An Overview of NASA Space Cryocooler Programs—2006

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ABSTRACT

Mechanical cryocoolers represent a significant enabling technology for NASA's Earth and Space Science Enterprises. Many of NASA's space instruments require cryogenic refrigeration to improve dynamic range, extend wavelength coverage, or enable the use of advanced detectors to observe a wide range of phenomena—from crop dynamics to stellar birth. Reflecting the relative maturity of the technology at these temperatures, the largest utilization of coolers over the last fifteen years has been for instruments operating at medium to high cryogenic temperatures (55 to 150 K). For the future, important new developments are focusing on the lower temperature range, from 6 to 20 K, in support of studies of the origin of the Universe and the search for planets around distant stars. NASA's development of a 20 K cryocooler for the European Planck spacecraft and a 6 K cryocooler for the MIRI instrument on the James Webb Space Telescope (JWST) are examples of the thrust to provide low-temperature cooling for this class of future missions.

COOLERS ON NEAR-TERM EARTH AND SPACE SCIENCE MISSIONS

Since 1991, which included the launch of the Upper Atmospheric Research Satellite (UARS) with the Improved Stratospheric and Mesospheric Sounder (ISAMS) instrument, NASA's Earth and Space Science Program has launched 18 long-life cryocoolers into space, 12 of which are still operating on multi-year missions.[1] By the late 1990s, 5-year-life space cryocoolers built on the Oxford-cooler compressor concept of the original ISAMS instrument were considered flight proven, and many long-life space cryocoolers were developed using this compressor concept together with both Stirling and pulse tube expanders.

Starting in December 1999, three large NASA Earth Observing System platforms (Terra, Aqua and Aura) were launched. Together, they included nine long-life cryocoolers in five separate Earth-science instruments. A final category of cryocoolers are those associated with observing space physics and planetary phenomena. These include gamma-ray and infrared instruments to examine the Universe and the surfaces of other planets. Table 1 summarizes the status of long-life cryocoolers used on NASA space science missions. These, together with other short-term NASA cooler flights over the past 15 years, are detailed in the following paragraphs.

Presented at the International Cryocooler Conference
Annapolis, MD, Juner 14-6, 2006

Table 2. NASA space cryocooler flight operating experience as of June 2006.

Cooler / Mission	Running Hours	Comments	
Ball Aerospace 60K Stirling (HIRDLS)	16,000	Turn-on: 8/04; ongoing no degrad.	
Creare Turbo Brayton (NICMOS)	38,000	Turn-on: 3/02; ongoing no degrad.	
Fujitsu and Mitsubishi Stirling			
ASTER (2 units)	55,000	Turn-on: 3/00; ongoing no degrad.	
NGST (TRW) Cryocoolers			
Hyperion (Mini PT)	49,000	Turn-on: 12/00; ongoing no degrad.	
SABER (Mini PT)	39,000	Turn-on: 1/02; ongoing no degrad.	
AIRS (10cc PT (2 units))	35,000	Turn-on: 6/02; ongoing no degrad.	
TES (10cc PT (2 units))	16,000	Turn-on: 8/04; ongoing no degrad.	
Oxford/BAe/MMS/Astrium Stirling			
ISAMS (80 K Oxford (2 units))	15,800	Turn-on:10/91; instrument failed 7/92†	
MOPITT (50-80K BAe (2 units))	51,000	Turn-on: 3/00; one displacer failed at 10,300 hours; other still running†	
Ricor			
CRISM (80K Stirling (3 units))	20	Full-time operation starts in fall 2006	
Sunpower RHESSI Stirling	38,000	Turn-on: 2/02; ongoing no degrad.	

† Cooler operating hours less than calendar hours due to instrument downtime

NASA Flight Cooler Missions Since 1990

1991—ISAMS. In September 1991, the original Oxford University 80 K Stirling cooler (Fig. 1) was launched as part of the Improved Stratospheric and Mesospheric Sounder (ISAMS) instrument on NASA's Upper Atmospheric Research Satellite (UARS).[2,3] The success of this first long-life flexure-bearing Stirling cooler with clearance-type piston seals led to a worldwide adoption of the key features of this important technology.

