Status and development trends of the space 2 K mechanical cryocooler

Z Y Liu1,2, Y X Ma1, J Quan1, Y J Liu1,*, J Wang1, J G Li1 and J T Liang1,2

1 Key Laboratory of Technology on Space Energy Conversion, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China
2 University of Chinese Academy of Sciences, Beijing, China

*E-mail: yjliu@mail.ipc.ac.cn

Abstract. The space 2 K cryogenic technology is one of the critical supporting technologies for deep-space explorations. With the development of space detectors, such as infrared and X-ray detectors, the demands for the space 2 K cryogenic technology have become much more urgent. Early space detection missions used superfluid helium cryostats (SHCs) to meet their requirements. However, cryostats have been gradually replaced by the 2 K mechanical cryocoolers due to the large volume, heavy weight, and short life of cryostats. Hybrid Joule-Thomson (J-T) cryocoolers are the best alternative to cryostats in the 2 K mechanical cryocoolers because of their relatively higher efficiency at 2 K. This paper provides an up-to-date review of space missions involving 2 K hybrid J-T cryocoolers and a summary on the key issues that need to be solved in the 2 K J-T cryocoolers.

1. Introduction
The space cryogenic technology is an indispensable part of space explorations. A proper low-temperature environment can significantly reduce the thermal noise and improve the accuracy and sensitivity of space detectors.

Different detectors have different operating temperatures. For instance, a temperature of 1-2 K range is required for the Superconducting Nanowire Single-Photon Detectors (SNSPDs) to guarantee its excellent performance. In addition, the 1-2 K cryogenic environment can also precool space cryocoolers operating at mK temperatures, such as Adiabatic Demagnetization Refrigerator (ADR) and Dilution Refrigerator (DR).

Superfluid helium cryostats (SHCs) were used to reach 2 K and cool space detectors in the early years. However, SHC is gradually replaced by 2 K mechanical cryocoolers due to cryostats’ shortcomings, such as large volume and short lifetime. This article summarizes space 2 K cryogenic applications with particular emphasis on 2 K mechanical cryocoolers.

2. Development status of the space SHC
Since the first space infrared astronomical satellite IRAS launched in 1983, SHC has been used widely in the space exploration. Table 1 shows space exploration missions equipped with SHCs [1-7].
Table 1. Overview of space missions with SHCs.

| Missions   | Launched time | Working temperature | Participating countries | The carrying volume of liquid helium | Satellite lifetime |
|------------|---------------|---------------------|-------------------------|--------------------------------------|-------------------|
| IRAS       | 1983          | 1.6K                | Netherlands, USA, UK    | 720N L                               | 10 months         |
| COBE       | 1989          | 1.6K                | USA                     | 650L                                 | 10 months         |
| ISO        | 1995          | 1.8K                | Europe                  | 2300L                                | 2.5 years         |
| IRTS       | 1995          | 1.7K(0.3K)          | Japan                   | 90L                                  | 1 month           |
| Spitzer    | 2003          | 1.4K                | USA                     | 360L                                 | 5 years           |
| Astro-F    | 2006          | 1.8K                | Japan, Europe           | 170L                                 | >500 days         |
| Herschel   | 2009          | 1.7K(0.3K)          | Europe                  | 2000L                                | 3 years           |

The space SHC is a highly complex system. This technology is mainly mastered by Europe, America, and Japan. The superfluid helium can directly provide a low temperature of 1-2 K for detectors and can be used as a precooling stage for cryocoolers at a lower temperature. For example, in the Herschel satellite, the superfluid helium was used as the precooling stage of the 0.3 K adsorption cryocooler.

In recent years, the space SHC technologies have become increasingly mature, including its adiabatic system, the cryostat structure, and the superfluid helium space gas-liquid separation technology. The lifetime of SHC is still very short compared to the space mechanical cryocooler, although these advancements have extended the on-orbit lifetime of SHC. Astro-F is the first space detection mission to run stably using a hybrid cryogenic system that combines mechanical cryocoolers and SHC to intercept SHC’s heat leakage. Two two-stage Stirling cryocoolers (2SCs) were used to cool the outer cryogenic shield in the cryogenic system of Astro-F, which extended the lifetime of superfluid helium by 358 days [6]. Therefore, replacing SHC with space mechanical cryocoolers with lighter weight, more compact structure, and longer lifetime is the development trend of the space 2 K cryogenic technology.

