Cryogenic Technology for CMB-Pol: Mechanical cryocoolers for the 4K to 200K temperature range

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Abstract. Future space telescopes such as CMBPol, SAFIR, DARWIN, SPICA and XEUS will require a combination of mechanical cryocoolers and passive cryocoolers to provide the necessary refrigeration for cooling detectors, telescopes and sunshades reliably over the life of the mission. Mechanical cryocoolers represent a significant enabling technology, especially at the lower temperatures where the passive coolers' effectiveness is limited and their accommodation on spacecraft is difficult. At higher temperatures the mechanical cooler can be seen as enhancing mission performance in providing extra cooling of sunshades, the interception of heat from the many sensor leads or the current leads of sub-Kelvin magnetic refrigerators, or in cooling of vapor shields of cryogen tanks to eliminate, or at least minimize, boil-off from the cryogen tanks. Great strides have been made to improve cryocooler efficiencies to increase their capacity and reduce their mass to better accommodate them on missions. The demonstrated high reliability and ever increasing efficiency of mechanical coolers have opened many new uses for active cryocoolers on space missions. However even further enhancements will be necessary to meet the cooling demands for the great astronomy observatories of the future.

1. Introduction

There have been some significant advancements in cryocooler development since Ron Ross presented a paper entitled "Aerospace Coolers: A 50-Year Quest for Long-life Cryogenic Cooling in Space" at the Cryogenic Engineering Conference in 2005[1]. Widely variable flight payload requirements have driven the cooler design and development in all directions. There has been a push for both lower and higher cooler operating temperatures, with both larger and smaller scale heat lift capability, and the miniaturization of cryocoolers with the incorporation of MEMs technology. Active development work continues for improved mechanical cooler and electronics efficiencies, reduced mechanical cooler parts count for lowering cost, building larger drive electronics towards the kilowatt size, and also simplifying electronics by removing unnecessary control loops for small coolers.

The proven high reliability and the increased efficiency of the mechanical cryocoolers continue to generate new uses for active refrigeration, including vapor shield cooling of cryostats, zero boil-off for stored cryogens, LOX production for planetary missions, and sunshade and telescope cooling applications using active coolers. The push in mechanical cryocooler development has been broad, with a mix and match of cooler types (Stirling/pulse tube, J-T, reverse turbo-Brayton) to fill in the parameter space (temperature, size, capacity and cost) of mechanical cryocoolers.

The intention of this paper is to identify some of the more recent technology development areas that may prove beneficial to future Astrophysics missions such as CMBPol. This paper is not intended to indentify and include all cooler developments, and no slight is intended if some significant cooler development efforts have been unintentionally omitted.

2. Cryocooler systems on present space missions

There are currently more than 31 known long-life coolers successfully operating in space [1-3]. Three additional coolers were still operating when the mission ended. The high reliability of cryocoolers has allowed many missions to be extended far beyond their original intended life. Among them, the Rutherford Appleton Lab (RAL) cooler on ATSR-2, which launched in 1995, has been operating for 13 years. The two TRW (NGST) mini pulse tube coolers have been operating for more than 10 years on the C/X mission since its launch in 1998. The majority of the flight instruments to date require cooling at medium to high cryogenic temperatures (50-150K) which has been accomplished using single stage coolers.

The more recent launch of the Japanese AKARI (ASTRO-F) infrared astronomy satellite in February 2006 has been flying two 2-stage Stirling coolers to cool the inner radiation shields for the AKARI cryostat to prolong the superfluid helium supply. Each cooler was providing 350mW of refrigeration at 40K using 50W input power from the bus [4]. While AKARI ran out of its cryogen in August, 2007, the 35-K Stirling coolers have enabled the mission observations to continue at the shorter wavelengths.

3. Cryocooler development for near-term missions

Building on the cryocoolers used in past missions, a large number of new or enhanced cryocoolers- some with multiple coldheads and many with lower operating temperatures ranges- have been developed, or are under development and test, for future missions. The majority of these are focusing on the lower operating temperatures from 6-20K.