1995—CSE. The first launch of a U.S.-built cryocooler with Oxford-like flexure springs occurred on STS-77 in February 1995. This was a 2W 60 K Standard Spacecraft Cryocooler (SSC) built by Hughes Aircraft Co. (now Raytheon). The cooler (Fig. 2) was developed in the early 1990s under contract to the U.S. Air Force and was launched as the key feature of the Cryo System Experiment (CSE), a NASA In-Space Technology Experiments Program (IN-STEP) flight. The flight not only demonstrated the cooler's successful operation in space, but also demonstrated an experimental diode oxygen heat pipe, also made by Hughes.[4] Such a heat pipe provides a means of conducting heat from a remote cryogenic load and thermally disconnecting the load when the cooler is off.

1996—MIDAS. The Materials in Devices as Superconductors (MIDAS) experiment was a NASA cryogenic facility for the characterization of high temperature superconductors during extended flights. It was based on a Stirling cooler capable of 1W cooling at 80K, with a maximum

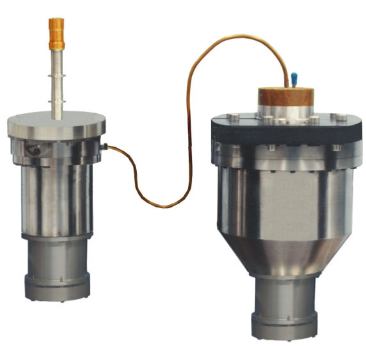

Figure 1. Oxford University ISAMS 80 K Stirling cooler.

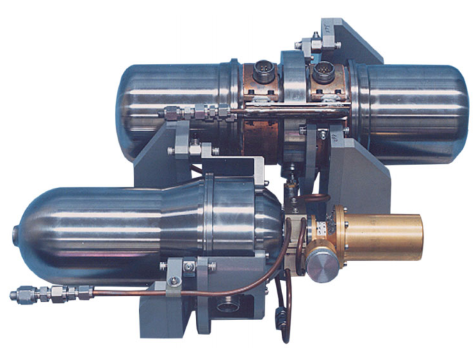

Figure 2. Hughes (now Raytheon) 2W 60 K SSC Stirling cooler.

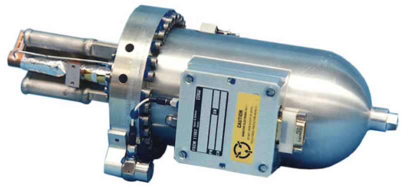

Figure 3. TRW mini pulse tube cryocooler.

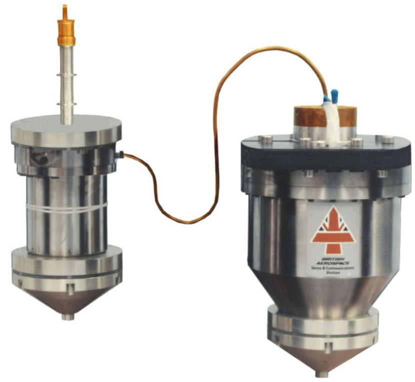

Figure 4. BAe 50-80 K cryocooler.

power consumption of 60 W.[5] Launched on STS-79 it was installed on board the Russian space station MIR where it operated for about 3 months before returning to Earth.

1996—BETSCE. In May 1996 the Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) flew on board STS-77. Jointly funded by the DoD, this JPL sorption cooler experiment demonstrated the capability to cool a 100 mW load to ~11 K in less than two minutes and maintain the load at temperature for 10-20 minutes.[6,7] After this period, the sorption cryocooler recycled in preparation for another cooling cycle. The periodic nature of the cooler allowed the required input power to be averaged over the four-hour recycle time, thus providing a fast-cooldown 150 mW 10 K cooler for a relatively low average power. This was the first flight demonstration of hydride sorption cooler technology.