3. Development status of the space 2K mechanical cryocoolers

The hybrid J-T cryocoolers have higher efficiency at a temperature below 4 K than other mechanical cryocoolers. It is easy for hybrid J-T cryocoolers to isolate vibration and shield electromagnetic interference because there are no moving parts at cryocoolers’ cold ends. J-T cryocoolers can also transmit cooling power over a long distance. Thus, the hybrid J-T cryocooler is widely used in space exploration. Table 2 shows space missions equipped with 4 K space J-T cryocoolers [8-17]. This technology is mainly mastered by the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), and Japan Aerospace Exploration Agency (JAXA).

Table 2. Overview of space missions with 4K J-T cryocoolers.

| Satellite      | R&D institutions | Cryocooler types               | JT cryocooler Performance | Lunch time |
|----------------|------------------|--------------------------------|--------------------------|------------|
| Planck         | ESA, NASA        | H₂ J-T+⁴He J-T+DR              | 4 K                      | 2009       |
| SMILES         | JAXA             | 2SC+⁴He J-T                   | 20 mW@4.5 K              | 2009       |
| Astro-H        | JAXA, NASA       | 2SC+⁴He J-T+SHC+ADR           | 40mW@4.5K                | 2016       |
| SPICA          | JAXA, NASA, ESA  | 2SC+⁴He J-T                   | 50 mW@4.5 K              | 2020s      |
| JWST (ACTDP)   | NASA, Northrop Grumman | 2PTC⁺⁺⁺⁴He J-T      | 65 mW@6 K                | ~ 2021     |
| LiteBIRD       | JAXA, NASA, ESA  | 2SC+⁴He J-T+ADR               | 40 mW@4.5 K              | ~ 2027     |
| ATHENA         | ESA, JAXA, RAL   | 2SC+⁴He J-T                   | 40 mW@4.5 K              | ~ 2031     |

a Adsorption Cryocooler.
b Three-stage Pulse Tube Cryocooler.
Based on the 4 K space J-T cryocoolers, space 2 K J-T cryocoolers are designed, tested, and used in future space missions. At present, a series of exploration satellites that will carry 1-2 K space mechanical cryocoolers are under development.

3.1. The 1.7 K J-T cryocooler of Astro-H
The Astro-H satellite developed by NASA and JAXA was launched in 2016. In the original design, the cryogenic system included 20 K 2SCs, 2 K J-T cryocooler, 1.3 K SHC (36 L), and 50 mK ADR, as shown in figure 1 [11]. The 1.7 K space J-T cryocooler was used to cool the cryogenic shield of the SHC to reduce the heat leakage. Then, the SHC, which had a stable temperature of 1.3 K, precooled the two-stage ADR.

The 1.7 K J-T cryocooler using $^3$He as working fluid was precooled by two 2SCs. When the total input power of the J-T cryocooler was 131 W (89 W for 2SCs and 42 W for the J-T cycle), a cooling capacity of 10.1 mW at 1.72 K was achieved. The supply pressure was 532 kPa, and its mass flow rate was 2.5 mg/s [11]. The J-T cycle used a four-stage compression structure which was integrated two compressors. However, in the final design of the cryogenic system, the 1.7 K J-T cryocooler was replaced by the 4 K J-T cryocooler.

![Figure 1. Schematic diagram of Astro-H cryogenic system.](image)

3.2. The 1.7 K J-T cryocooler of SPICA
The Space Infrared Telescope for Cosmic and Astrophysics (SPICA) is a mid-to-far infrared detection mission that JAXA, ESA, and NASA support. The mission was scheduled to be launched in the 2020s. SPICA’s cryogenic system uses a combination of the mechanical cooler system and the radiative cooling system. The mechanical cooler system is shown in figure 2 [18]. It needs two kinds of J-T cryocoolers which work at 4.5 K and 1.7 K separately, to precool the hybrid 50 mK cooler. This hybrid 50 mK cooler comprises a 300 mK sorption cryocooler and a 50 mK single-stage ADR. Each J-T cryocooler uses three 2SCs for precooling.

The structure of the 1.7 K J-T cryocooler is shown in figure 3. The J-T cycle uses four-stage compression. This J-T cryocooler uses $^3$He as the working medium. When the power consumption of the J-T cycle and the 2SC were 76.6 W and 89.0 W, respectively, the J-T cryocooler obtained a cooling capacity of 16 mW at 1.7 K [13].

In addition, this hybrid J-T cryocooler was used to establish the 300 mK - 50 mK cryochain of ATHENA in a cryostat named “cryostat 1”. This part will be described in detail in section 3.3. This cryostat can verify the feasibility of the SPICA thermal link between the J-T cryocooler and the hybrid 50 mK cooler and their cryogenic performance. This cryochain has successfully obtained a low temperature of 50 mK. This J-T cryocooler has also successfully operated [19].