3.1. SMILES

Sumitomo Heavy Industries built the 4.5K Joule-Thomson (J-T)/Stirling cooler for the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES), to cool SIS mixers and low-noise HEMT amplifiers [5]. The SMILES 4.5-K cooler consists of a ^{4}He Joule-Thomson lower stage to produce 20mW of cooling at 4.5K and a 2-stage Stirling precooler at 20K that also cools HEMT amplifiers at 20K and at 100K. (The 2-stage Stirling cooler is the same as the coolers used on AKARI). The total system input power for the cooler is on the order of 140W. SMILES is to be operated aboard the Japanese Experiment Module (JEM) of the International Space Station (ISS). This instrument was to be delivered to the ISS in 2007, but shuttle delays forced the postponement of the mission launch to 2009.

3.2. MIRI

The NGST hybrid J-T/Pulse Tube cryocooler for the Mid Infrared Instrument (MIRI) on the James Webb Space Telescope (JWST) is designed to cool the 90-kg MIRI instrument to 7K [6]. Current cooling requirements for the cryocooler are for 70mW @ 6K along with 70mW @ 18K for 400W of system input power. The cryocooler consists of a 3- stage pulse tube cooler to reach 17K, with a J-T circuit to provide the 6-K refrigeration to the MIRI instrument. The pulse tube cooler is located on the JWST bus, with the MIRI instrument located within the JWST Instrument Module behind the telescope, about 8 meters from the precooler. MIRI will fly a single mechanical cryocooler system with block-redundant drive electronics. This cooler has been demonstrated to a TRL level of 6 in 2007. JWST is scheduled for launch in 2013.

The MIRI cryocooler was selected from the coolers being developed in the Advanced Cryocooler Technology Development Program (ACTDP) for TPF, JWST and Con-X [7]. Three ACTDP cooler development efforts were being conducted: two hybrid systems using J-T/Stirling and J-T/pulse tube combinations, and a four-stage pulse tube with an optional integral flow loop. The two hybrid systems used a 3-stage Stirling (or pulse tube) cooler to precool the J-T circuit to less than 18K, and a single stage of compression for the J-T circuit provided a sufficient compression ratio to achieve the required 6K refrigeration. All three ACTDP vendors demonstrated the feasibility of operating the ACTDP coolers at 4K through the use of ^{3}He as the working fluid in place of ^{4}He. The ACTDP program ended with the transition into the flight cooler program for JWST/MIRI.

3.3. Planck 20K Sorption Cooler

This hydrogen sorption cryocooler has been designed to deliver approximately 1 watt of refrigeration at 18-20K for the Planck spacecraft to cool the 20K HEMT amplifiers for the Planck Low Frequency instrument (LFI) (~80% of the total heat lift) and to simultaneously provide the pre-cooling for the RAL 4.5K J-T refrigeration stage in the Planck High Frequency Instrument (HFI) m(~20% of the total heat lift). The 4.5K J-T cooler is the upper stage precooler for the HFI 0.1K dilution refrigerators. The Planck sorption cooler requires a total input power of 470W (End of Life), and relies on passive cooling support at three passive radiators (170K, 100K and 60K) to provide pre-cooling to 60K prior to a final counterflow heat exchange and expansion through the J-T valve to produce the 18K refrigeration. The redundant Planck sorption cryocoolers have been integrated in to the Planck spacecraft in preparation for the 2008 launch [8].

3.4. GIFTS

The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) instrument, built in partnership between the Space Dynamics Lab (SDL) and the NASA Langley Research Center, is an advanced weather observing instrument that was originally scheduled to be launched on NASA New Millennium Earth Observing (EO3) spacecraft in 2005. It is still looking for an alternate launch opportunity. The GIFTS instrument uses a two-stage Lockheed Martin pulse tube cooler to cool the spectrometer’s focal plane to 55K and the optics to 140K. System-level testing of two-stage pulse tube cooler integrated into the GIFTS instrument was performed at SDL [9].

