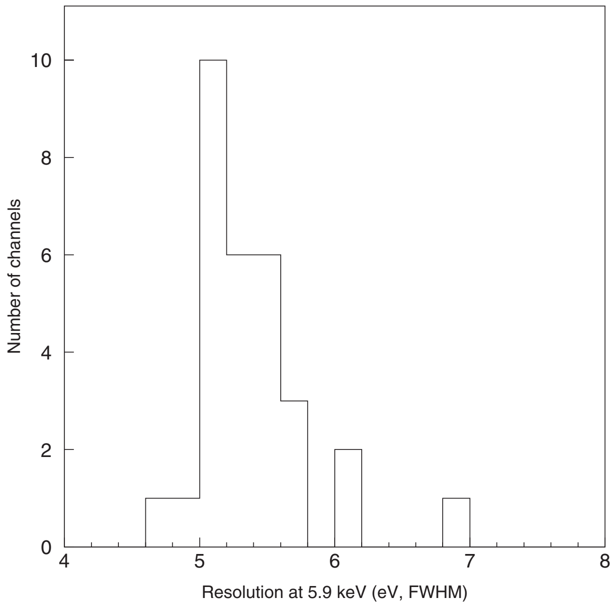

Fig. 5 Distribution of energy resolutions for each pixel across the array. One pixel outlies in this plot, which has an energy-dependant resolution of 14 eV at 6 keV.

higher energy band (see also Fig. 5), are combined together. The gray line shows the intrinsic line shape and the black line shows the best fit curve with a Gaussian instrumental function. The composite resolution was 5.68±0.03 eV (FWHM), which is even better than the results of the ground calibrations at NASA/GSFC and SHI. The detector response has been measured to be entirely Gaussian to almost three orders of magnitude down from the peak of the line or line complex.

Figure 5 shows a histogram of energy resolution for each pixel across the array for a fit to Mn K_α lines. The resolution distributes mainly between 5 and 6 eV with a mean resolution of 5.4 eV. The resolution is only slightly energy-dependent with an increase of about 1 eV from 6 keV up to 10 keV. One pixel, which has the strongest energy-dependant resolution of 14 eV at 6 keV, is not shown on this plot.

4. Summary

The detailed ground calibration tests for the flight XRS instrument were carried out in US and Japan in the last one year. On the spacecraft, an extremely low noise environment has been realized, and the energy resolution was better than 6 eV at 6 keV for most of the pixels. We also confirmed that the energy scale can be reproduced with accuracy better than 1 eV across the 4.5–12 keV energy band, using an empirical fourth order polynominal function. The line spread function is expressed well by a Gaussian function. Response matrices will be produced based on these results. One of the remaining challenges is to understand the gain drift due to the temperature change of the helium bath and the neon tank interface. Futher study is needed using the ground and the inflight data.

The XRS, the first X-ray microcalorimeter array in orbit, is almost ready for flight. The spectroscopic capability of the XRS will bring us completely new discoveries in cosmic plasmas and surely lead to great advances in high energy astrophysics.

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