MICRO-X, THE HIGH RESOLUTION SOUNDING ROCKET X-RAY IMAGING SPECTROMETER

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ABSTRACT

The NASA-funded Micro-X instrument is a rocket-borne X-ray imaging spectrometer operating in the energy range from 0.3 to 2.5 keV. A Transition-Edge-Sensor (TES) microcalorimeter array, cooled to a temperature of 50 mK, is used to obtain images and spectra of astrophysical objects with an energy resolution of 2-4 eV at 3 keV, which constitutes an improvement of more than an order of magnitude over currently operating non-dispersive spectrometers on X-ray space telescopes. A thin-foil conical Wolter mirror with an effective collecting area of 200 cm^2 at 1 keV and a focal length of 2165 mm focuses the X-rays from the observation target onto the detector array. The instrument has a field of view (FOV) of 11.8 arcmin. We describe the design of the Micro-X instrument and its planned flights, and report the current status of hardware development and testing.

1. MICRO-X SCIENCE

Much of the detailed physics of astronomical sources is accessible only through diagnostics that provide high resolution ($E/dE = R >> 20$) spectroscopy. Currently operating instruments, such as the Chandra and XMM Newton grating spectrometers have demonstrated the power of high resolution spectroscopy in X-rays [1], but their slitless, dispersive nature has sharply limited their use for sources with any significant angular extent. This leaves virtually all of the extended sources in the sky inaccessible for detailed study at the highest spectral resolution. It is this gap that will be filled by Micro-X.

Three flights are currently planned with the Micro-X instrument, with the first one scheduled for January 2011. The first flight will target a recently discovered, silicon-rich region in the galactic supernova remnant Puppis A [2]. The spectrum of this Si knot obtained with the orbiting X-ray astronomy satellite Suzaku is shown in Fig. 1, and compared with results of a simulation of the expected Micro-X response. Although it looks noisy, the Micro-X spectrum has separated and can identify the many discrete atomic emission lines

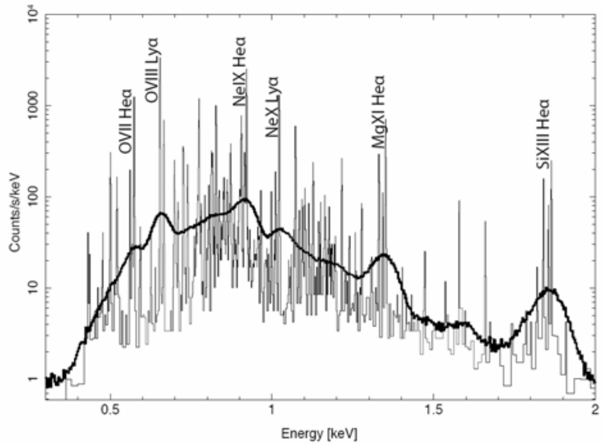

Figure 1. Spectrum obtained with Suzaku (thick line) and a simulated Micro-X spectrum (thin line) of the Si knot in the Puppis A supernova remnant.

which underlie the "spectral bumps" seen in the Suzaku low-resolution spectrum. The high resolution spectrum of the Si knot obtained with Micro-X will be used to:

- search for **velocity shifts** in the multitude of emission lines and measure the line structures to obtain information about the dynamics of the various ejecta elements,
- perform **plasma line diagnostics** to constrain the properties of the plasma including its temperature structure, ionization state and element abundances, and
- refine estimates of **element abundances** in the ejecta.

The second flight, slated for mid 2012, will target the M87 galaxy in the Virgo cluster. The high resolution spectrum will help to better understand the interplay between the complex physical processes occurring at the cores of clusters of galaxies, such as rapid radiative cooling, star formation, AGN-induced feedback, and turbulence. The third flight, planned for early 2014, will see substantial upgrades to the Micro-X instrument,

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possibly including a new mirror and a new detector array with a larger number of pixels. The target for the third flight is the Cassiopeia A supernova remnant (Cas A). As with Puppis A, velocity and line diagnostics can be done using the bright Si lines of Cas A. In addition, Micro-X will disentangle the "iron forest" of lines near 1 keV to give the flux and temperature of the Fe-L emission.

In addition to achieving the above mentioned science goals before the expected launch of the Japanese led ASTRO-H mission, Micro-X will perform the first flight of a TES microcalorimeter, demonstrating and advancing the technology readiness level of state-of-the-art detector and read-out technologies which are prime candidates for the planned International X-Ray Obervatory (IXO).

