State of the Profession Considerations White Paper
In Support of Future Candidate Large Missions and Probe Missions Prepared for 2020 Decadal Survey on Astronomy and Astrophysics

Advanced Mechanical Cryocooler Technology Maturation

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1. State of the Profession Considerations

1.1. Need for 4K Mechanical Cryocoolers for Future Astrophysics Missions

Efficient, long-life, lightweight mechanical cryocoolers with low exported vibrations are a critical enabling technology for future long-infrared, X-ray and cosmic microwave background space missions. These astrophysics missions are aimed to gain understanding of the origins and underlying physics of the cosmos and to study stellar activity on exoplanet habitability. Missions conducting far-IR surveys aim to achieve ultrahigh sensitivity that is limited by cosmos background rather than by self-emission from the telescopes and detectors. Thus, their telescopes need to be cooled below 4 K and the detectors need to at sub-kelvin temperatures. These missions include ORIGINS Space Telescope and The Galaxy Evolution Probe (GEP) (Table 1). Specifically, ORIGINS Space Telescope (OST) requires eight mechanical coolers (for redundancy and 100% cooling margin) to provide 200 mW of cooling at 4 K for its Optical Telescope Element (OTE), instruments, surrounding baffles, and its 50 mK Adiabatic Demagnetization Refrigerator (ADR) that provides cooling for the High Resolution Spectrometer (HRS). The cooling system also needs to provide cooling to 20 K and 70 K for thermal intercepts. The exported vibrations from the mechanical coolers must be very low to minimize microphonics on detectors (DiPirro et al 2017). The overall design of the OST is driven by thermal and cooling considerations. The cooling system in this mission will enable the use of advanced detectors to achieve sensitivity approaching the fundamental limit of a given aperture, enabling increased mission science returns.

The cosmic microwave background mission, Probe of Inflation and Cosmic Origins (PICO), also requires a 4 K cryocooler to absorb heat rejected from the 100 mK ADR for its polarimeter. The X-Ray mission, Lynx X-Ray Observatory (LYNX), needs a 4 K cryocooler as well to provide precooling for the 50 mK ADR for its Transition-Edge Sensors (Table 1).

Table 1. Cryocooling Needs from Mechanical Coolers for Far-IR and X-Ray Missions				
Missions	ORIGINS Space Telescope (Cooray et al. 2018)	Lynx X-Ray Observatory (Özel et al. 2018)	The Galaxy Evolution Probe (Glenn et al. 2018)	Probe of Inflation and Cosmic Origins (Hanany et al., 2019)
Mission Type	Large Mid and Far-IR Mission	Large X-Ray Mission	Mid and Far-IR Probe	Cosmic Microwave Background Probe
Cooling temperature	4 K cooling for OTE, instruments and baffles, 20 K cooling for HEMTs, and additional 70 K and 20 K cooling for thermal intercept	4.5 K cooling for telescope baffles and 50 mK ADR, and 70 K and 20 K cooling for thermal intercept	4 K cooling for mirrors, amplifier and 100 mK ADR, and higher temperature cooling for thermal intercept	4.5 K cooling for the aperture stop, secondary reflector, and for 100 mK cADR
Cooling load near 4K	200 mW at 4 K. About 100mW for telescope and 100 mW for instruments, including precooling for sub-kelvin ADR	20 mW active dissipation at 4.5 K with 100% margin plus thermal intercept at higher temperatures	100 mW (28% margin) cooling at 4.2 K for ADR and at 4.5 K for telescope and intercept	42 mW at 4.5 K
Environment	Sun-Earth L2			
Vibration requirement	Minimize but no specific requirements			
Distributed cooling?	Yes	No	Yes	Yes
Baseline Active Cooling Approach	Four JWST/MIRI cryocoolers operating in parallel (8 in total for block redundancy)	4-stage pulse tube cooler or 3-stage Reverse Brayton cooler	JWST/MIRI cooler with an additional stage on the J-T loop	JWST/ MIRI cryocooler
Mass and power input	8 × 46 kg mass 4 × 500 W input per cooler (4 coolers will be active at a time) (DiPirro et al 2017)	35 kg and 653 W for 4-stage pulse tube cooler; 39 kg and 350 W for 3-stage RB cooler (DiPirro et al 2019)	> 46 kg (MIRI Cooler) and 636 W (Moore et al. 2018)	350 W maximum expected and 46 kg (MIRI Cooler)

