Development of adiabatic demagnetization refrigerator for the HUBS mission

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A R T I C L E  I N F O

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Hot Universe Baryon Surveyor (HUBS) is a space X-ray probe that is proposed to answer some of the outstanding questions on structure formation and evolution in the universe [1]. Specifically, it focuses on two primary scientific objectives: (1) addressing unresolved issues regarding galaxy ecosystems [2]; and (2) searching for “missing baryons” in large-scale structures [3]. Both objectives rely on detecting faint X-ray emission from low-density, diffuse hot gas (of about $10^6$ K), which would require unprecedented detection sensitivity at soft X-ray energies. HUBS is designed to meet the requirement by employing X-ray microcalorimeters for the focal-plane detector array of its scientific payload [4].

A microcalorimeter is capable of measuring the energy of each incident X-ray photon with precision of the order 1 eV. It consists of an absorber, a temperature sensor, and a weak thermal link to the substrate. When an X-ray photon deposits its energy in the absorber, the temperature of the detector increases slightly and subsequently recovers, as heat leaks out through the weak link to the substrate, forming a temperature pulse signal. The peak amplitude of the pulse provides a measure of the photon energy. For HUBS, superconducting transition-edge sensor (TES) technology is adopted for temperature measurement. In the transition between the normal and superconducting states, the resistance of a TES is extremely sensitive to temperature variation, so it is capable of converting a weak temperature pulse to an amplified electrical pulse, which can then be read out. The energy resolution of a microcalorimeter is given by $\Delta E = \xi \sqrt{\frac{E}{T}}$ [5], where $T$ is the detector temperature, $C$ is the heat capacity, $\xi$ is a dimensionless parameter of the order of unity, and $x = \frac{E}{\Delta E}$, which defines TES sensitivity. Clearly, lowering temperature reduces the $\Delta E$ and thus improves the energy resolution of a microcalorimeter. To meet the requirement of HUBS on energy resolution [1], the microcalorimeters must be operated at temperatures below 100 mK.

However, it is quite challenging to reach and maintain such a low temperature in a satellite mission, partly due to microgravity environment, but also to constraints on the payload, including power consumption, lifetime, mass, and volume. It is typically realized through a multi-stage cooling chain in a sophisticated cryogenic system that couples different types of coolers. The cooling chain can often be divided into two parts: a precooling stage for reaching temperatures of 1–4 K with sufficient cooling power, and a cold stage for enabling detector operation. To date, only three astronomy satellites have achieved temperature at or below 100 mK. The XRS payload on the Suzaku satellite adopted a precooling stage consisting of a superfluid-helium cryostat, a solid-neon dewar, and a Stirling-cycle cooler, and a cold stage consisting of an adiabatic demagnetization refrigerator (ADR) [6]. Unfortunately, the payload failed. It was re-designed for the Hitomi satellite. In this case, the precooling stage is composed of two 2-stage Stirling cryocoolers, one Joule–Thomson (JT) cooler, one superfluid helium dewar, and the cold stage of a 3-stage ADR system [7]. On the other hand, the Planck satellite is equipped with three passive radiators, a hydrogen sorption cooler, and a JT cooler for the precooling stage, and an open-cycle dilution refrigerator (DR) for the cold stage [8]. Compared with a DR, an ADR does not rely on gravity-driven circulation of fluid for its operation, so is well suited for space application. In addition, it has no moving parts and consumes no refrigerant.

For HUBS, the temperature of the detector needs to be maintained below 100 mK, with fluctuation of the order 1 μK. To this end, a fairly unique design of the cooling system is being studied. The precooling stage, which is developed by the HUBS collaborators at TIPC, involves two-stage pulse tube (PT) coolers which can achieve cooling capacity of 10 mW at 3 K and 40 mW at 4.8 K [9] and improve reliability, while a 2-stage ADR is employed for the cold stage, as shown in Fig. 1a. The idea of using a 2-stage
ADR for space astronomical applications is not new, with various choices of salt pills, e.g., Ref. [10], or two independent magnets, e.g., Refs. [11,12], but realizing actual applications has been challenging.