![Figure 2. The SPICA cooling chain and the mechanical cooler system.](image)
3.3. The 2 K J-T cryocooler of ATHENA

The ATHENA X-ray telescope in the Cosmic Vision program of ESA is expected to be launched in 2031, which is designed to investigate how clusters evolve and research supermassive black holes.

The ATHENA needs a low temperature of 50 mK, so its cryogenic system is very complicated. Firstly, a radiant radiator and five pulse tube cryocoolers (PTCs) are used to precool the J-T cryocooler at 120 K~150 K and 15 K separately. Then, 4 K J-T cryocoolers are used to cool the 4 K cryogenic shield. 2 K J-T cryocoolers provide the cooling capacity of 20 mW for hybrid $^3$He adsorption-ADR which can obtain a low temperature of 50 mK. The cryogenic system is shown in figure 4 [20].

---

**Figure 3.** Schematic diagram of SPICA 1.7 K J-T cryocooler.

**Figure 4.** Schematic diagram of ATHENA cryogenic system.
To test the thermal performance of the ATHENA, ESA has designed and manufactured a Detector Cooling System (DCS), including a Focal Plan Assembly (FPA) coupled with a cryostat which is called “cryostat 1” and mentioned in section 3.2. The cryostat uses ground system equipment (GSE) to cool the cryogenic shield and mechanical supports. The system consists of a 2 K $^3$He J-T cryocoolers (JT2K) precooled by a PTC (PT15K), a 4 K $^4$He J-T cryocoolers (JT4K) precooled by a 2SC, and a hybrid $^3$He sorption-ADR, as shown in figure 5. The 15 K PTC can provide 400 mW of cooling power at 15 K and 3 W at 90 K, provided by Air Liquide [21]. JAXA provides the JT2K and the JT4K. This system has achieved a cooling capacity of 0.4 μW at 50 mK [22].

The 2 K J-T cryocooler obtained the cooling power of 19 mW at 1.77 K with the precooling temperature of 9.9 K provided by the 15 K PTC [23], which exceeded the performance with 2SC precooling.

JAXA provides the 2 K J-T cryocooler used in the “cryostat 1”, which may be replaced by the J-T cooler designed by Rutherford Appleton Laboratory (RAL). Based on Planck’s 4 K J-T cryocooler, a cooling capacity of 14 mW at 2 K is achieved for the J-T cryocooler with a precooling temperature of 15 K [24]. However, RAL uses GM cryocooler as the precooler of the JT cooler.

3.4. The 1.7K J-T cryocooler developed by NIST
The superconducting nanowire single-photon detector (SNSPD) is outstanding in efficiency, speed, time jitter, and dark count. Once the SNSPDs are successfully used in space, the efficiency and safety of space communication will be significantly improved. The SNSPD needs a temperature of about 2 K to exhibit its superior performance. Therefore, the space 2 K cryocooler is one of the critical components for SNSPDs’ space application. The National Institute of Standards and Technology (NIST) developed a space 2 K J-T cryocooler for SNSPDs.

**Figure 5.** Details on the 300K–50mK cryochain and thermal links.

**Figure 6.** Schematic diagram of NIST J-T cryocooler.

**Figure 7.** Load curves for the J-T cycle at different supply pressure.
The J-T cryocooler developed by NIST is shown in figure 6. The system used a three-stage PTC to precool the J-T cycle at 80 K, 25 K, and 10 K, respectively. The cooling power of 5 mW at the 3rd stage and 80 mW at the 2nd stage was measured in the PTC. Since the suitable space compressor had not been successfully developed, this J-T cycle used $^4$He as the working medium for the open-loop experimental test and obtained the cooling performance of 1.4 mW@1.7 K [25]. Figure 7 shows the performance of the J-T cryocooler with different supply pressure. The scroll compressor is under development which will be used to drive the J-T cycle.

3.5. 2 K J-T cryocoolers developed by Chinese institutes

In 2018, Key Laboratory of Technology on Space Energy Conversion (TSEC), Technical Institute of Physical and Chemical (TIPC) of Chinese Academy of Sciences (CAS) successfully developed a 2 K hybrid J-T cryocooler. The lowest no-load temperature of 2.65 K was obtained. The cooling capacity of 1.48 mW was obtained at 2.71 K in this case [26].