2. X-RAY MICROCALORIMETERS

The principle of operation of a microcalorimeter is very simple. An absorber is connected to a low-temperature cold bath through a weak thermal link as depicted in Fig. 2. When a photon is incident on the absorber, the photon's energy is converted into thermal energy causing the absorber to heat; it subsequently cools back down as heat flows out of the absorber and into the cold bath to its initial temperature. The graph on the right of Fig. 2 shows a typical “pulse” response. The height of the pulse is proportional to the energy of the photon.

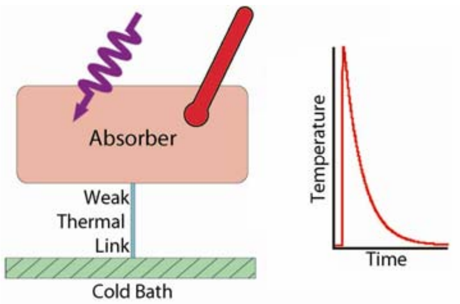

Figure 2. The working principle of a microcalorimeter.

A high-resolution thermometer is required to read out the temperature of the absorber. The Micro-X team has focused on the development of transition-edge sensors (TESs). A TES is a superconducting film biased in its normal-to-superconducting transition. In the transition, the resistance of the film has a very strong dependence on temperature.

To reduce thermal noise, X-ray TES microcalorimeters are typically coupled to a cold bath at a temperature of 50 mK. Such devices consistently achieve energy resolutions of 2-3 eV full-width at half-maximum (FWHM) for 6 keV X-rays [3].

Arrays of up to 32 × 32 pixels have been fabricated at the NASA Goddard Space Flight Centre (GSFC). An 8 × 8 microcalorimeter array is shown in Fig. 3. Such arrays are manufactured using photolithography.

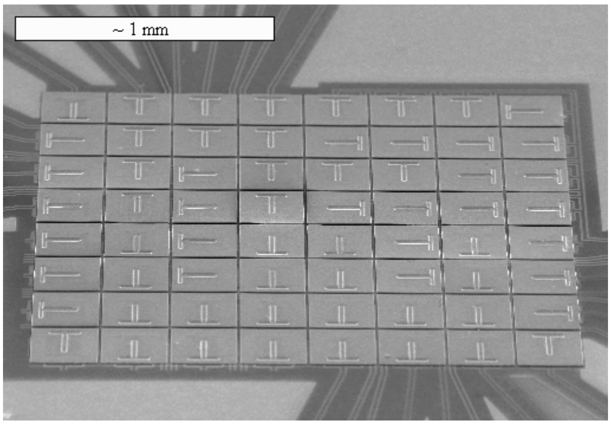

Figure 3. A GSFC 8 × 8 TES Microcalorimeter Array.

The Micro-X array will consist of 128 pixels with a pixel size of 590 µm × 590 µm pixels on a 600 µm pitch giving a 97% fill fraction and essentially 100% quantum efficiency in the 0.2 - 3 keV bandpass. Coupled to the 2165 mm focal-length mirror, the plate scale is 0.98 arcmin per pixel with an 11.80 arcmin FOV.

3. TIME DIVISION SQUID MULTIPLEXING

TESs are usually read out with superconducting quantum interference devices (SQUIDs), which are well matched to TESs due to their low impedance and excellent noise performance. The conventional readout scheme for a single TES detector employs a single SQUID, connected to a series array (100 SQUIDs in series), which amplifies the signal to a level at which it can be handled by room-temperature electronics.

A SQUID multiplexing scheme [4] reduces the number of wires (and thus the heat load) to the detector stage, easing the requirements on the cryogenic system. Micro-X will use two independent 64-channel time-division SQUID multiplexing (TDM) systems to read out the 128 pixel detector array. The two separate readout systems are completely separated from each other, as they have separate power supplies, and are connected to separate telemetry systems. This design mitigates risk, since a failure in a readout system results in only half of the detector data being lost.

The schematic diagram for a four-pixel TDM read-out system is shown in Fig. 4. The TESs are arranged in “rows” and “columns”. Each TES is connected to a dedicated first stage SQUID amplification module, called SQ1. There is one second and third stage amplifier (SQ2 and series array SQUID) in each of the columns. All SQ1 amplifiers in one row can be addressed at the same time. All columns are then simultaneously read out. After that, the SQ1 amplifiers of the row which has just been read out are turned off, and the next row is addressed. This cycle continues until all rows have been read out, and then starts from the beginning.

