

# Design and status of the Micro-X microcalorimeter sounding rocket

A J F Hubbard<sup>1</sup>, J S Adams<sup>2,3</sup>, R Baker<sup>2</sup>, S R Bandler<sup>2</sup>, N Bastidon<sup>1</sup>, M E Danowski<sup>4,5</sup>, W B Doriese<sup>6</sup>, E Figueroa-Feliciano<sup>1</sup>, D C Goldfinger<sup>4</sup>, S N T Heine<sup>4</sup>, G C Hilton<sup>6</sup>, R L Kelley<sup>2</sup>, C A Kilbourne<sup>2</sup>, R E Manzagol<sup>1</sup>, D McCammon<sup>7</sup>, T Okajima<sup>2</sup>, F S Porter<sup>2</sup>, C D Reintsema<sup>6</sup>, P Serlemitsos<sup>2</sup>, S J Smith<sup>2,3</sup> and P Wikus<sup>4,8</sup>

<sup>1</sup> Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA

<sup>2</sup> Goddard Space Flight Center, Greenbelt, MD 20770, USA

<sup>3</sup> University of Maryland, Baltimore, MD 21250, USA

<sup>4</sup> Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

<sup>5</sup> Current address: Wallops Flight Facility, Wallops Island, VA 23337, USA

<sup>6</sup> National Institute of Standards and Technology, Boulder, CO 80305, USA

<sup>7</sup> University of Wisconsin, Madison, WI 53706, USA

<sup>8</sup> Current address: Bruker BioSpin AG, Fllanden, Switzerland

E-mail: [ahubbard@northwestern.edu](mailto:ahubbard@northwestern.edu)

**Abstract.** The Micro-X High Resolution Microcalorimeter X-Ray Imaging Rocket is a sounding rocket mission that will observe Supernova Remnants and search for keV-scale sterile neutrino dark matter. Micro-X will combine the excellent energy resolution of Transition Edge Sensor microcalorimeters with the imaging capabilities of a conical imaging mirror to map extended and point X-ray sources with an unprecedented combination of energy and spatial resolution. The payload has been designed to operate in the challenging conditions of a sounding rocket flight and to achieve sensitive results, in a single five-minute exposure, for each of these science goals. Micro-X's unique design considerations are presented here, along with the status of the instrument and projections for the upcoming flights. The first Micro-X flight in 2018 will observe the Puppis A supernova remnant, where it will attain nearly 13,000 counts in the 300 s exposure. The second Micro-X flight will observe the Galactic Center to search for keV-scale dark matter and explore the nature of the unexplained 3.5 keV line observed by X-ray satellites.

## 1. Introduction

Micro-X is a sounding rocket-borne X-ray imaging telescope. Each rocket flight provides a 300 s exposure above an altitude of 160 km. Acquiring the required data in this short time window requires an appropriate technological design and a bright target.

Micro-X will provide a groundbreaking combination of collecting area and spectral and angular resolution in its 0.2 - 3.0 keV region of interest (ROI). The transition-edge-sensor (TES) array, the first to fly in space, has an intrinsic energy resolution of 4.5 eV at 6 keV. The array is at the focal point of a conical imaging mirror with a 11.8' field of view (FOV) and a measured angular resolution of 2.5' Half Power Diameter. The effective area of the mirror, taking into account the bandpass filters, is 300 cm<sup>2</sup> at 1 keV. Even with a single flight exposure, Micro-X will provide observations of unprecedented precision.



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

## 2. Science goals

Micro-X will observe bright Supernova Remnants (SNRs) and search for keV-scale dark matter. The first flight will image the Puppis A SNR, and the second will point to the Galactic Center to search for sterile neutrino dark matter.

### 2.1. First flight: Puppis A supernova remnant

The first flight of Micro-X, in 2018, will map the X-ray spectrum of the bright, middle-aged galactic SNR Puppis A. It will target the Bright Eastern Knot (BEK), the interaction site of the SNR with a dense ambient cloud, to study the importance of charge-exchange (CX) and particle acceleration at the shock.

CX may have been observed in the BEK by XMM-Newton [2], but the detector response to such an extended source is difficult to analyze. The high resolution Micro-X observation will establish the presence of CX at the BEK.

The BEK's shock velocity is believed to be too low for efficient cosmic ray (CR) acceleration, but *Fermi*-LAT observes significant  $\gamma$ -ray emission from the eastern side of Puppis A [3]. Micro-X will constrain the kinematics and thermal properties of the BEK plasma, exploring if the  $\gamma$ -ray spectrum can be explained with a CR re-acceleration model.

