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The X-ray microcalorimeter instruments on the Astro-E2 and Constellation-X X-ray observatories

Richard L. Kelley*

NASA/Goddard Space Flight Center, Code 662, Greenbelt, MD 20771, USA

Abstract

X-ray microcalorimeter arrays are well suited to address key problems in high-energy astrophysics. The Japan/US Astro-E2 mission will deploy a 32-pixel array of microcalorimeters with 6 eV resolution. This mission is scheduled for launch in 2005. Beyond Astro-E2, NASA is formulating the Constellation-X mission to provide a dramatic increase in collecting area with four separate spacecraft each with large area optics and 1 k-pixel calorimeter arrays providing an energy resolution of 2–4 eV.We will describe the microcalorimeter instrumentation on these missions and mention some of their scientific objectives.

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1. Introduction

The Astro-E2 observatory is a rebuild of the original Astro-E observatory that was lost during launch in February 2000, and will still be the first orbiting observatory to employ a microcalorimeter array for high resolution, high throughput X-ray spectroscopy in the 0.3–12 keV band [1]. The Japanese Institute of Space and Astronautical Science (ISAS) is developing the observatory with significant contributions from the US. Other instruments on Astro-E2 include a set of four CCD cameras and a combination photo-diode/scintillator detector system that will extend the band pass up to nearly 700 keV. The observatory will be launched into low earth orbit on a Japanese M–V rocket in early 2005. The high-resolution X-ray spectrometer (XRS) is a cryogenic instrument designed to last at least 2 years in orbit. Thereafter, the CCD cameras will provide the basic imaging and spectroscopy function of the mission. A significant feature of Astro-E2 is that all of the instruments are coaligned and simultaneously operated. With its high spectral resolution and collecting area for spectroscopy above 1 keV, Astro-E2 will provide a powerful new tool for observing high-energy processes in the universe and create the potential for new discoveries.

Constellation-X (Con-X) is a NASA mission now under formulation to provide a 100-fold increase in collecting area with 15″ imaging and a <4 eV energy resolution microcalorimeter arrays with 1000 pixels [2]. The mission will consist of 4 identical observatories located at the Sun–Earth

*Tel.: +1-301-286-7266; fax: +1-301-286-1684.
E-mail address: richard.l.kelley.@milkyway.gsfc.nasa.gov (R.L. Kelley).

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L2 point. Con-X is currently planned for a launch of the first two satellites in 2013 and the remaining two a year later.

2. The Astro-E2/XRS

The basic design of the XRS has been presented in more detail elsewhere [3, 4]. Here we give a very brief description of the instrument and highlight some important changes with respect to Astro-E.

The XRS features an array of 32 microcalorimeters based on ion-implanted Si thermistors and HgTe absorbers [5]. The array is heat sunk to 60 mK and is current-biased through a voltage divider. The voltages across the thermistors are read out with 32 JFETs operating at 130 K for minimum noise [6]. The base temperature of the array is maintained by a FAA paramagnetic salt adiabatic demagnetization refrigerator (ADR). The ADR is heat sunk to a 32-l superfluid He cryostat pumped to 1.3 K. This system is located inside a 120 l solid Ne Dewar pumped to 17 K.

Following the loss of Astro-E, proposal efforts in Japan and the US were immediately begun to replace the mission. By March 2002, all of the rebuild efforts were approved and fully underway. In parallel with this, technical work was undertaken to enhance the performance and reliability of the XRS. Among the most significant of these was the detector. The original XRS array consisted of two rows of pixels with rectangular geometry and a spectral resolution of about 12 eV.A new array has been developed with square geometry and a resolution of about 6 eV [7].

The new array design afforded an opportunity to improve the in-flight calibration of the array. A pixel identical to the array pixels is located out on the frame of the array that will be illuminated by a collimated ^{55}Fe source. This will provide gain-correction data without flooding the entire array, producing much lower non-rejectable background.

The heat loads and volume of the solid Ne determined the cryogen lifetime of the original XRS instrument. The liquid He lifetime would have been a little over 3 years if the solid Ne lasted equally long. Consequently, a single stage Stirling cycle mechanical cooler developed by the SHI Corporation of Japan has been added. The compressor is attached to the main shell of the dewar and the cold head is connected to the outer-most vapor-cooled shield of the dewar. This will increase the lifetime of the Ne cryostat from about 2–3 years, which should match the He lifetime.

Another significant change is in a portion of the high current carrying leads for the ADR magnet and cryogenic valve motors. Using the new superconducting compound MgB_2 ($T_c \sim 39$ K), we have developed an assembly that allows for improved heat sinking, and thus more stable operation during periods of dewar servicing. The leads were developed by W. Goldacker and his group at Karlsruhe by extruding the compound inside stainless-steel tubing.

The dewar gate valve will now have a Be window (1 cm $\phi \times 100\,\mu$m) to enable additional ground testing and redundancy. Finally, a mechanical pre-collimator has been added to the X-ray mirrors to significantly reduce stray light from off-axis sources.