1.2. Current Mechanical Cryocooler Technology Is Not Adequate To Support Future Missions

The strategies for providing cooling at approximately 4 K for these candidate missions build upon the state-of-the art for low-temperature cryocoolers, such as the cooling system onboard Planck (about 15 mW at 4.6 K), and the JWST/MIRI cooler (55 mW at 6.2K) that is currently at TRL 8. The low temperature cooling in these current systems is achieved by a hybrid cooler consisting of a ^{4}He Joule-Thomson (J-T) lower stage precooled by an upper stage at a temperature round 18 K. For the Planck mission, the upper stage is a sorption cooler; for the JWST/MIRI cooler, the upper stage is a pulse tube cryocooler. Alternative candidate technologies include multi-stage pulse tube cryocoolers developed under the Advanced Cryocooler Technology Development Program (ACTDP) for 6 K cooling (Ross and Johnson 2006), and Reverse Brayton (RB) cryocoolers using high speed turbomachines. An RB cooler can potentially achieve 4.5 K cooling with a three-stage system (DiPirro et al. 2019). However, 4 K mechanical cryocoolers with a cooling capacity that can meet the requirements of these future missions are still at TRL 4-5 at the integrated cryocooler level. Further technology maturation of 4 K mechanical cryocoolers is needed in the form of enhanced thermal efficiency, reduced mass, reduced exported vibration, and improved affordability.

Extending cooling temperature from 6 K to 4 K requires significant enhancement to cooler designs. For a J-T cooler, the low-side pressure must be below the working fluid saturation pressure at the target cooling temperature if it is below the critical temperature. Reducing the low-side pressure effectively decreases the cooling temperature but also increases the compressor suction volumetric flow rate and thus the piston swept volume for a fixed operating frequency. It also requires a higher pressure ratio to maintain the cycle efficiency. Specifically, the low-side pressure must be below 81.5 kPa, the ^4He saturation pressure at 4 K. This pressure is almost 5 times lower than the low-side pressure of a 6 K J-T cooler, which can be higher than 400 kPa, as in the MIRI cooler (Petach et al. 2016). To achieve the same cooling power per unit mass flow rate as the MIRI cooler with a precooling temperature of 18 K, the pressure ratio in the 4 K J-T cooler needs to be about 9.5, which is much higher than the pressure ratio of 2.85 for the MIRI cooler.

Similarly, for an RB cryocooler, reducing the cooling temperature also requires reducing the low-side pressure, increasing the size and mass of the recuperators. Reducing the cooling temperature also increases the fabrication challenges of the turboexpander to maintain its efficiency at lower temperatures. For a multi-stage pulse tube cooler, in addition to the need for a larger compressor, maintaining regenerator thermal efficiency at lower temperatures is a technical challenge because of limited heat capacity of regenerator materials at very low temperatures.

For all these systems, it may be necessary to use ^3He or a ^3He-^4He mixture as the working fluids to enable the coolers to efficiently reach the 4 K cooling temperature.

1.3. Low-Temperature Mechanical Cryocoolers are not Affordable and Their Supply are not Reliable

The cost of low-temperature mechanical coolers for future missions is driven by the technology readiness. Besides once-a-decade large space missions, there is very little commercial or military applications for high-performance cryocoolers that provide cooling below 10 K. Consequently, the private sector has very little incentive to underwrite the investment for advancing low-temperature cooler technical readiness. Current 4 K cooling needs for ground applications can be met with low-cost, albeit inefficient, Gifford-McMahon (G-M) coolers, while military airborne and spaceborne mid- to long-wave IR imaging systems in missile defense systems only need cooling above 10 K. Therefore, government support is needed to advance the 4 K cryocooler technology readiness for space-flight to improve long-term affordability.