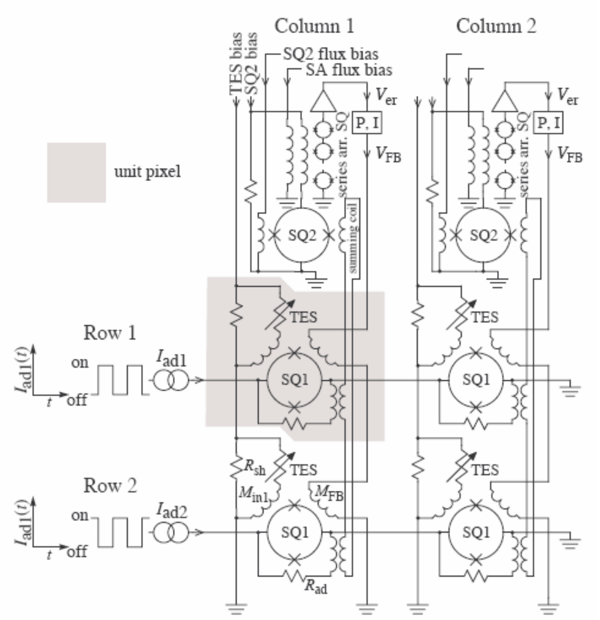

Figure 4. Schematic of the Time-Division SQUID Multiplexing System.

Each of the two Micro-X TDM systems is organized in 4 columns and 16 rows. Switching between rows will occur with frame times of approximately 10.3 µs, i.e. each pixel is read out with a frequency of 97.6 kHz. Due to limitations of the available telemetry bandwidth, the signal from each pixel will be decimated by a factor of three. The resulting sampling frequency of approximately 30 kHz is a good match to the detectors' time constant of 2 ms.

4. CRYOGENIC SYSTEM

The Micro-X cryostat houses the detector array and the cryogenic front end of the SQUID multiplexer. It provides a stable heat sink for the detector array at a temperature of 50 mK. The entire system is pre-cooled with liquid helium at reduced pressure. The liquid helium bath also serves as a heat intercept at a temperature of 1.6 K. Cooling to the detector array's operating bath temperature of 50 mK is achieved with a single stage Adiabatic Demagnetization Refrigerator (ADR). These cryogenic refrigerators use the entropy changes in a paramagnetic salt subjected to a changing magnetic field to provide cooling. The magnetic field is generated with a superconducting magnet, which regulates the field to compensate for parasitic heat loads and maintain a stable temperature. ADRs are thus not capable of providing continuous cooling. After the cooling capacity of the ADR has been exhausted, it has to be recycled. Typical hold times at cooling powers of 1 µW and at a temperature of 50 mK amount to several hours.
As a consequence, the Micro-X ADR has to be cycled on the ground before launch, and keep the detector array cold for the duration of the entire flight. As the

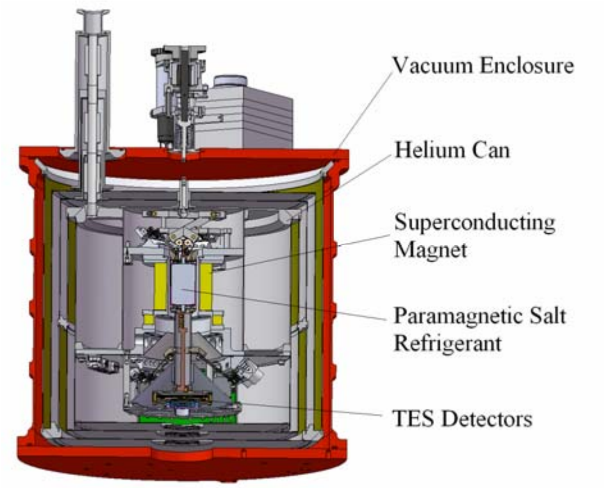

Figure 5. The Micro-X Cryogenic System.

dissipation of mechanical energy originating from undamped launch vibrations would cause a heat input exceeding the capacity of the ADR, the cold stage is mounted on a three-stage damping system with staggered resonant frequencies. Kevlar strings support the cold stage of the cryostat, providing excellent mechanical strength, while minimizing heat flow into the cold stage, as it has a very low thermal conductivity.
The Micro-X flight cryostat is based on the very successful design of a similar system, which was used on the X-Ray Quantum Calorimeter (XQC) sounding rocket [5], which measured spectra of the X-Ray background with Si-thermistor based microcalorimeters. Changes to the XQC design were necessary since, in contrast to Si-thermistors, TESs are susceptible to magnetic fields.
A three-level shielding system has been devised to minimize the magnetic field in the detector region. In addition, the superconducting magnet and the detectors are separated by a larger distance than in XQC. This modification, and the higher mass of the cold stage (approximately 300 g), necessitated the development of a new geometry for the Kevlar suspension system.