1997—Lewis. The first two pulse tube cryocoolers launched into space were on this NASA spacecraft that failed prior to turn-on of the payloads. The spacecraft contained a TRW mini pulse tube cooler (Fig. 3) for TRW's HSI hyperspectral imager and a second TRW mini pulse tube cooler for the NASA Goddard LEISA instrument.[8]

1999—MOPITT. The Measurements Of Pollution In The Troposphere (MOPITT) instrument was launched on NASA's EOS Terra space platform in December 1999. It contains a pair of back-to-back British Aerospace 50-80 K cryocoolers (Fig. 4), which are an enhanced version of the original 80 K Oxford Stirling cooler shown in Fig. 1. The coolers cool two separate sensors to 80 K.[9] Although one displacer failed after 11,000 hours of operation, the compressors and second displacer remain running as indicated in Table 1.

1999—ASTER. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument was also launched on NASA's EOS Terra space platform in December 1999. It contains a pair of sensors each cooled by a Japanese 80 K Oxford-style Stirling cooler; one cryocooler was made by Fujitsu, and the other was made by Mitsubishi.[10] The coolers and instrument remain in continuous operation at this time.

2000—Hyperion. Launched on NASA's New Millennium EO-1 spacecraft in November 2000, the Hyperion instrument was a technology demonstrator to support evaluation of hyperspectral technology for future Earth observing missions. It has a single telescope and two spectrometers, one of which covers from 0.9 to 2.5 microns and is cooled to 110 K by a TRW mini pulse tube cryocooler (Fig. 3).[11] The cooler and instrument are currently in healthy operation, with plans to continue at least through 2007.

2001—SABER. Launched in December 2001 on the TIMED spacecraft, SABER uses a 10-channel IR radiometer operating from 1.27 to 17 µm to investigates the relative importance of radiative, chemical, and dynamical sources and sinks of energy in Earth's atmosphere. Its focal plane is cooled to 75K by a TRW mini pulse tube cryocooler (Fig. 3).

2002—RHESSI Gamma-Ray Spectrometer. Launched in February 2002, the Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) uses an array of nine large germanium gamma-ray detectors to observe solar flares from 3 keV to 25 GeV. The detector array is cooled to 75 K by a

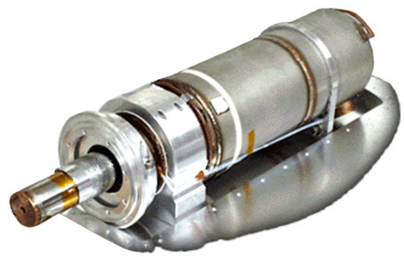

Figure 5. Sunpower M77B Stirling cryocooler mounted on the RHESSI radiator structure.

Figure 6. The flight NICMOS Cooling System in preparation for installation on HST.

Sunpower M77B Stirling cooler (Fig. 5) running at 65 K.[12] This mission represents the first application of a low-cost commercial cooler to achieve multi-year operation in space. Additionally, the cooler uses a heat intercept strap clamped to the Stirling coldfinger to provide simultaneous cooling to the instrument's higher temperature radiation shields at 155 K. This technique provides the dual-temperature capability of a two-stage cooler with an off-the-shelf single-stage cooler. Since launch, the cooler has maintained the gamma-ray detectors at or below their required 75K temperature, far surpassing the original on-orbit life goal of up to two years operation.[13,14] Though the detector temperature rose from 65 K to 75 K during the first two years of operation—apparently due to an increasing heat load on the cooler—when the spectrometer was vented to space in February 2004, the detector temperatures stabilized at 75 K and have held at this level ever since.