In the past decade, the investment in cryocooler technology research from NASA and other government agencies including Department of Defense has been very limited. This, along with a very limited commercial market for spaceborne cryocoolers, has caused many space cryocooler providers to exit the business area. As of today, there are only three active low-temperature (<20 K) space mechanical cryocooler suppliers in the United States: Northrop Grumman Corporation, Lockheed Martin's Advanced Technology Center and Creare LLC. Because of the lack of research programs, these companies have lost critical personnel mass in this technology area over the last decade. It is uncertain if these companies will be able to retain their already limited research capacity and key personnel in the next 5 to 10 years to support future low-temperature cryocooler technology maturation.

1.4. Significant Performance Gain through Technology Maturation can be Expected

The thermal efficiency of current low-temperature cryocoolers is well below the thermodynamic limit, as shown in Figure 1. The overall Carnot efficiency of cryocoolers with cooling temperatures below 6 K is on the order of 1%, an order of magnitude lower than that of cryocoolers providing cooling above 50 K. Therefore, it can be expected that the efficiency of the low-temperature cryocoolers can be appreciably increased by means of technology maturation to substantially reduce their power consumption. For the large cooling need of 200 mW at 4 K for the OST mission, it is predicted by extrapolation from today's technology that approximately 2 kW of power is needed for the four mechanical cryocoolers. A modest efficiency gain can substantially reduce the power requirement for the cooling system, and thus reduce the mission cost. Similarly, the size and mass of the mechanical coolers can also be expected to decrease appreciably with technology maturation. Even eliminating a modest fraction of the predicted cooler mass of 368 kg (including 4 redundant coolers) would results in a large mass savings.

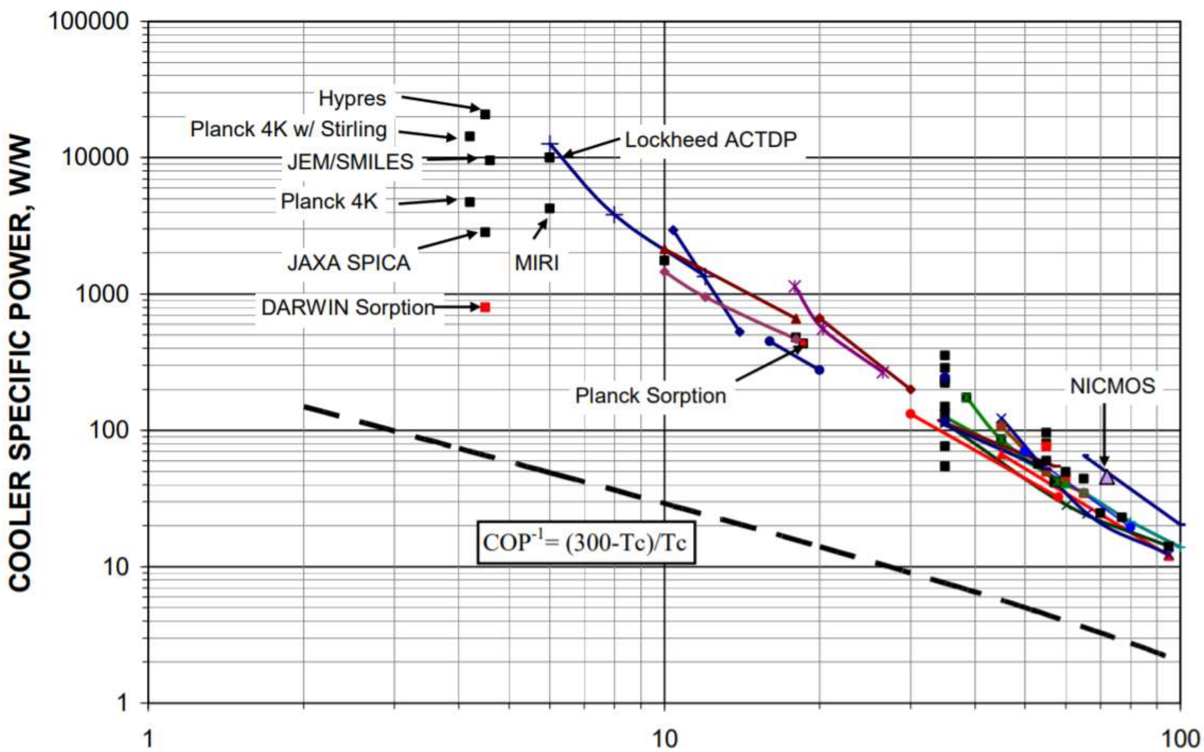

Figure 1. Specific power of single and multi-stage coolers based on the total power into the cooler but only on the heat lift at the cold stage. The ideal Coefficient of Performance (COP) is shown for comparison (Johnson, 2008)