5. THE MICRO-X ROCKET PAYLOAD

5.1. Payload Overview

The Micro-X payload consists of the science instrument, which has been developed by the experimental collaboration, and several standard payload systems which will be supplied by the NASA Sounding Rocket Office Contractor (NSROC).
The entire payload is shown in Figure 6, and consists of an Ogive Recovery System Assembly (ORSA); a celestial attitude control system (ACS) with a pointing accuracy of 10 arcsec; a S-19 boost guidance system; two 20 Mbit/s telemetry systems for the science data

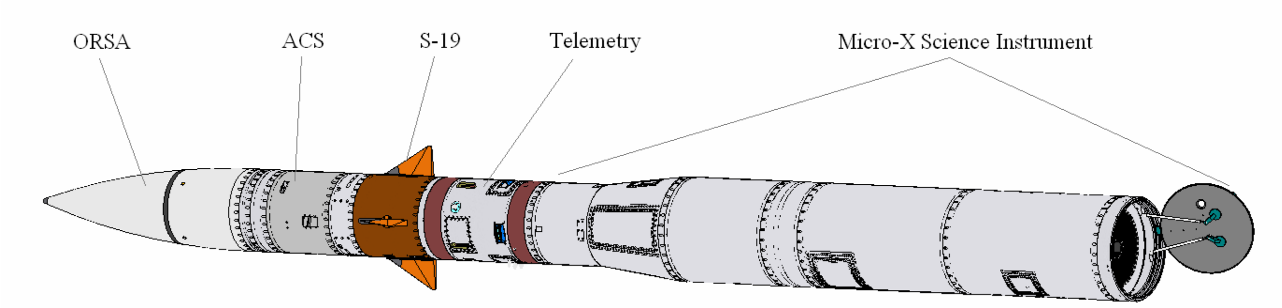

Figure 6: The payload section of the Micro-X sounding rocket.

and one 4 Mbit/s telemetry system for housekeeping data; and the Micro-X science instrument.
The science instrument is aligned such that the optical axis is parallel to the rocket's thrust axis. X-rays enter the instrument from the aft end of the rocket through an opening which is exposed after despin has been effected and the booster has been jettisoned.
Micro-X will be launched by a Terrier MK70 Black Brant MK1 (Mod 2) booster from the White Sands Missile Range. The total payload mass is 520 kg. The flight performance simulation determined that this configuration will reach an altitude of 300 km with 351 s above the minimum observation altitude of 160 km.

5.2. The Science Instrument

The Micro-X science instrument consists of all subsystems necessary to operate the TES microcalorimeters and focus X-rays onto the array. The science instrument has a length of 3727 mm and a mass of 231 kg (including the skin section). Its main components are

- the optical section consisting of the X-ray mirror and optical bench,
- the cryogenic system housing the TES microcalorimeter array, and the SQUID amplification stages,
- several structural components, most importantly a hermetic bulkhead, to which the cryogenic system and the optical components are mounted, and
- an avionics assembly for reading out the detectors and controlling the ADR.

A section view of the Micro-X science instrument is shown in Fig. 7. The mirror, the optical bench and the ADR are accommodated inside a hermetic 22 inch skin section. A ST-5000 star tracker is accommodated in the central bore of the mirror. It is used for celestial attitude control. At the instrument's aft end, the hermetic section is sealed with an automatic shutter door. Towards the forward end, the optical section is sealed with a hermetic bulkhead, the main structural component of the payload. The cryogenic system is mounted on the forward end of the hermetic bulkhead. The vacuum space of the cryogenic system is connected to the

