NASA SBIR 2021 Phase I Solicitation

S1.09 Cryogenic Systems for Sensors and Detectors

Lead Center: GSFC

Participating Center(s): JPL

Scope Title:

Low-Temperature/High-Efficiency Cryocoolers

Scope Description:

NASA seeks improvements to multistage low-temperature spaceflight cryocoolers. Coolers are sought with the lowest temperature stage typically in the range of 4 to 10 K, with cooling power at the coldest stage larger than currently available, and high efficiency. The desired cooling power is application specific, but an example is 0.2 W at 4 K. Devices that produce extremely low vibration, particularly at frequencies below a few hundred hertz, are of special interest. System- or component-level improvements that improve efficiency and reduce complexity and cost are desirable. In addition to the large coolers, there has recently been interest in small, low-power (~10-mW) 4 K coolers. For example, the Origins Space Telescope mission concept includes a cold telescope, requiring cooling to 4 K; and the Lynx X-ray Observatory mission concept requires a state-of-the-art cryogenic system to enable high-precision and high-resolution x-ray spectroscopy.

Expected TRL or TRL Range at completion of the Project: 2 to 5
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors
Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Proof-of-concept demonstration.

Phase II: Functioning hardware ready for functional and possibly environmental testing.

State of the Art and Critical Gaps:

Current spaceflight cryocoolers for this temperature range include linear piston-driven Stirling cycle or pulse tube cryocoolers with Joule-Thompson low-temperature stages. One such state-of-the-art cryocooler provides 0.09 W of cooling at 6 K. For large future space observatories, large cooling power and much greater efficiency will be needed. For cryogenic instruments or detectors on instruments with tight point requirements, orders-of-magnitude improvement in the levels of exported vibration will be required. Some of these requirements are laid out in the "Advanced cryocoolers" Technology gap in the latest (2017) Cosmic Origins Program Annual Technology Report.

Relevance / Science Traceability:

Science traceability: Goal 1 and Objective 1.6 of NASA’s Strategic Plan: Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space Objective 1.6: Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars. Low-temperature cryocoolers are listed as a "Technology Gap" in the latest (2017) Cosmic Origins Program Annual Technology Report. Future missions that would benefit from this technology include two of the large missions under study for the 2020 Astrophysics Decadal Survey: Origins Space Telescope and Lynx microcalorimeter instrument.

References:

For more information on the Origins Space Telescope, see: https://asd.gsfc.nasa.gov/firs/

For more information on LYNX, see: https://wwwastro.msfc.nasa.gov/lynx/docs/science/observatory.html

Scope Title:

Actuators and Other Cryogenic Devices

Scope Description:

NASA seeks devices for cryogenic instruments, including:

- Small, precise motors and actuators, preferably with superconducting windings, that operate with extremely low power dissipation. Devices using standard NbTi conductors, as well as devices using higher temperature superconductors that can operate above 5 K, are of interest.
- Cryogenic heat pipes for heat transport within instruments. Heat pipes using hydrogen, neon, oxygen, argon, and methane are of interest. Length should be at least 0.3 m. Devices that have reduced gravitational dependence and that can be made low profile, or integrated into structures such as radiators, are of particular interest.

Expected TRL or TRL Range at completion of the Project: 3 to 4
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors
Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Proof-of-concept test on a breadboard-level device.

Phase II: Working prototypes ready for testing in the relevant environments.

State of the Art and Critical Gaps:

Motors and actuators: Instruments often have motors and actuators, typically for optical elements such as filter wheels and Fabry-Perot interferometers. Current cryogenic actuators are typically motors with resistive (copper) windings. While heat generation is naturally dependent on the application, an example of a recent case is a stepper motor used to scan a Fabry-Perot cavity; its total dissipation (resistive + hysteric) is ~0.5 W at 4 K. A flight instrument would need heat generation at least 20× smaller.

Cryogenic heat pipes: Heat transport in cryogenic instruments is typically handled with solid thermal straps, which do not scale well for larger heat loads. Currently available heat pipes are optimized for temperatures above ~ 20 K. They have limited capacity to operate against a gravitational potential.

Relevance / Science Traceability:

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand The Sun, Earth, Solar System, and Universe

Almost all instruments have motors and actuators for changing filters, adjusting focus, scanning, and other functions. On low-temperature instruments, for example on mid- to far-IR observatories, dissipation in actuators can be a significant design problem.

