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News & Views

First stirling-type cryocooler reaching lambda point of ^{4}He (2.17 K) and its prospect in Chinese HUBS satellite project

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The issue of "missing baryons" is always an unsolved mystery in galaxy cosmology, and an important reason for the great uncertainty of the galaxies' formation and evolution. To find the "missing" baryons, extra high-resolution spectral observation and imaging of the soft X-ray band (<1 kev) is required. However, the existing observation methods cannot meet this requirement. Therefore, Tsinghua University leads and proposes the Chinese "Hot Universe Baryon Surveyor (HUBS)" satellite program. The HUBS is planned to detect large-scale fiber structure and distribution of matter around the galaxy by launching satellites and developing advanced wide-field, high-efficiency, high-resolution X-ray imaging and spectrometers. To reveal the spatial distribution of the "missing" matter in the universe and relative physical and chemical properties, the cosmological issue of "missing baryons" can be solved thereby [1,2].

The key point of high-resolution X-ray imaging and spectrometers in the HUBS is to use the superconducting transition edge sensor (TES) to measure the temperature change of the micro-energy meter to detect the incident X-rays' energy. The high-resolution TES detectors needs to work at extreme low temperatures (<100 mK). Obtaining extreme low temperatures (<100 mK) in space is extremely challenging. Simultaneously, a complex mechanical pre-cooling system and an extreme low-temperature refrigeration system are required. Relative technology has been developed in foreign countries [3,4]. In order to enable the HUBS to be implemented smoothly and also meet the needs of similar space programs in China, the development of high-performance space cryogenic refrigeration systems with Chinese own technology is imperative.

At present, the ASTRO-H satellite project led by Japan Aerospace Exploration Agency (JAXA) and ATHENA satellite project led by European Space Agency (ESA) represent two kinds of typical space mK-class cryogenic cooling chain for TES sensor. ASTRO-H satellite inherits the wet-type cooling chain in which a 1.2 K superfluid helium dewar is used to precooling the adiabatic demagnetization refrigerator system (ADR) to bath the TES sensor at 50 mK. Under the premise of using the 30 L superfluid helium at 1.3 K chiefly as the heat sink of the two-stage 50 mK ADR, another strategy of using a 4.5 K J-T cryocooler to precool an ADR to 1.3 K will play as the backup heat sink for the two-stage 50 mK ADR. For reducing the dewar's heat leakage to 1 mW, two two-stage Stirling cryocoolers, the 4.5 K J-T cryocooler and vapor-cooled shields compensate for radiation leakage together [3]. ATHENA satellite uses dry-type cooling chain to promise the long-time running of TES sensor. Some two-stage stirling-type pulse tube cryocoolers precool a 1.7 K J-T cryocooler using ^{3}He. Meanwhile, the 1.7 K J-T cryocooler using ^{4}He works together with a 4.5 K J-T cryocooler using ^{4}He as the heat sink of a sorption system to 300 mK. At last, the ADR system is used to achieve 50 mK for the TES system. The precooling system also compensates for the radiation leakage for the sorption and ADR system. The dry-type system is in lower complexity than the wet-type system and is better for long-time operation [4].

The HUBS satellite is planned to serve in orbit more than 10 years and its TES sensor will work at below 100 mK. A dry-type precooling system and a mK-class ADR system are indispensable for the space cryogenic cooling chain. The schematic diagram of this cooling chain is shown in Fig. 1a. In China, the technology of 4 K multi-stage Stirling-type cryocooler is developing rapidly. So, a high-performance multi-stage Stirling-type cryocooler is an important candidate for Chinese HUBS project.

If precooling system can offer a heat sink around 3 K, a single-stage ADR system is enough to obtain the temperature below 100 mK and which directly reduces the total weight of the cryogenic system. To develop a prototype of main cryocooler of precooling system, Technical Institute of Physics and Chemistry of CAS in China has just finished relative experimental tests of a novel multi-stage Stirling-type cryocooler called Vuilleumier hybrid pulse tube cryocooler (VM-PTC). The basic structure of VM-PTC is shown in Fig. 1b. This VM-PTC only rejects heat at 77 K while absorbs heat from ambient temperature and two cold ends. For