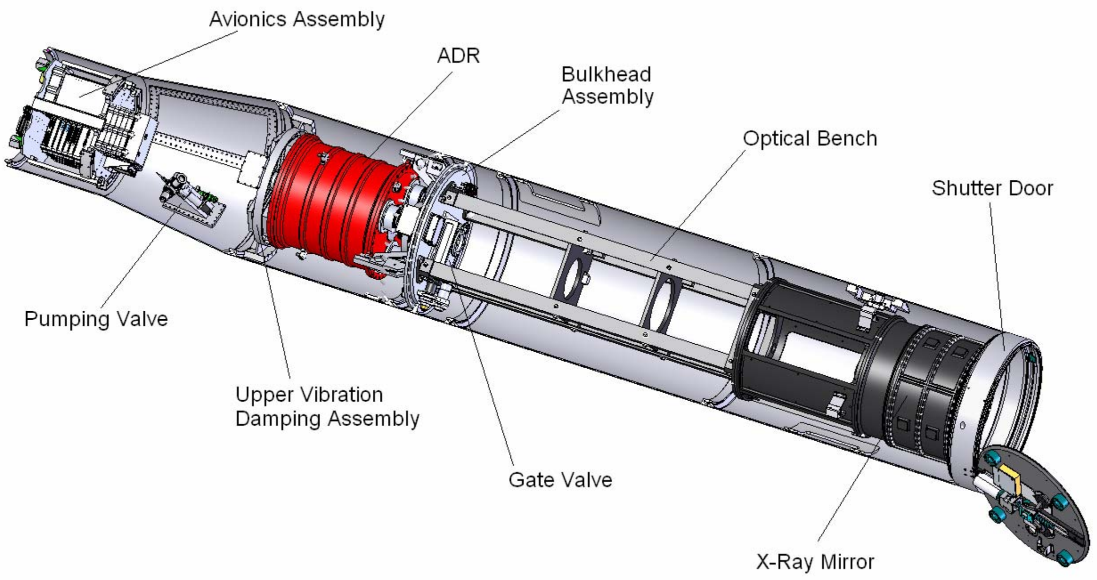

Figure 7: The Micro-X Science Instrument.

hermetic section through a passage which can be closed off with an automatically operated gate valve. This valve will be opened when the instrument reaches the minimum observation altitude, and expose the detector array to the X-rays focused by the mirror.

The electronics for the science instrument are located inside a standard 17.26 inch skin, which is joined to the 22 inch section by a conical adapter. The empty volume inside this conical adapter allows for pre-launch access to the ADR, which is required to perform a liquid helium transfer before the flight.

Since the ADR is mounted on soft rubber dampers to reduce the coupling of launch vibrations into the cold stage, a clamping mechanism is required to ensure correct alignment between the X-ray optics and the detector array inside the ADR. This clamping mechanism will be actuated in the coasting period between rocket motor burnout and the science observation. A set of lasers and position sensitive photo diodes is used to verify the correct positioning of the ADR with respect to the rocket structure.

6. MISSION PROFILE

The first flight of Micro-X is planned for 2011 and will target the Puppis A supernova remnant. At launch time, Puppis A should be as high above the horizon as possible to minimize X-ray absorption in the residual atmosphere. To avoid interference with photons emitted by the sun, launch must occur close to local midnight; a solar zenith angle of more than 120 degrees is required. In addition, it is required that the angular distance between the moon and the science target is larger than 30 degrees to ensure accurate operation of the star tracker. In 2011, launch opportunities with the elevation of Puppis A exceeding 10 degrees exist during the months of January through mid-April, and in November and December. The first flight is currently slated for mid-January 2011, when Puppis A reaches an elevation of almost 15 degrees above the horizon.

Approximately 30 minutes before launch, the detectors will be cooled to their final operating temperature of 50 mK. The correct operation of the detector array will then be confirmed, and pre-launch calibration data will be taken from a radioactive source inside the instrument. During powered flight, the temperature of the detector array will be allowed to float. After payload separation, the shutter door will be opened and the ACS starts to point the telescope at the science target. 15 seconds after payload separation, at an altitude of approximately 113 km and 77 seconds into the flight, temperature control will be re-enabled. At the same time, the clamping mechanism will be actuated to align the ADR with the optical system.

At an altitude of 160 km, and 105 seconds into the flight, science observations start. The gate valve on the hermetic bulkhead is opened, and X-rays from the science target can impact on the detector array. Due to bandwidth limitations imposed by the telemetry system, the pulse data from the detector array is sent to the ground at a reduced rate, and stored in on-board memory at the rate required to obtain highest energy resolution for all pixels.

The observation continues until the payload reaches an altitude of 160 km on its downleg, approximately 456 seconds into the flight. At this altitude, the gate valve and the shutter door are closed, and the ADR clamping mechanism is released. The payload then re-enters into the atmosphere and descends on a parachute. Again, calibration data is taken from an on-board radioactive source.

7. PROJECT STATUS

The design of the Micro-X payload has been finished and flight hardware manufacturing has commenced. Critical components, such as the cold stage of the ADR and some mechanical systems (such as the gate valve and the clamping mechanism) have been prototyped.

Integration of the complete flight instrument is planned for early 2010, system level functional testing and calibration for the summer of the same year, and flight qualification testing for November 2010. The development of the Micro-X instrument is on schedule for its first launch in January 2011.

8. REFERENCES

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