In this work, we present results on the fabrication and testing of a 2-stage ADR prototype of our design. Fig. 1b shows the prototype. The first stage uses gadolinium gallium garnet (GGG) as refrigerant, while the second stage uses a chromium potassium alum (CPA) paramagnetic salt pill. The GGG stage is thermally connected to the 4 K stage, which is maintained by cryocoolers, with a mechanical heat switch, and is capable of cooling the CPA from 4 K to below 1 K. The CPA stage is thermally connected to the GGG stage with a gas-gap heat switch (GGHS) at one end and to the cold plate (where the detector is to be mounted) on the other, and offers further cooling when the GGHS is OFF. Mechanically, the refrigerant is suspended from the 4 K stage via a Kevlar support system.

The ADR works as follows. With both heat switches at ON state, the GGG and CPA stages are both magnetized to 4 T with superconducting magnets. The excess heat generated in the magnetization process is dumped to the 4 K stage and taken away by the cryocoolers. After thermal equilibrium is reached (at 4 K), the mechanical heat switch is opened, isolating the refrigerant thermally. Then, the GGG stage is demagnetized at proper rate, cooling the two stages until its lowest temperature is reached. Finally, the GGHS switches off, followed by demagnetization of the CPA stage. After a preset temperature of the cold plate is reached, temperature regulation is accomplished through precise control of current through the magnet. Cooling power is exhausted when the current drops to zero, reaching the end of an ADR cycle. The process is repeated for the next cooling cycle. The duration of a cycle depends mainly on the overall heat load on the CPA stage, which should be minimized in practice, as well as on the mass and quality of the CPA salt pill.

We have developed a process to grow large CPA crystals and thus to make high-quality salt pills. Briefly, a hot, saturated CPA solution is injected into a specially-designed brass container, with pre-strung copper wires serving as thermal busses to facilitate thermal connections to the heat switch and to the cold plate. As the solution is gradually cooled according to an optimized curve, crystals are grown and tightly bonded to the thermal busses. This will repeat many times through replacing solution. By this method, the grain size of CPA crystal can be more than 1 cm. When the crystals fill the container, the salt pill is sealed with Stycast 2850 to prevent dehydration. Fig. 1c shows a salt pill assembly containing about 40 g of CPA crystals.

The ADR prototype was built and tested in the lab. Fig. 1d shows the typical cooling curves of the GGG stage and the CPA stage, respectively. The results show that the CPA stage eventually reaches a temperature of 44 mK, while the GGG stage reaches about 0.74 K. In another test, we started temperature regulation when the CPA stage reached 100 mK. Fig. 1e shows the results. The temperature of the cold plate was held steadily for about 183 min, implying a parasitic heat load of about 6 μW and a relative Carnot efficiency of 95.3%, based on the entropy curve [13], which is higher than the Hitomi ADR. We believe that the heat load is contributed by the off-state conduction through the GGHS after excluding other factors such as through Kevlar.

In conclusion, the development of a 2-stage ADR for the HUBS mission has reached important milestones, in terms of the lowest

![Fig. 1.](Image)

(Color online) Illustration of the ADR prototype and experiment results. (a) Schematics of a preliminary design of the HUBS cooling system. (b) The photo of the ADR prototype. (c) The photo of a CPA salt pill assembly. (d) The cooling curves of the CPA and GGG stages. (e) CPA temperature regulation test. Note that the magnet runs out of current about 183 min after the regulation began.
temperature reached (44 mK) and hold time. The path forward is fairly clear. Firstly, the off-state thermal conduction of the GGHS needs to be reduced significantly, in order to minimize residual heat load on the ADR and thus to increase hold-time. Secondly, the ADR needs to be integrated with the cryocoolers in the precooling stage in a sufficiently compact configuration, in order to satisfy the constraints on the payload.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Chunyang Jiang performed the experiments and analytical calculations, and wrote the original draft of the manuscript. Hai Jin designed and led the experiments, and contributed to the revision of the manuscript. Chengzhe Li participated in the experiments, and contributed to the revision of the manuscript. Wei Cui supervised the project, revised and finalized the manuscript.

References


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