2002—NICMOS Turbo-Brayton Cryocooler. After the damaged solid-nitrogen dewar of the NICMOS instrument ran out of cryogen in January 1999, there was interest in restoring the instrument to life using a cryocooler. The 5 W 65 K turbo-Brayton cooler developed by Creare in the early 1990s was the only cooler candidate with the cooling power and near-zero vibration required for use on the Hubble Space Telescope (HST). By adding a turbine-pumped fluid loop to the turbo-Brayton cooler (Fig. 6), a system was devised to cool the instrument to 77 K via the cooling coils originally used to freeze the cryogen in the dewar.[15] Astronauts installed the cooler, fluid loops, and a capillary-pumped-loop (CPL) heat rejection system in February 2002. Prior to installation on HST, the cooler was flown in 1998 on STS-95 as part of the Hubble Orbital Systems Test (HOST). The cooler retrofit was a resounding success, and NICMOS is now expected to operate continuously throughout the remainder of Hubble's life.[16]

2002—AIRS instrument. JPL's Atmospheric Infrared Sounder (AIRS) instrument was launched in May 2002 on NASA's Earth Observing System Aqua platform. Its mission is to measure the atmospheric air temperature using a HgCdTe focal plane cooled to 58 K by a redundant pair of 55 K NGST (TRW) pulse tube coolers.[17,18] The instrument was designed and built under JPL contract by Lockheed Martin Infrared Imaging Systems, Inc. (now BAE Systems IR Imaging Systems). Initiated in 1994, the cryocooler development effort was the first space application to select a pulse tube cryocooler. The highly collaborative development effort, involving cryocooler development at TRW and extensive cryocooler testing at JPL and Lockheed Martin, has served as the pathfinder for much of the pulse tube development to date. The AIRS flight pulse tube coolers, shown in Fig. 7, were originally delivered to JPL for testing in October 1997, and completed spacecraft-level testing in September 2001. Since being launched in May 2002, the instrument has been in continuous operation gathering record breaking science.[19,20]

2004—TES Instrument. The EOS Tropospheric Emission Spectrometer (TES) instrument was the next large JPL cryogenic infrared instrument after AIRS. TES is designed to measure the state of the Earth's troposphere and was launched into polar orbit aboard NASA's third earth observing systems spacecraft (EOS-Aura) in July 2004. TES uses two 57 K NGST pulse tube coolers (Fig. 8) to cool two separate focal planes to 62 K. The two coolers are identical and are a variant of

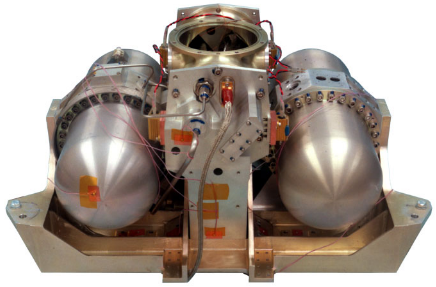

Figure 7. NGST AIRS pulse tube cooler system.

Figure 8. NGST TES pulse tube cryocooler.

the NGST AIRS pulse tube cooler, but configured with the pulse tube hard mounted to the compressor.[21,22] Since being launched in July 2004 the instrument and coolers continue to operate flawlessly.[23]

2004—HIRDLS Instrument. On the same Aqua spacecraft as the TES instrument, the High Resolution Dynamics Limb Sounder (HIRDLS) instrument was an international joint development between the USA and UK. It uses a single-stage Stirling cryocooler (Fig. 9) manufactured by Ball Aerospace under contract to Lockheed Martin. Though, during launch in July 2004 the instrument suffered an optical blockage that has severely restricted the acquisition of science data, the instrument has been in continuous operation with its infrared detectors cooled to 65 K by the HIRDLS cooler.[24,25] The cooler, similar in design to a two-stage 30 K cooler delivered to GSFC in 1997, incorporates radial position sensors for establishing and monitoring the clearance seals in the cooler prior to closeout of the housing.