References:

For more information on earlier low-temperature heat pipes, see:

- Brennen, et al.: AIAA paper 93-2735, https://doi.org/10.2514/6.1993-2735 NTRS Document ID: 19930062491
- Prager, R.C.: AIAA paper 80-1484, https://doi.org/10.2514/6.1980-1484
- Alario, J. and Kosson, R.: AIAA paper 80-0212, https://doi.org/10.2514/6.1980-212

Scope Title:

Ultra-Lightweight Dewars

Scope Description:

NASA seeks extremely lightweight thermal isolation systems for scientific instruments. An important example is a large cylindrical, open-top dewar to enable large, cold balloon telescopes. In one scenario, such a dewar would be launched warm and so would not need to function at ambient pressure, but at altitude, under ~4 mbar external pressure, it would need to contain cold helium vapor. The ability to rapidly pump and hold a vacuum at altitude is necessary. An alternative concept is that the dewar would be launched at operating temperature, with some or all of the needed liquid helium. In both cases, heat flux through the walls should be less than 0.5 W/m^2, and the internal surfaces must be leak tight against superfluid helium. Initial demonstration units of greater than 1 m inner diameter and height are desired, but the technology must be scalable to an inner diameter of 3 to 4 m with a mass that is a small fraction of the net lift capability of a scientific balloon (~2,000 kg).

Expected TRL or TRL Range at completion of the Project: 3 to 4
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors
Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Subscale prototypes that demonstrate critical properties of the concept, including scalability and leak-free containment of superfluid helium

Phase II: A working prototype of the scale described is desired.

State of the Art and Critical Gaps:

Currently available liquid helium dewars have heavy vacuum shells that allow them to be operated in ambient pressure. Such dewars have been used for balloon-based astronomy, as in the Absolute Radiometer for Cosmology, Astrophsyics, and Diffuse Emission (ARCADE) experiment. However, the current dewars are already near the limit of balloon lift capacity and cannot be scaled up to the required size for future astrophysics measurements.

Relevance / Science Traceability:

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand the Sun, Earth, Solar System, and Universe.

The potential for ground-based far-infrared astronomy is extremely limited. Even in airborne observatories, such as SOFIA, observations are limited by the brightness of the atmosphere and the warm telescope itself. However, high-altitude scientific balloons are above enough of the atmosphere that, with a telescope large enough and cold enough, background-limited observations are possible. The ARCADE project demonstrated that at high altitudes, it is possible to cool instruments in helium vapor. Development of ultra-lightweight dewars that could be scaled up to large size, yet still be liftable by a balloon would enable ground-breaking observational capability.

References:

For a description of a state-of-the art balloon cryostat, see:

- Singal, et al.: "The ARCADE 2 instrument," *The Astrophysical Journal*, 730:138 (12pp), 2011 April 1.

Scope Title:

Miniaturized/Efficient Cryocooler Systems

Scope Description:

NASA seeks miniature, highly efficient cryocoolers for instruments on Earth and planetary missions. A range of cooling capabilities is sought. Two examples include 0.2 W at 30 K with heat rejection at 300 K and 0.3 W at 35 K with heat rejection at 150 K. For both examples, an input power of ?5 W and a total mass of ?400 g is desired. The ability to fit within the volume and power limitations of a SmallSat platform would be highly advantageous. Cryocooler electronics are also sought in two general categories: (1) low-cost devices that are sufficiently radiation hard for lunar or planetary missions, and (2) very low cost devices for a relatively short term (~1 year) in low Earth orbit. The latter category could include controllers for very small coolers, such as tactical and rotary coolers.

For many infrared (IR) spectrometer instrument systems, the spectrometer can operate at a temperature more than 60 K higher than the focal plane array. A miniature two-stage cryocooler is ideal for this type of application to minimize the cooler input power. Therefore, NASA is seeking an innovative miniature two-stage cryocooler technology with low-exported vibrations. The lowest cooling temperature of interest for the lower stage is 80 K, and the maximum cooling power is about 1 W. The cooling temperature of the second stage should be 60 to 80 K higher than the lower stage, and the cooling power should be about 2 W. It is desirable that the cooler can efficiently operate over a wide heat sink temperature range, from -50 to 70 ºC.

Expected TRL or TRL Range at completion of the Project: 2 to 4
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors
Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Proof-of-concept demonstration.

Phase II: Desired deliverables include miniature coolers and components, such as electronics, that are ready for functional and environmental testing.

State of the Art and Critical Gaps:

Present state-of-the-art capabilities provide 0.1 W of cooling capacity with heat rejection at 300 K at approximately 5 W input power with a system mass of 400 g.

Cryocoolers enable the use of highly sensitive detectors, but current coolers cannot operate within the tight power constraints of outer planetary missions. Cryocooler power could be greatly reduced by lowering the heat rejection temperature, but presently there are no spaceflight systems that can operate with a heat rejection temperature significantly below ambient.

Relevance / Science Traceability:

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand the Sun, Earth, Solar System, and Universe.