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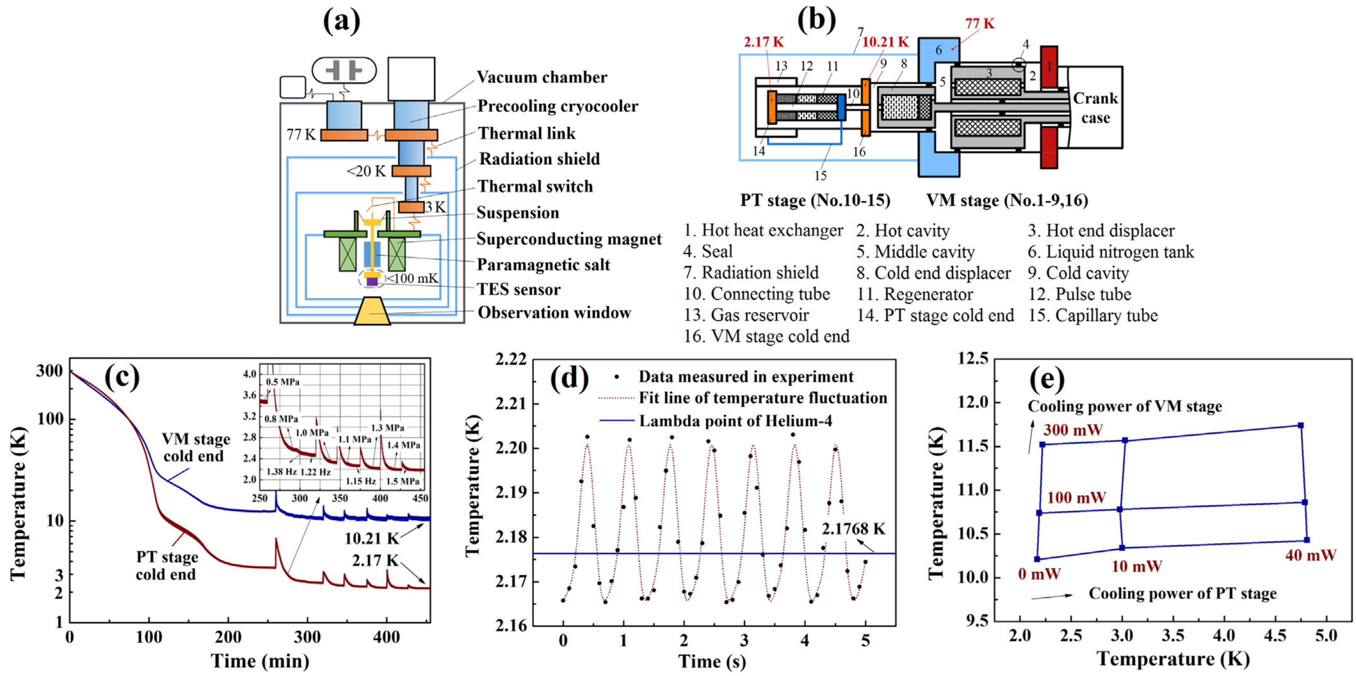

Fig. 1. (Color online) The basic structure and cooling performance of the VM-PTC's prototype. (a) The mK-class cooling chain for TES sensors in HUBS project. (b) The basic structure of the VM-PTC's prototype. (c) The cooling curve of the VM-PTC at 1.15 Hz and 1.5 MPa. (d) The steady temperature fluctuation of the PT stage cold end. (e) The cooling power map of the VM-PTC's prototype.

testing the prototype, liquid nitrogen is used to work as the 77 K heat sink for VM-PTC. A high-efficiency Stirling-type pulse tube cryocooler will quickly replace the liquid nitrogen and complete a total cryogen-free precooling system for HUBS. After optimizing the filling pattern of Gd_2SO_2, $HoCu_2$ and Er_3Ni in the coldest regenerator and the working parameters, the VM-PTC can successfully obtained the lowest temperature of 2.17 K by using ^4He as the working fluid. This is the first time for the Stirling-type cryocooler obtained the lambda point of saturated ^4He (2.1768 K) and verified Prof. Yuan Zhou's prediction about Vuilleumier cryocooler in 2011 [5]. The cooling curve is shown in Fig. 1c. The cooling process consumes 460 min and the working frequency and pressure are 1.15 Hz and 1.5 MPa respectively. The lowest temperature of the VM cold end and PT cold end are about 2.17 and 10.21 K. The temperature fluctuation of the PT cold end is measured by Cernox-cx1050 sensor and is shown in Fig. 1d. The peak to peak temperature difference is about 0.04 K. The average temperature of the PT cold end is about 2.18 K while the lowest temperature reaches 2.165 K. Fig. 1e shows the two stage cooling power map of the VM-PTC. The PT stage can provide 10 mW at 3 K and 40 mW at 4.8 K. Only up to 0.03 K temperature difference on PT stage cold end when 0–300 mW is attached on the VM stage cold end. When the PT cold works as the heat sink of the ADR system, the cooling power of VM cold end can be used to compensate for radiation leakage. A precooling system with VM-PTC as the primary role can basically provide three radiation shields at 77, 11 and 3 K respectively for inner system and a 3 K heat sink for the ADR system. To design the next generation VM-PTC aimed for practical application in HUBS project, many modifications including replacing the crack case by a low-frequency (<2 Hz) and large-stroke (>20 mm) linear motor and changing the present "displacer hybrid pulse tube" structure to multi-stage pulse tube cryocooler are processing now in our laboratory.

In conclusion, a high-performance prototype of Vuilleumier hybrid pulse tube cryocooler has been tested and optimized in TIPC of CAS in China and the lowest temperature of 2.17 K was obtained. This is the first time for the Stirling-type cryocooler obtaining the lambda point of the saturated ^4He. Its multi-stage cooling capacity shows good potential to work as the precooling system in Chinese HUBS project.

Conflict of interest

The authors declare that they have no conflict of interest.

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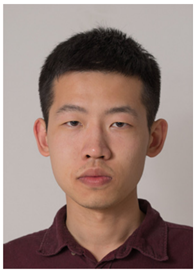

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