The elements and morphological features in the BEK are well-suited to Micro-X's spectral and angular resolution. A simulation based on the Chandra spectrum of the BEK (see Figure 1) projects Micro-X to detect 17,000 counts in a 300 s observation.

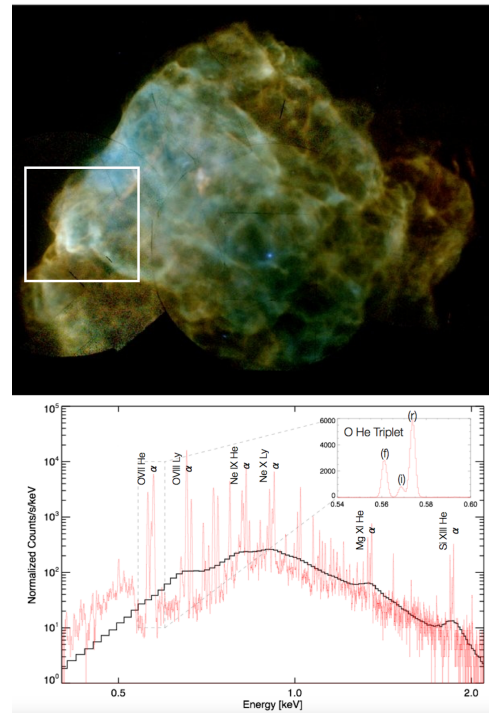
### 2.2. Second

#### flight: keV-scale sterile neutrino dark matter

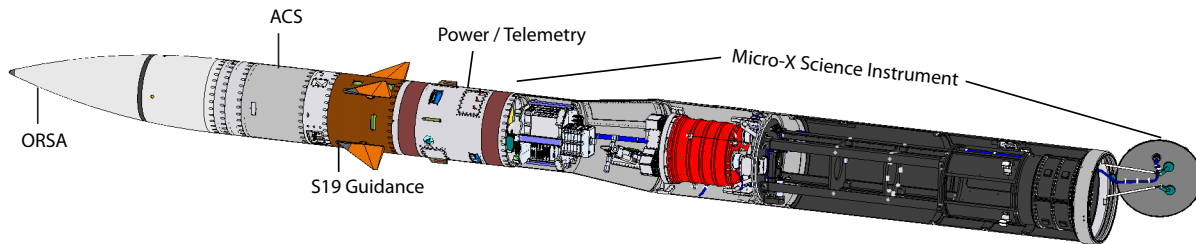
The second flight will search for a monoenergetic X-ray signature of keV-scale dark matter interactions, like that predicted from sterile neutrinos. This search is gaining interest as conflicting hints of a 3.5 keV line appear in the X-ray satellites [4]. Micro-X's resolution will be able to separate this line from nearby atomic lines and map its redshift across the Galaxy as a dark matter signature. Modifications will be made to the payload for this flight to increase the FOV and change the ROI. See [5] for details.

## 3. Design of the payload

The Micro-X science instrument (see Figure 2) consists of a cryostat, an optics assembly, and the instrument electronics. The instrument is  $\sim 500$  lbs and spans 12 ft. It will fly on a Terrier Mk70 Black Brant Mk4 vehicle, reaching a 250 km altitude. The instrument is constructed by the Micro-X collaboration. The other rocket elements (launch vehicle, pointing, antennae, timers, parachutes, etc.) are constructed by the NASA Sounding Rocket Operations Contract team.



**Figure 1. Top:** Image of Puppis A, where red, green, and blue correspond to 0.5–0.7 keV, 0.7–1.2 keV, and 1.2–5.0 keV, respectively. The white square indicates the Micro-X FOV. **Bottom:** Projected Micro-X spectrum of the BEK from a 300 s exposure, overlaid with the Chandra spectrum in black. The inset shows the oxygen He-like triplet. Figure from [1].



**Figure 2.** The Micro-X payload, including the parachute recovery system (ORSA), the pointing systems (ACS, S19), telemetry, and the science instrument. The launch vehicle is not shown.