2004—Messenger. NASA's first trip to Mercury in 30 years was launched in August 2004 with a small Ricor K508 tactical cryocooler (Fig. 10) used to cool its germanium gamma-ray detector to 90 K. The mission objective is to conduct a study of gamma-ray emissions from the Mercurian crust as well as solar winds and cosmic rays as it flies by the planet in 2008 and 2009, and eventually orbits around Mercury in 2011.

2005—CRISM. Launched on NASA's Mars Reconnaissance Orbiter spacecraft in August 2005, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument is designed to identify minerals on the surface of Mars, especially those likely to be formed in the presence of water. To cool the instrument's focal plane to 105 K, it uses a set of three parallel Ricor K508 tactical cryocoolers similar to the one shown in Fig. 10. Switching between the three cryocoolers is enabled by connecting each cooler to the focal plane through its own methane diode heatpipe which serves as a thermal switch. The coolers have been successfully turned on as part of the instrument checkout, but currently remain off awaiting completion of the spacecraft's aerobraking phase that is scheduled to end in early fall 2006. During the two to three-year life of the instrument, the coolers will be run one at a time, using the heatpipes to switch in another cooler when the proceeding one reaches wearout.

Figure 9. Ball Aerospace HIRDLS Stirling cryocooler.

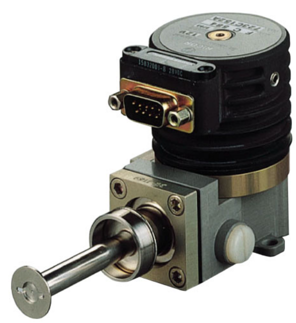

Figure 10. Tiny Ricor K508 tactical Stirling cooler.

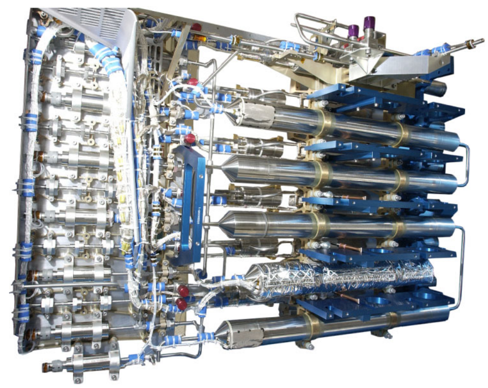

Figure 11. JPL 20 K Planck sorption cooler compressor system.

Figure 12. Sunpower M87 cryocooler used to cool the AMS-2 Charged-Particle Spectrometer.

CRYOCOOLER DEVELOPMENT FOR FUTURE NASA MISSIONS

Building on the cryocoolers used in the past NASA missions, a large number of new or enhanced cryocoolers—some with multiple coldheads and lower temperature ranges—have been developed, or are under development and test, for future missions. A particularly important technology push within NASA over the past several years has been to achieve flight-qualified long-life cryocoolers in the 6-20 K temperature range.[26,27] Four of the missions described below baseline these 6-20 K cryocoolers.

Because these coolers are largely funded by the flight project for which the coolers are intended, they are listed below by their mission association. To reflect their relative maturity, the applications are ordered by date of proposed launch—though launch date, from past experience, has a modest uncertainty.

Planck 20 K Sorption Cooler. For this first low-temperature cryocooler mission, JPL has developed and delivered a redundant pair of 1 watt at 18-20 K hydrogen sorption cryocoolers (Fig. 11) for the Planck spacecraft of the European Space Agency.[28] The objective of the Planck mission is to produce very high resolution mapping of temperature anisotropy in the cosmic microwave background (CMB) radiation. Planck's Low Frequency Instrument (LFI) will have an array of tuned radio receivers based on High Electron Mobility Transistors (HEMTs) to detect radiation in the range 30-100 GHz. These receivers will be operated at a temperature of about 20 K. The High Frequency Instrument (HFI) will use bolometers operated at 0.1 K for frequencies from 100 GHz to 900 GHz. The JPL hydrogen sorption cryocoolers have been designed to cool the LFI detectors to 18 - 20 K and to precool the Rutherford Appleton Lab (RAL) 4 K helium J-T that cools the 0.1 K dilution refrigerators in the HFI cooling system. The Planck sorption coolers are currently undergoing spacecraft integration in Europe in preparation for launch in 2007.[29]