2. Strategic Plan

2.1. NASA Needs to Invest in Maturing Low Temperature Cryocooler Technology

To address the previously discussed issues of long-term affordability and supply reliability of low-temperature cryocoolers for space missions, it is in NASA's best interest to invest in its research centers to maintain and grow in-house expertise in this area, in academic institutes which will produce the next generation of cryogenic engineers, and in the private sector for hardware fabrication and integration.

Past NASA investment has demonstrated great success with this approach. For example, the government-sponsored programs under the leadership by NASA and DoD from late 1980s to early 2000s drastically advanced the cryocooler technologies, enabling cryogen-free operation for many industrial, scientific, and defense applications. These investments also enabled relatively affordable space cryocoolers to routinely provide cooling above 50 K with impressive on-orbit reliability that extends the mission and significantly increases science returns compared to missions using stored cryogens. More recently, the Advanced Cryocooler Technology Development Program (ACTDP), under the leadership at NASA JPL, has successfully extended space mechanical cryocoolers cooling temperature down to 6 K (Ross and Johnson 2006).

NASA investment in the technology maturation of low-temperature cryocoolers would pay dividends for future missions by reducing long-term cost, power consumption, and size and mass.

2.2. Public-Private Partnership to Efficiently Advance Technology Readiness

Given the current low technical readiness of 4 K mechanical cryocoolers and the lack of sufficient research capacity in individual private companies to efficiently carry out the efforts to mature the technology, it is most logical to pool the research resources from NASA, the private sector, and academic institutes together, forming a public-private partnership geared toward providing long-term affordable solutions for future astronomy and astrophysics missions. The jointed technology maturation effort can be structured as a two-phase process, namely (Phase I) cooler configuration optimization and enabling technologies maturation led by NASA and (Phase II) cooler design, prototype fabrication and demonstration led by commercial partners, with NASA as the potential system integrator.

At the current state, it is arguable that NASA has larger research capacity than any individual companies or organizations, and thus it is most appropriate for NASA to lead the maturation phase of the program. This arrangement would allow NASA to distribute new research findings from the first phase of the program among all the partners, avoiding the situation where commercial companies could place strict limitations on the free use of new ideas developed in the first phase of the program. The aforementioned situation would inhibit both further research and the development of valuable commercial and government applications. This approach also opens up the possibly of building an integrated cooler stage using components from different companies to expedite the maturation process and increase future 4 K cooler affordability.

2.3. Phase I – Cooler Architecture Optimization and Enabling Technologies Maturation

First, NASA will lead the overall cooling system configuration optimization based on the mission requirements and inputs from the partners. The system design effort includes selecting candidate mechanical cooler configurations, their corresponding working fluids (i.e. ^{4}He, ^{3}He or ^{4}He+^{3}He mixture) and the cooling temperatures of upper stages to maximize the overall system efficiency. Candidate configurations include (1) a hybrid cooler consisting of a Pulse Tube upper stage and a J-T lower stage, similar to the MIRI cooler, (2) a hybrid cooler consisting of a Pulse Tube upper stage and a reverse Brayton stage, (3) a multi-stage pulse tube cooler, and (4) a multi-stage Reverse Brayton cooler. NASA and its university partners will conduct thermal design analyses to assess the performance of these systems for candidate missions, and work with selected cooler providers to identify common technical areas that needs to be matured for the candidate cooler configurations. The result from this activity will be (1) candidate cooler configurations and their predicted performance, including predicted thermal efficiency, size, mass reliability, exported vibrations, and their ability to provide remote, distributed cooling; and (2) a list of technical challenges, risks and solutions to advance the technical readiness and performance of individual candidate coolers.