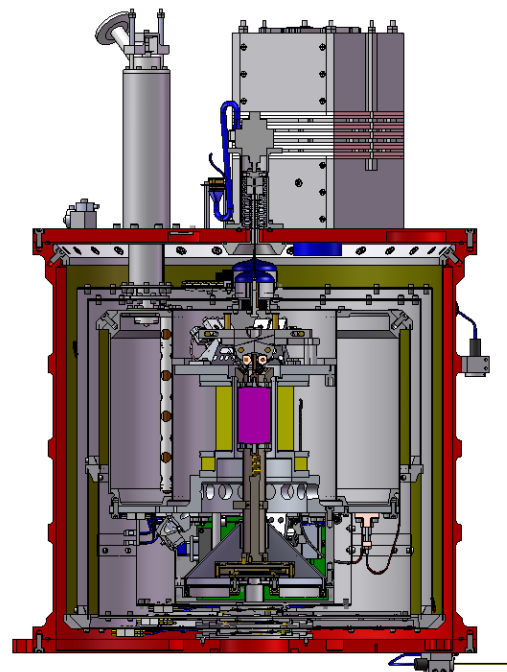
### 3.1. Inside the cryostat

The cryogenic Micro-X detectors run inside a cryostat (see Figure 3) with an Adiabatic Demagnetization Refrigerator (ADR) to operate at the required  $75\text{ mK} \pm 3\text{ }\mu\text{K}_{RMS}$ . The ADR has a hold time of 9 hours and has the cooling capacity to successfully operate after absorbing 5 simulated launch loads. Vibration isolation ensures the detectors only warm up by 14 mK during the 17g launch vibration [6].

The TESs in the 128-pixel array are Mo/Au proximity-effect bilayers with Au/Bi absorbers. The intrinsic energy resolution of the detectors is 4.5 eV at 6 keV. The detector array is operated in a time-division multiplexed mode, and signals are read out via a 3-stage SQUID readout chain. Details on the TESs and the readout chain can be found in [1, 7].

Three stages of magnetic shielding protect the detector and SQUIDs from the 4 T magnet required to operate the ADR: a bucking coil is placed in series with the ADR magnet; a Niobium can repels external magnetic fields; and a field coil inside the Nb can cancels any frozen-in field. Details can be found in [7].

To monitor the detector response in flight, a calibration source ( $\sim 0.6$  events/s/pixel) is located next to the detector plane. The source is a CsI scintillator that is excited by  $^{55}\text{Fe}$  photons.



**Figure 3.** Cross-section of the Micro-X cryostat. X-rays enter from the gate valve at the bottom of the image to hit the detectors inside the Nb can (triangular cross-section).

### 3.2. Optics

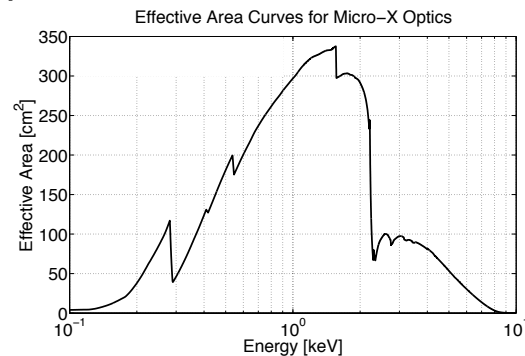
The core of the optics assembly is the X-ray mirror, a segmented, thin foil, conical mirror that was flown on the 1988 SXS sounding rocket. It has a 2.1 m focal length and an effective area of  $300\text{ cm}^2$  at 1 keV (see Figure 4). The  $11.8^\circ$  FOV images with a measured angular resolution of  $2.5'$  Half-Power Diameter.

An optical bench runs the distance of the focal length, structurally maintaining the mirror to the rocket exterior (“rocket skins”) and to the cryostat assembly, to maintain alignment during flight. Magnetic brooms are bolted to the optical bench to deflect charged particles out of the

focal beam. A set of filters are installed between the optics and the detectors to stop optical and infrared photons from getting to the TES array.

In flight, the ST5000 star tracker in the central bore of the mirror is used to maintain the pointing of the instrument to within  $2.5'$  ( $1\sigma$ ) accuracy. The optics section is pumped out before flight, and a hermetic seal is maintained until the shutter door on the aft end of the assembly opens to the vacuum of the upper atmosphere.

A laser positioning system uses a series of 4 lasers that hit position-dependent photocathodes to determine if the cryostat has moved with respect to the rocket skin. This information is used after launch to check alignment over the duration of the flight.



**Figure 4.** Effective area curve for the optical assembly (including filters).

### 3.3. Electronics

The Micro-X electronics system is fundamentally divided into the cryostat electronics and the science chain electronics. Each set of electronics is used to control its respective system and to read data out from it. Wiring inside the cryostat interfaces to the room temperature electronics via connectors on the cryostat lid.

The ADR Control system (ADRC) reads out the ADR monitoring information and sends commands to control the ADR magnet. Monitoring information is passed as RS422 differential data to the telemetry system, where it is sent to an encoder and transmitted to the ground in real time. There is no uplink during flight, so the commands issued by the ADRC in flight are triggered by on-board timers that flip 28 V relays. The timers are initialized by a mechanical separation that occurs when the rocket leaves the ground. All motor and valve actuations are also issued through timers during flight.

