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First high-frequency pulse tube cryocooler down to 2.5 K and its promising application in China's deep space exploration

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From the Moon, Mars, to the central body of the solar system, the Sun, and even exoplanets, deep space exploration [1] has promoted research on the formation and evolution of the solar system and the universe, especially, in terms of tracing life's origins. The inherent characteristic of high energy flux density determines that space detectors cannot fully dissipate heat through radiative cooling under the cosmic microwave background radiation temperature of 2.7 K. Consequently, active refrigeration technology is the crucial guarantee of high signal-to-noise ratio (SNR), and further, high accuracy for space detectors due to cosmic background noise in deep space exploration [2]. In China, the current on-orbit refrigeration system is almost working in the liquid-nitrogen temperature range [3]. Thus far, research on the corresponding development of space refrigeration technology with lower temperatures in the liquid-hydrogen and liquid-helium temperature ranges is still in its infancy, and only several cryocooler prototypes have been investigated in laboratory studies [4,5]. However, the space astronomy programs being promoted by China in recent years require a low working temperature of 4–30 K, particularly even down to mK-class temperature. Thus, conducting studies on extremely low-temperature refrigeration technology, which aims at offering liquid-helium temperature and below, are an urgent task. For example, Tsinghua University took the lead in proposing the deep space exploration mission called Hot Universe Baryon Surveyor (HUBS) to solve major scientific problems at the frontier of astronomy [6]. The project aims to realize the first systematic observations of hot gas (known as "hot baryon") in the universe to solve the two major problems in the field of galaxy formation and evolution under the framework of cosmology: the absence of cosmic baryons and feedback physics. The key to solving these problems lies in the precise detection of hot baryons in the universe; thus, HUBS must be equipped with a high-efficiency, high-resolution X-ray imaging and spectrometer that requires mK-class temperature (<100 mK) to achieve excellent spectral performance. At present, the preliminary scheme is using a hybrid cooling chain of adopting a 4 K-class cryocooler to pre-cool an adiabatic demagnetization refrigerator (ADR) to provide the required cooling power [7]. In addition, another exploration project called Miyin Program [8] aims to find habitable planets in the solar system, that is, to find another

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Earth. By deploying a mid-infrared detector with wavelengths of 8–12 μm in the Sun-Earth libration point orbit, it can carry out imaging and spectral detection of the nearby planetary system and the distribution of water in the solar system. To achieve the spatial resolution of 0.01 arc second, the detector must work at a low temperature of 6 K. Obviously, extremely low-temperature refrigeration technology has become a major bottleneck in the development of China's deep space exploration projects.

In comparison, several countries, such as the United States, France, and Japan, have mastered extremely low-temperature refrigeration technology. In 2002, the National Aeronautics and Space Administration (NASA) proposed the landmark space exploration project, James Webb Space Telescope (JWST) [9], to explore the mystery of the origin of the universe by probing the infrared band with a wavelength of 0.6–29 μm in the universe. To provide a heat sink for the Mid InfraRed Instrument (MIRI) carried by JWST, which normally works at 6 K, the project adopted a hybrid cooling chain using a three-stage high-frequency pulse tube cryocooler (HPTC) pre-cooling a ^{4}He Joule-Thomson (JT) cryocooler [10]. Subsequently, the European Space Agency (ESA) proposed the Advanced Telescope for High-Energy Astrophysics (ATHENA) program in 2011 [11], the purpose of which is to precisely detect space X-rays to address the science theme "the Hot and Energetic Universe". ATHENA is expected to launch in 2030, while the X-ray Microcalorimeter Spectrometer (XMS) on ATHENA requires an mK-class working temperature. A two-stage Stirling cryocooler was employed to pre-cool a ^{4}He JT cryocooler to obtain the liquid-helium temperature, which will further serve as a pre-cooler for a three-stage ADR working at 50 mK [12]. In recent years, the Japan Aerospace Exploration Agency (JAXA) has made tremendous advances in deep space exploration refrigeration technology. In fact, the Hitomi (ASTRO-H) satellite [13] was launched by JAXA on February 17, 2016, to investigate scientific problems in the high-energy universe. The main scientific facility onboard Astro-H is the Soft X-ray Spectrometer (SXS), which needs to be cooled down to 50 mK using an ADR. Thus, a 4 K -class hybrid cooling chain using two-stage Stirling cryocoolers to pre-cool a ^{4}He JT cryocooler was adopted as the heat sink of the ADR.

Referring to the technological progress in Europe and the United States, the main refrigeration method for obtaining the mK-class temperature in space is adopting a hybrid cooling chain that uses liquid helium or 4 K-class mechanical cryocoolers to obtain the temperature of 2–4 K, after which the mK temperature can be achieved by adopting ADR, a sorption refrigerator, or a dilution refrigerator. Particularly, 4 K mechanical cryocoolers have become a key science puzzle in studies on the entire refrigeration system. This is because they not only satisfy the cooling requirements of the space detector in the liquid-helium temperature range, but also serve as the crucial pre-cooling heat sink of mK cryocoolers. Currently, the common 4 K technical scheme is a hybrid approach combining Stirling-type cryocoolers (Stirling cryocooler or HPTC) and JT cryocoolers, in which the former is firstly used to cool down to 10–15 K, after which the latter works to achieve the temperature down to 4 K. The low-temperature stage JT cryocooler offers the advantages of fast cooling and large cooling powers in the liquid-helium temperature range. However, it has a non-negligible technical risk wherein the pipeline can be easily blocked at low temperatures, which seriously affects its on-orbit life. In addition, the refrigeration process is relatively complicated. Thus, aiming at China's astronomical deep space exploration missions, in this paper, a pure HPTC approach was proposed with a minimalistic refrigeration process in which only a single HPTC is adopted to obtain the liquid-helium temperature. Compared with the JT cryocooler, the number of the compressor is reduced from 4–5 to only 2 for the HPTC approach, significantly improving the compactness of the refrigeration system. However, directly obtaining 4 K from room temperature using a regenerative refrigeration cycle can be quite challenging due to the severe oscillating flow and heat exchange conditions in the liquid-helium temperature range.