NASA is moving toward the use of small, low-cost satellites to achieve many of its Earth science—and some of its planetary—science goals. The development of cryocoolers that fit within the size and power constraints of these platforms will greatly expand their capability, for example, by enabling the use of infrared detectors.

In planetary science, progress on cryogenic coolers will enable the use of far- to mid-infrared sensors with orders-of-magnitude improvement in sensitivity for outer planetary missions. These will allow thermal mapping of outer planets and their moons.

References:

- An example of CubeSat mission using cryocoolers is given at: https://www.jpl.nasa.gov/cubesat/missions/ciras.php

Scope Title:

Sub-Kelvin Cooling Systems

Scope Description:

Future NASA missions will require requiring sub-Kelvin coolers for extremely low temperature detectors. Systems are sought that will provide continuous cooling with high cooling power (>5 mW at 50 mK), low operating temperature (10 K), while maintaining high thermodynamic efficiency and low system mass.

Improvements in components for adiabatic demagnetization refrigerators are also sought. Specific components include:

1) Compact, lightweight, low-current superconducting magnets capable of producing a field of at least 4 tesla (T) while operating at a temperature of at least 10 K, and preferably above 15 K. Desirable properties include:

- A high engineering current density (including insulation and coil packing density), preferably >300 A/mm^2.
- A field/current ratio of >0.33 T/A, and preferably >0.66 T/A.
- Low hysteresis heating.
- Bore size between 22 and 60 mm, depending on the application.

2) Lightweight active/passive magnetic shielding (for use with 4-T magnets) with low hysteresis and eddy current

losses as well as low remanence. Also needed are lightweight, highly effective outer shields that reduce the field outside an entire multistage device to <5 µT. Outer shields must operate at 4 to 10 K and must have penetrations for low-temperature, noncontacting heat straps.

3) Heat switches with on/off conductance ratio >30,000 and actuation time of <10 s. Materials are also sought for gas gap heat switch shells: these are tubes with extremely low thermal conductance below 1 K; they must be impermeable to helium gas, have high strength, have stability against buckling, and have an inner diameter >20 mm.

4) High cooling power density magnetocaloric materials. Examples of desired materialsinclude $GdLiF_4$, $Yb_3Ga_5O_{12}$, GdF_3, and Gd elpasolite. High-quality single crystals are preferred because of their high conductivity at low temperature, but high-density polycrystals are acceptable in some forms. Volume must be >40 cm^3.

5) 10 to 300 mK high-resolution thermometry.

6) Suspensions with the strength and stiffness, but lower thermal conductance from 4 to 0.050 K.

Expected TRL or TRL Range at completion of the Project: 2 to 4
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors
Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: For components, a subscale prototype that proves critical parameters. For systems, a proof-of-concept test.

Phase II: For components, functioning hardware that is directly usable in NASA systems. For systems, a prototype that demonstrates critical performance parameters.

State of the Art and Critical Gaps:

The adiabatic demagnetization refrigerator in the Soft X-ray Spectrometer instrument on the Hitomi mission represents the state of the art in spaceflight sub-Kelvin cooling systems. The system is a 3-stage, dual-mode device. In the more challenging mode, it provides 650 µW of cooling at 1.625 K, while simultaneously absorbing 0.35 µW from a small detector array at 0.050 K. It rejects heat at 4.5 K. In this mode, the detector is held at temperature for 15.1-h periods, with a 95% duty cycle. Future missions with much larger pixel count will require much higher cooling power at 0.050 K or lower, higher cooling power at intermediate stages, and 100% duty cycle. Heat rejection at a higher temperature is also needed to enable the use of a wider range of more efficient cryocoolers.

Relevance / Science Traceability:

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand The Sun, Earth, Solar System, And Universe

Sub-Kelvin coolers are listed as a "Technology Gap" in the latest (2017) Cosmic Origins Program Annual Technology Report.

Future missions that would benefit from this technology include two of the large missions under study for the 2020 Astrophysics Decadal Survey:
• Origins Space Telescope (contact: michael.j.dipirro@nasa.gov)
• LYNX (microcalorimeter instrument) (contact: simon.r.bandler@nasa.gov)

Also: Probe of Inflation and Cosmic Origins, POC: Shaul Hanany, University of Minnesota

References:

For a description of the state-of-the-art sub-Kelvin cooler in the Hitomi mission, see:

- Shirron, et al.: "Thermodynamic performance of the 3-stage ADR for the Astro-H Soft-X-ray Spectrometer instrument," Cryogenics 74 (2016) 24–30, and references therein.

For articles describing magnetic sub-Kelvin coolers and their components, see the July 2014 special issue of Cryogenics:

- Cryogenics 62 (2014) 129–220.