Next, NASA will lead the technology maturation by working closely with academic collaborators and selected cooler providers. The program will focus on two or three high-priority technical areas identified at the beginning of the program. Potential example areas include:

- Developing modular designs for cryocoolers to allow the use of different combinations of key components to customize coolers for different mission needs and thus reduce cooler build-time and improve long-term affordability. This feasibility has been demonstrated in commercial cryocooler sector by using the same cold finger for different compressors or vice versa to build a wide range of coolers while minimizing the number of components needed for their production lines (Willems et al. 2016). A proper modular design could keep the compromise in thermal performance at an acceptable level. A modular design approach will also allow the use of key components that have flight heritage or components already at high TRL from different companies to assemble flight coolers, expediting the maturation process.
- Developing advanced low-temperature regenerators with high thermal efficiency. The loss due to the limited performance of the regenerator dominates the overall performance of current low-temperature regenerative cryocoolers. Current low-temperature regenerators use rare earth alloys with curie temperatures near their local operating temperatures to enhance the regenerator heat capacity. This is achieved by utilizing the high magnetic entropy change during the paramagnetic-ferromagnetic phase transition. Because of the poor fabricability of these rare earth alloys, it is still a challenge to fabricate regenerator matrices out of these alloys with optimal channel geometry needed for high heat transfer and low pressure drop.
- Developing high fidelity cooler simulation models with low computation cost from academic institutes to allow speedy optimization of cryocooler designs in practical applications.

The results from this activity will be passed on all the private companies involved, enabling all the cooler providers to be benefited from the research findings.

Finally, in second half of the Phase I program, with the new findings from NASA and academic institutes, each partnered cooler provider will produce a detailed preliminary design for their proposed cryocooler or subsystem, documented in a final study report which will be evaluated by NASA and serve as the primary basis for down-selection to Phase II.

2.4. Phase II --Cooler Design, Prototype Fabrication and Demonstration

In Phase II, each selected cooler provider will work with NASA to develop final design of their system, and test and deliver an Engineering Model. The hardware deliverables can be key components for a cooler such as a regenerator or a cold finger assembly, or an integrated cooler stage (i.e. an upper pulse tube stage, a lower reverse Brayton stage, etc.). NASA will then integrate the subsystem hardware from these suppliers together and conduct final testing of the integrated cooler system.

3. Organization, Partnerships, and Current Status

The cryocooler technology research community is a small and well-connected one. NASA has close partnership with all space cryocooler suppliers and academic institutes who are active in cryogenics research. Northrop Grumman is working with JPL to supply the JWST/MIRI cooler; Lockheed Martin is collaborating with JPL to supply their miniature pulse tube cooler for the Mapping Imaging Spectrometer for Europa (MISE) instrument for Europa Clipper mission; and Creare is working with NASA GSFC to develop low-temperature cryocoolerto remove heat rejected from the lower stage continuous ADR through SBIR programs. NASA also has been directly and indirectly funding University of Wisconsin and Georgia Institute of Technology through STTR/SBIR programs, who are two leading academic research institutes in cryogenics.

4. Schedule

It is estimated that it would take about five years to carry out the technology maturation effort, as shown in Table 2. The effort will start with generation of detailed requirements and specifications in early 2020 and identifying optimal cooler configurations, leading to identification of key component and system integration technologies needed to mature 4 K cryocooler technology by the middle of 2020. Next, the effort would be on maturing these technologies by design and testing efforts at NASA centers and universities. This allows the findings to be disseminated to all private sector partners by the end of 2021 to facilitate the preliminary system design by the first half of 2022. Based on the preliminary system designs, and other performance metrics, two companies will be down-selected to move on to Phase II where each company will design, build, demonstrate and deliver a cooler subsystem. NASA will then integrate these subsystems together near the end of 2024.

Table 2. Program Schedule, Work Scope and Budget

Phase	Participants	Scope	2020	2021	2022	2023	2024
I_A	NASA Centers (lead), Universities and Three Private Companies	System Architecture and Enabling Technologies Maturation	$3M	$3M			
I_B	Three Private Companies (lead) + NASA	Preliminary system design		$1M	$1M		
II	Two Private Companies (lead) + NASA	Prototype fabrication and demonstration			$4M	$6M	$6M

5. Cost Estimates

The rough cost estimate for this program is $24M, with $8M for Phase I cooler architecture optimization and enabling technologies maturation, and the remaining $16M for Phase II cooler design, prototype fabrication and demonstration, as shown in Table 2.

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