The designed prototype is shown in Figure 1(a). As can be seen, it has a very compact configuration and appears to be a single-stage structure on the exterior. The cryocooler utilizes a three-stage configuration that adopts a single-stage pre-cooler thermal-coupling a two-stage gas-coupled HPTC. In addition, 250# stainless steel (SS) wire mesh, layered 450# SS and 635# SS wire meshes, and 50–90 μm $HoCu_2$ spheres were used as the regenerator materials for the pre-cooling stage, first stage, and second stage, respectively. At the same time, rhodium-iron thermometers calibrated by the Cryogenic Metrology Station of the Chinese Academy of Sciences (1.3–300 K) with an accuracy of 0.1 K were used as the temperature sensors. Unlike our previous 4 K refrigeration scheme of low-frequency Vuilleumier cryocooler [14], the HPTC prototype offers significant competitive advantages, including high stability, compact structure, and long lifetime benefiting from no moving parts at the cold end and high working frequency (20–30 Hz) in space exploration. Focused on optimizing the low-temperature stage regenerator (2nd stage in Figure 1(a)), especially for the low-temperature phase shifters including the inertance tube and double-inlet, a no-load temperature of 2.5 K was achieved using ^{4}He as the working fluid, making it the first high-frequency Stirling-type cryocooler working down to 2 K. The typical temperature profile is 77, 30, and 2.5 K, as shown in Figure 1(b). More importantly, using ^{4}He to obtain a low temperature below 3 K alleviates the predicament of the severely short supply of its rare isotope ^{3}He. Figure 1(c)

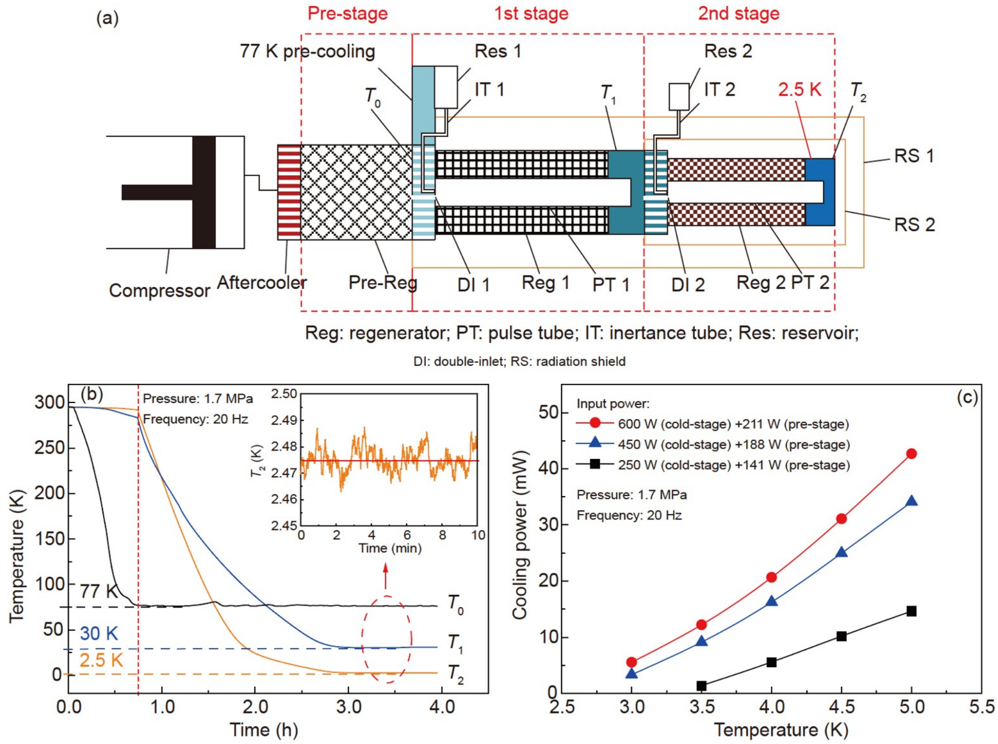

Figure 1 (Color online) The developed HPTC working below 3 K. (a) The structure of the prototype; (b) the cooling curve at 600 W input power (cold-stage); (c) the cooling powers at various input powers.

shows the cooling power curve of the prototype. As shown in the figure, the cryocooler can afford an adequate heat sink for the Miyin Program, while up to tens of milliwatts of cooling power at 4 K can be provided for pre-cooling the mK-class ADR of HUBS. Notably, the peak-to-peak temperature difference of the cryocooler at such a high frequency is less than 0.1 K. The low-temperature fluctuation and vibration at the cold end helps reduce the interference to the detection accuracy of the space detector. Thus, the pure HPTC refrigeration approach is expected to provide strong technical support for China's deep space exploration projects.

In summary, the first HPTC working down to 2.5 K was designed to meet China's goal of vigorously developing deep space exploration missions. This cryocooler obtained the lowest temperature record among Stirling-type cryocoolers under high-frequency conditions. In this way, the cooling power of several to tens of milliwatts in the liquid-helium temperature range can be provided, guaranteeing a low-temperature environment for the effective operation of China's deep space exploration projects, such as the Miyin and the HUBS Programs.

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