3. The Constellation-X/XMS

A block diagram of the X-ray Microcalorimeter Spectrometer (XMS) is shown in Fig. 1. Although still very much under development, a reference design has been adopted that consists of a 32×32 array of $250 \times 250\,\mu$m microcalorimeters with superconducting Transition Edge Sensor (TES) thermometers. The TES pixels are read out using SQUID amplifiers. There will be first stage SQUIDs transformer-coupled to each pixel, and these in turn will be coupled and multiplexed to 32 second stage SQUIDs for amplification and coupling to the external electronics [8]. Surrounding a large part of the array will be an active anticoincidence detector based on a thermal detector sensitive to ballistic phonons produced by the charged particles. This will also be read out with SQUID amplifiers to simplify the design of the detector system.

We are adopting a cooling system with no stored cryogens for maximum lifetime/mass ratio. Cooling of the detector stage will be achieved using a

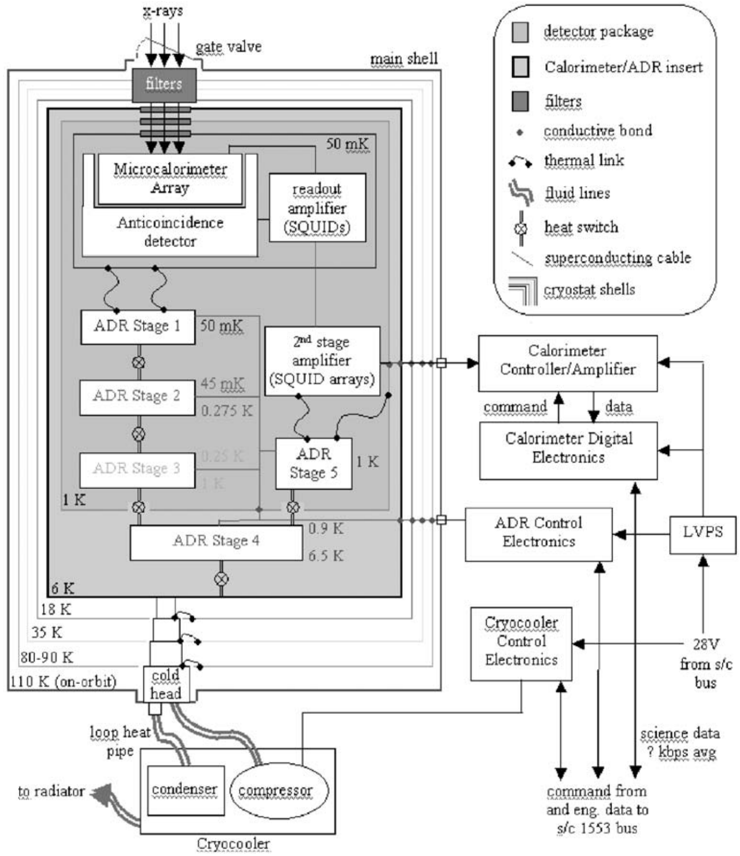

Fig. 1. Block diagram of the Constellation-X X-ray microcalorimeter spectrometer.

multistage ADR, which provides the necessary cooling power down to 50 mK [9]. The warmer stages of the ADR are sequentially linked through heat switches and then cycled to transfer the heat to the relatively warm cryocooler interface. A mechanical cryocooler will provide the 4–6 K heat sink for the ADR and will actively cool several thermal shields within the cryostat. It will also thermally anchor internal XMS signal and ADR current leads.

The blocking filters in the aperture of the cryostat prevent heating of the detector stage by non-X-ray radiation. The transmission of these filters determines the low-energy limit to the bandpass ($\sim$0.25 keV). The high-energy limit is determined by the X-ray absorption efficiency of the absorber and the X-ray mirror reflectivity, and will be about 12 keV.The overall effective area is shown in Fig. 2.

Among the prime areas for investigation with these missions are the regions close to the event horizons of black holes and the nature of the large-scale structure in the local universe. Astro-E2 will make major contributions to the understanding of active galaxies through the measurement of black hole properties via relativistically broadened Fe-K emission lines. The XRS will enable sensitive studies of nucleosynthesis from X-ray spectroscopy of supernova remnants. Another major area will be determining the fate of the gas falling into clusters of galaxies and especially the dynamics of the hot gas. A central science goal of the Con-X

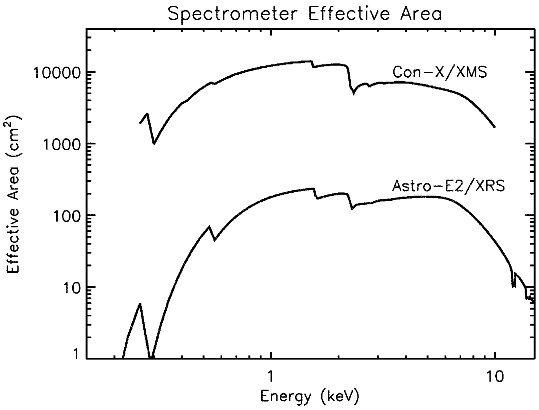

Fig. 2. Effective area curves for the Astro-E2 and Con-X microcalorimeter instruments. The curve for Con-X includes all four spacecraft.

mission is the measurement of the properties of the baryons in the local intergalactic medium by detecting X-ray absorption lines in the spectra of background objects.

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