OCO. The Orbiting Carbon Observatory (OCO) mission is designed to generate precise global maps of the abundance of CO_2 in the Earth's atmosphere as part of the study of the role of this principal driver of climate change. The OCO instrument payload consists of three classical grating spectrometers with their focal planes operating from 120 to 180 K. The cooling of the focal planes is carried out by a single NGST pulse tube cryocooler of the type flown on TES in 2004 (see Fig. 8). The project is a collaborative effort with Hamilton Sundstrand Sensor Systems providing the spectrometers, Orbital Sciences Corporation providing the spacecraft, Space Dynamics Lab providing the focal-plane integration, and the Jet Propulsion Laboratory providing overall management and the cryocooler system. The instrument is scheduled for integration and test in fall 2006, and launch is scheduled for 2008.[30]

AMS-2 Charged-Particle Spectrometer. The Alpha Magnetic Spectrometer−2 (AMS-2) instrument has been designed to be mounted on the International Space Station and use a large superconducting magnet assembly to search for antimatter nuclei from cosmic sources. To help cool the outer thermal shield of its 2500 liter helium tank, the design uses a set of four Sunpower M87 coolers of the kind shown in Fig. 12. With a mass of over 2000 kg for the superconducting

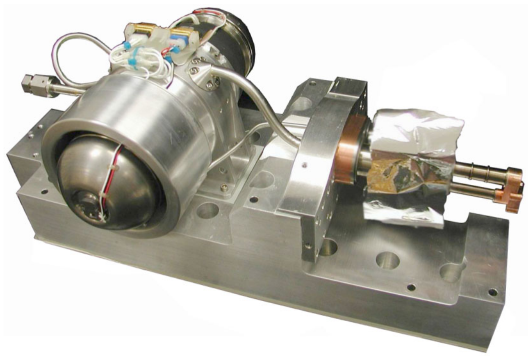

Figure 13. Lockheed Martin 55 K/140 K GIFTS Cryocooler.

Figure 14. NGST 2-stage 180 K/55 K cryocooler.

magnets and helium tank, it is extremely challenging to provide enough thermal isolation to allow a 3-year lifetime, even with the coolers operating at nominal power. The four coolers, each capable of 6 to 7 watts of heat lift at 77 K, will be run at reduced power to provide a total of 20-25 W of cooling on the shield at 77 K. The coolers, operating in the stray field of the magnet system, are being specially qualified for operation in a magnetic field of 750-1000 gauss.[31,32]

Gifts. The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) instrument is an advanced weather observing instrument originally scheduled to be launched on NASA's New Millennium Earth Observing 3 (EO3) spacecraft in 2005. Now looking for an alternate launch opportunity, the GIFTS-IOMI instrument is designed to collect atmospheric data to help scientists analyze temperature, wind patterns, cloud cover, water vapor, and pollutants in the Earth's atmosphere. GIFTS includes a new two-stage Lockheed Martin pulse tube cryocooler (Fig. 13) to cool the spectrometer's focal planes and optics to 55 K and 140 K, respectively; it also contains many other new instrument technologies. Presently the Lockheed cryocoolers are undergoing instrument integration testing at USU's Space Dynamics Lab as described in a companion paper.[33]

ABI. NOAA's POES (polar-orbiting) and GOES (geosynchronous) spacecraft provide the familiar satellite weather photos seen nightly on television news broadcasts. The next generation of GOES spacecraft will incorporate major upgrades to the instruments, including a new Advanced Baseline Imager (ABI) developed by ITT for NASA. ABI will have significantly better spatial, spectral, and temporal resolution than the current imager, partly due to the use of colder detectors in the focal planes. A two-stage split pulse tube cooler manufactured by Northrop Grumman will cool the Mid-wave/Long-wave IR focal plane to 60 K, and the Visible/Near IR focal plane to 200 K. The low-temperature cryocooler stage is a standard NGST HEC cryocooler, tuned for 45 K. A transfer line from the HEC compressor drives a remote stage, operating at 183 K. Except for the transfer line routing, the design is identical to the cooler shown in Fig. 14. The life test and prototype models are currently in assembly at NGST, with the first flight unit scheduled for delivery in Sept 2007.