The science chain system is responsible for controlling the reading out of the science data from the detectors and biasing all four stages of the detector system (TES and 3 stages of SQUIDs). It controls the time-division multiplexing on the first-stage SQUIDs and supplies both the feedback signal and the DC bias for the field coil, SQUIDs and TES detectors.

Precautions are taken to lower the risk of a potential electronics failure during flight. The detector array is divided into two independent 64-pixel science chains so that half of the detector can continue to read out if the other science chain fails. Each science chain data stream is 66 Mbit/s, all of which gets recorded onto on-board flash memory in the science instrument. As a further preventative measure, a 20 Mbit/s subset of data from each science chain is passed as LVDS differential data into the telemetry system, which passes it through an encoder and transmits the data to the ground in real time. In the case of a successful payload recovery, the on-board data will be used for analysis. If the payload is destroyed upon impact, the telemetered subset will be used. The science chain operating parameters are set before flight; there is no uplink, and no changes are made in flight. On-board data recording begins at launch ignition.

### 3.4. Launch

Micro-X will launch from the White Sands Missile Range in New Mexico. The launch date is set by the altitude of the target in the sky and the relative location of the Sun, Moon, and large planets with respect to the target.

The rocket is launched with the cryostat at 300 mK, the detectors biased, and all valves to the outside of the instrument closed. At ignition, the science chain begins writing data to on-board flash, and the rocket leaves the rail. The first stage of the launch vehicle burns out at 3 km altitude, and the second at 40 km altitude. The ADR magnet is then ramped to reach the operating temperature. At 90 km altitude, the rocket is pointed towards the target, and the shutter door is opened now that the exterior is at vacuum. The gate valve between the optics section and the cryostat is opened, and the detectors begin to see X-rays at roughly 100 s after ignition. A maximum altitude of 250 km is reached, and then the descent begins. At 100 km altitude on the way down, the valves are closed again to protect the science instrument. The parachutes are deployed a few kilometers above the ground, but the payload still hits the desert floor with a 30g impact. A crush bumper on the payload absorbs as much of the impact as possible. The on-board flash continues to write post-launch calibration data until it is full.

#### 4. Status

Micro-X has designed and built a functional payload. The focus has turned from design and construction to optimization, integration, and flight readiness. The cryostat passed vibration tests in 2015, keeping the detector array acceptably cold under a launch vibration load [6]. Current work on the cryostat focuses on improving resolution, lowering system noise, and optimizing the flight parameters [8].

The electronics are moving from the lab setup to the flight configuration. The cryostat is successfully controlled by the flight ADRC in lab testing, and the science chain electronics both bias the detectors and read out data successfully. The ADRC and the science chain electronics recently passed the “handshake” test in which flight commands and data readout are tested between the instrument and the telemetry section. Current work on the electronics focuses on mechanical preparations for surviving flight and running with a fully integrated system.

The optics have passed their preliminary alignment checks. Current work focuses on characterizing the effect of launch vibration on the alignment and integrating the science instrument components with those supplied by the launch team.

#### 5. Conclusions

The Micro-X sounding rocket will be the first program to fly TES microcalorimeters in space, with the first flight in 2018. It will return an unprecedented combination of energy resolution and imaging capabilities that will allow the exploration of new physics in SNRs and keV-scale sterile neutrino dark matter. Micro-X was carefully designed to withstand the challenging conditions of a sounding rocket launch and to return significant results from after single flight.

#### Acknowledgments

Micro-X operates under NASA grant NNX10AE25G. DCG is supported by the NASA Space Technology Research Fellowship.

#### References

- [1] Figueroa-Feliciano E *et al.* 2012 *Proc. SPIE* **8443** 84431B-1
- [2] Katsuda S *et al.* 2012 *Astrophys. J.* **756** 49
- [3] Xin Y-L *et al.* 2017 *arXiv* 1703.03911
- [4] Abazajian K N 2017 Sterile neutrinos in cosmology *arXiv* 1705.01837
- [5] Figueroa-Feliciano E *et al.* 2015 *Astrophys. J.* **814** 82  
Hubbard A J F *et al.* 2017 *Proc., 13th Rencontres du Vietnam: Neutrinos*
- [6] Danowski M E *et al.* 2016 *J. Low Temp. Phys.* **184** 597-603
- [7] Heine S N T 2014 High-Resolution Studies of Charge Exchange in Supernova Remnants with Magellan, XMM-Newton, and Micro-X. *PhD thesis, Massachusetts Institute of Technology*
- [8] Goldfinger D C *et al.* 2016 *Proc. SPIE* **9905** 99054S-1