In 2021, TSEC’s J-T cryocooler was improved. The J-T orifice was optimized to about 20 μm. In addition, the hybrid J-T cryocooler has a more compact structure and a lower mass than before. The J-T cycle was precooled by a two-stage PTC at 78 K and 18 K and was driven by a four-stage oil-free linear compression system. This J-T cryocooler obtained the lowest temperature of 2.17 K and the cooling capacity of 4 mW at 2.39 K [27]. This hybrid JT cryocooler was coupled with the SNSPD developed by the Shanghai Institute of Microsystems and Information Technology (SIMIT), CAS. After installing the SNSPD, the minimum working temperature of the J-T cryocooler was 2.4 K. This SNSPD system had a maximum system detection efficiency (SDE) of 93% at 1550 nm [28].

Besides, in 2021, the Shanghai Institute of Technical Physics (SITP) of CAS developed a 1-2 K cryogenic system for cooling SNSPD. This system achieved the lowest temperature of 1.52 K in its experimental study [29]. Institute of Refrigeration and Cryogenics of Zhejiang University also has some research work on the 4 K J-T cryocooler [30].

4. Discussion

These 2 K J-T cryocoolers mentioned above are summarized in table 3. As can be seen, the lowest temperature obtained by closed-cycle $^4$He J-T cryocooler which has been reported is 2.17 K. Most 2 K J-T cryocoolers use $^4$He as the working medium due to it is easier to obtain lower temperature because the saturated vapor pressure of $^3$He is higher than that of $^4$He.

The saturated vapor pressures of $^4$He and $^3$He at different temperatures are shown in table 4. As can be seen, to obtain the temperature of 2.2 K, low pressure of 4.8 kPa must be achieved when $^4$He is used while 26.8 kPa for $^3$He. However, 4.8 kPa is an excellent challenge for a low-pressure stage J-T compressor. On the other hand, the displacement of the J-T compressors determines the mass flow rate
of the J-T cycle, which in turn determines the cooling capacity. In short, the development of the high-reliability J-T compressor, which can provide lower suction pressure and higher mass flow rate, is of great importance. It is also one of the key challenges in the research of 2 K hybrid J-T cryocoolers.

Table 3. Overview of 2K J-T cryocoolers for space applications.

| Cryogenic System | R&D institutions       | Cryogenic performance | Cryocooler types | J-T compression system |
|------------------|------------------------|-----------------------|------------------|------------------------|
| Astro-H          | JAXA, NASA             | 10.1mW@1.72K          | 2SC+\(^4\)He J-T | 4-stage               |
| SPICA            | JAXA, NASA, ESA        | 16mW@1.7K             | 2SC+\(^4\)He J-T | 4-stage               |
| ATHENA           | ESA                    | 19mW@1.77K            | 2PTC+\(^3\)He J-T | 4-stage               |
| NIST             | NIST                   | 1.4mW@1.7K            | 3PTC+\(^4\)He J-T | Open-loop             |
| TSEC             | TSEC (TIPC, CAS)       | 2.17 K                | 2PTC+\(^4\)He J-T | 4-stage               |

Table 4. Saturated vapor pressures of \(^4\)He and \(^3\)He at different temperatures.

| Temperature (K) | \(^4\)He | \(^3\)He |
|-----------------|----------|----------|
| 1.70            | -        | 4.856    |
| 2.17            |          | 23.730   |
| 3.00            |          | 81.826   |
| 4.20            |          | 98.470   |

Besides, the performance of precooling stages directly affects the cooling capacity of the J-T cryocoolers. 2SCs were used as precooling stages of J-T coolers in Astro-H and SPICA. A new generation of space mechanical cryocoolers, the multi-stage PTCs, are used as precooling stages of J-T cryocoolers by ESA, NIST, and TSEC. The multi-stage PTC demonstrates higher reliability and lower vibration than the 2SC because of the absence of moving parts at the cold end. The 2 K J-T cryocooler with the PTC precooling should provide a larger cooling capacity than with the 2SC precooling. Moreover, the performance of the multi-stage PTC must be improved before the cooling capacity of the hybrid J-T cryocooler can be improved.

The J-T cryocooler relies on the expansion of helium through a fixed orifice, which is easy to block with contaminants over a long period of operating time (>3 years) [31]. The purification system must be introduced to the J-T cycle. In addition, there is cooperation between the J-T orifice and the J-T compression system. The diameter of the orifice is directly affecting the J-T effect. If the J-T orifice is larger, the mass flow rate would be higher. But it would be more difficult for the compression system to obtain the low suction pressure. This results in large cooling capacity, but a higher no-load temperature.

5. Conclusion
Space 2 K cryogenic technology has made remarkable progress over the last few decades. The SHC is commonly used in space missions since 1983. However, the 2 K J-T cryocoolers, characterized by lighter weight, more compact structure, and longer lifetime, are taking the place of cryostats in recent years.