MIRI on JWST. In 2002, NASA initiated the Advanced Cryocooler Technology Development Program (ACTDP) as a strategic technology investment within the Terrestrial Planet Finder project, to develop long-life cryocoolers for cooling remote space-observatory instruments to 6-18 K.[26,27, 34] The resulting successful demonstrations of 6-18 K cryocooler technology led to the decision in spring 2005 to use an ACTDP cryocooler to cool the Mid Infrared Instrument (MIRI) to 6 K on the James Webb Space Telescope (JWST). JWST is currently scheduled for launch in 2014 as the NASA replacement for the Hubble Space Telescope, which has been in orbit since 1990. After a competitive selection process in winter 2006, the Northrop Grumman ACTDP concept[35,36], shown in Fig. 15, was selected for the flight MIRI cooler. The two other ACTDP cooler concepts, a hybrid Stirling J-T cooler[37,38] by Ball Aerospace (Fig. 16) and a four-stage pulse tube cooler[39,40] by Lockheed Martin (Fig. 17), are under active consideration for other low-temperature missions such as TPF and Constellation-X, which are described next.

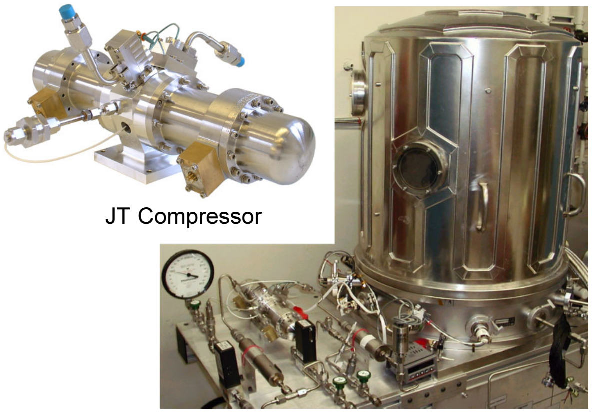

Figure 15. Northrop Grumman ACTDP J-T Compressor and system testing.

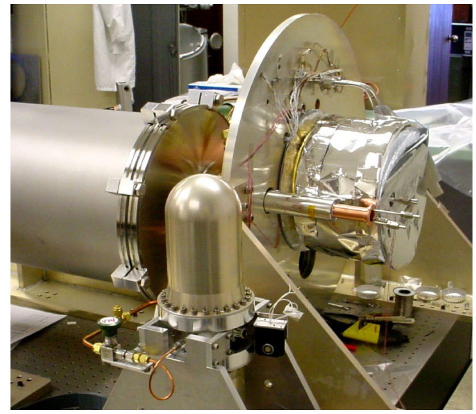

Figure 16. Ball ACTDP hybrid Stirling-JT cryocooler undergoing system testing.

Terrestrial Planet Finder (TPF). Credited with the highly successful development of the ACTDP cryocoolers, the TPF mission is designed to search for Earth-like planets around nearby stars by providing the first direct imaging of such planets and performing studies of their planetary atmospheres. To meet these objectives, one system architecture that has been studied is a formation-flying nulling infrared interferometer. This would involve infrared sensors at temperatures similar to those of the MIRI instrument on JWST, and like JWST, the optics on each spacecraft would require passive cooling to 30−50 K. For such a interferometric system, observing in the infrared from ~5-20 microns, cooling the detectors to around 6 K would be required over a mission lifetime of 5 to 10 years. Also like JWST, TPF is likely to require placement of the room-temperature, vibration-prone refrigerator compressors on the main spacecraft bus, possibly meters away from the cold and vibration-stabilized optics and detector module.[27]