Many works on space 2 K J-T cryocoolers have been carried out in Europe, the United States, and Japan. Japan’s space hybrid J-T cryocooler was continuously optimized in many successive space missions, such as Astro-F, Astro-H, SMILES, and SPICA. The 2 K hybrid J-T cryocooler, developed by RAL and Air Liquide, will be used as a precooling stage of \(^3\)He sorption-ADR in ATHENA. The NIST is developing a 2 K J-T cryocooler to support the space application of SNSPD. And China is also involved in the research of space 2 K J-T cryocoolers in recent years.

Overall, the hybrid \(^3\)He J-T cryocooler is the mainstream of 2 K mechanical cryogenic technology. Although no space 2 K J-T cryocoolers are working in space, the space 2 K J-T cooler development is in full swing. However, there are also many challenges for the space application of the 2 K hybrid J-T cryocoolers, including developing long-life oil-free valved compressors for the J-T cycle, the performance improvement of the precooling stage long-life operation of the J-T cycle without blocking, and the cooperative research between the J-T orifice and the J-T compression system.
6. References

[1] Neugebauer G, et al 1984 The Astrophysical Journal 278 L1-6
[2] Boggess N W, et al 1992. The Astrophysical Journal 397 420-9
[3] Kessler M 2002 Advances in Space Research 30 1957-65
[4] Murakami H, et al 1996 Publications of the Astronomical Society of Japan 48 L41-6
[5] Volz S M, Schweickart R B and Heurich B 2003 Proceedings of SPIE - The International Society for Optical Engineering 4850 1038-49
[6] Hirabayashi M, et al 2008 Cryogenics 48 189-97
[7] Passvogel T and Juillet J-J 2003 Proceedings of Spie the International Society for Optical Engineering 4850 598-605
[8] Bradshaw T and Orlowska A 1997 TECHNOLOGY 997 400
[9] Triqueneaux S, Sentis L, Camus P, Benoit A and Guyot G 2006 Cryogenics 46 288-97
[10] Otsuka K, Tsunematsu S, Okabayashi A, Narasaki K and Satoh R 2010 Cryogenics 50 512-5
[11] Sato Y, et al 2010 Cryogenics 50 500-6
[12] Sato Y, et al 2012 Cryogenics 52 158-64
[13] Sugita H, Sato Y, Nakagawa T, Murakami H, Kaneda H, Enya K, Murakami M, Tsunematsu S and Hirabayashi M 2008 Cryogenics 48 258-66
[14] Petach M and Michaelian M 2014 Cryocoolers 18 11-7
[15] Duval J-M, et al 2020 Journal of Low Temperature Physics 199 730-6
[16] Prouvé T, et al 2018 Cryogenics 89 85-94
[17] Crook M, Bradshaw T, Gilley G, Hills M, Watson S, Green B, Pulker C and Rawlings T 2016 Cryocoolers 19 9-18
[18] Shinozaki K, et al 2020 Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave International Society for Optics and Photonics 11443
[19] Nakagawa T, et al 2020 Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave International Society for Optics and Photonics 11443
[20] Pajot F, et al 2018 Journal of Low Temperature Physics 193 901-7
[21] Martin S, Charles I, Duval J, Prouvé T, Barbier P, Carpentier S, Butterworth J, Branco M and Linder M 2018 Cryocooler 20
[22] Prouvé T, et al 2020 Cryogenics 112
[23] Shinozaki K, et al 2019 IOP Conference Series: Materials Science and Engineering 502
[24] Crook M, Hills M, Gilley G, Rawlings T, Pulker C and Green B 2021 Cryocoolers 21
[25] Kotsubo V, Ullom J and Nam S 2018 Cryocoolers 20.
[26] Ma Y, Quan J, Wang J, Liu Y, Li J and Liang J 2019 Science China Technological Sciences 62 361-4
[27] Liu Z, Ma Y, Quan J, Liu Y, Wang J, Li J and Liang J 2021 Cryogenics 103347
[28] Hu P, et al 2021 Superconductor Science and Technology 34
[29] Dang H, Tan H, Zhang T, Zha R, Tan J, Zhao Y, Zhao B, Xue R and Li J 2021 IEEE Transactions on Applied Superconductivity 31 1-5
[30] Shen Y, Liu D, Liu L, Li S, Chen S, Gan Z and Qiu M 2020 Applied Thermal Engineering 178
[31] Bradshaw T W, Orlowska A H and Jewell C 2002 Cryocoolers 10 521-8.

Acknowledgments
This research is supported by the National Natural Science Foundation of China (Grant No. 51776213, No. 51806228) and the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDA18000000, No. XDA18040000).