Constellation-X Mission. The Constellation-X mission complements JWST and TPF by working in a different wavelength region of the electromagnetic spectrum—x-rays. It supports NASA's Beyond Einstein Program by focusing on unlocking the mysteries of black holes, galaxy formation, and the still undetected matter in the Universe. It consists of a group of four spacecraft, each carrying two x-ray telescopes. The key science detectors in Con-X's Spectroscopy X-ray Telescopes (SXT) are microcalorimeters. These must be maintained at 50 mK to achieve the very high spectral resolution required from 0.3−10 keV. To cool the detectors, a multistage refrigeration system is envisioned, consisting of a 6 K/18 K ACTDP cryocooler to cool from room temperature down to 6 K, followed by a multistage magnetic refrigerator to cool from 6 K to 50 mK.

This Continuous Adiabatic Demagnetization Refrigerator (CADR) needed to bridge the gap from sub-Kelvin to 6 K is under development at NASA GSFC with a goal of 10 μW of cooling at 50 mK. The CADR uses multiple stages, one of which cools the load while the others periodically

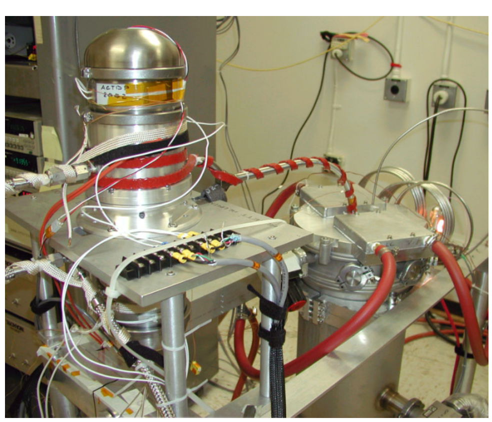

Figure 17. Lockheed Martin ACTDP multistage pulse tube in system test.

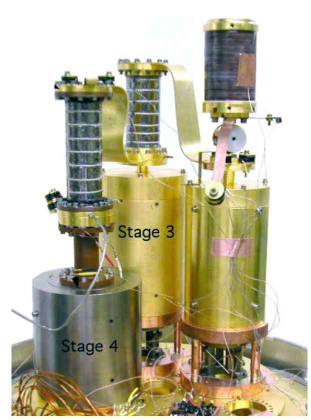

Figure 18. Sub-Kelvin ADR refrigerator under development for Constellation-X.

transfer heat to the 6 K heat sink. The architecture is very flexible, allowing stages to be added at the low end to achieve lower operating temperature, or at the high end to increase the heat rejection temperature. Over the past few years a 3-stage ADR that uses a superfluid helium bath as a heat sink has been assembled and tested. A 4-stage ADR that can operate with a 4.2 K helium bath is also under development.[41,42]

SUMMARY

Mechanical cryocoolers represent a significant enabling technology for NASA's Earth and Space Science missions. Since 1991, over 20 cryocoolers have been launched into space on NASA missions—12 of which are still operating in orbit on multi-year missions—and several more are scheduled for launch in the next few years. The largest utilization of coolers over the last 15 years has been for instruments operating at medium to high cryogenic temperatures (55 to 150 K). For the future, important new developments are focusing on the lower temperature range, from 6 to 20 K, in support of studies of the origin of the Universe and the search for planets around distant stars. NASA's development of a 20 K cryocooler for the European Planck spacecraft and a 6 K cryocooler for the MIRI instrument on JWST are examples of this important class of future cooler applications.

ACKNOWLEDGMENT

The work described in this paper was carried out by NASA Centers and contractors including the Jet Propulsion Laboratory, California Institute of Technology and the NASA Goddard Space Flight Center; it was sponsored by the National Aeronautics and Space Administration.

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