3.5. ABI

The next generation of the NOAA GOES (Geosynchronous) weather satellite will replace the passive cryocooler used on previous NOAA satellites with an active cryocooler. The Advance Baseline Imager (ABI) uses a pulse tube cooler manufactured by NGST with two separate cold heads. One cold head cools the Mid-Wave/Long-Wave IR focal plane to 60K, and the remote second coldhead is used to the optics and the Visible/Near IR focal plane to 200K. The Advance Baseline Imager will use redundant cryocoolers with each of its instrument packages [10].

3.6. AMS-02

The Alpha Magnetic Spectrometer-02 (AMS-02) instrument will be flown as an attached payload to the International Space Station. The instrument uses 4 Sunpower M87 Stirling coolers to maintain the outer vapor-cooled shield of the 2500 liter helium dewar at a temperature of 80K to extend the mission duration. The baseline performance of the coolers is a total of 16 watts of heat lift at 80K for 400 W of input power [11, 12].

4. Current cryocooler research and development efforts

4.1. 2K to 6K coolers

4.1.1. Hypres. There have been recent advances in 4K coolers for cooling ground-based superconducting electronics for high speed digital communications in the wireless communications field. The Hypres cooler built by Lockheed Martin presently provides 35mW of refrigeration at 4.5K with additional refrigeration for thermal shielding available at the upper stages: 50mW @ 10K, 150mW @ 25K and 5W @ 70K for 725 W of compressor power [13]. The Hypres refrigeration goal of 100mW @ 4.2K will require further technology advances to improve the cooler efficiency. While the Hypres program is a US Navy and DARPA program and not a space flight program, the development of this cooler will be a benefit to space cooler programs as well.

4.1.2. *University of Twente 4.5 K sorption cooler for DARWIN.* This sorption cooler consists of a cold hydrogen J-T stage operating from 80K to 14.5K and a helium J-T stage operating from 50K and delivering 5mW @ 4.5K. The 2 cooler stages need about 3.5W of total power and are sunk at two passive radiators at temperatures of about 50 and 80K [14]. The 50-K radiator area needed for the sorption cooler is about $2m^2$/mW of cooling at 4.5K [15]. The sorption cooler was tested in the laboratory using a Thales 5W at 50-K Stirling cooler to represent the passive cooler. The total refrigeration package including the 50-K cooler required less than 150W of input power and had a mass of less than 20kg. This laboratory test demonstrated that the cooler package could meet the Darwin power requirements of 200 W.

4.1.3. SPICA. The Japanese are working to develop the 20K, 4.5K and 1.7K coolers needed for the SPICA astronomical mission. The Japanese have made performance enhancements to the SMILES 4.5K cooler to increase the 4.5K capacity to 50mW (compared to 20 mW for SMILES) for a system input power of 145W. Much of the performance improvement was a result of the improvements to the 20K precooler; the cooler is now capable of producing 200mW of refrigeration at 16K (or 325mW @ 20K) plus 1W at 80K for under 90W of input power [16]. Substitution of ^{3}He in the J-T circuit has enabled them to demonstrate 16mW of cooling at 1.7 K [17].

4.2. 10K to 80K Multi-Stage Coolers

The development effort continues for a number of high capacity multi-stage cryocoolers for cooling VLWIR sensors planes at 10K, LWIR sensors at 35K or even MWIR sensors above 50K, while having a large capacity upper refrigeration stage for supporting thermal shielding and/or optical bench cooling. The 10K coolers have also become the precooler for 4K refrigerators. The large refrigeration requirements have led to the manufacture of large input capability of the compressors (up to 800W), necessitating the need for large throughput cooler drive electronics as well. A number of these cooler developments have been listed in the table below.

4.3. 80K-100K Coolers

The use of large scale refrigerators will be required for cryogen storage on long duration space missions. High capacity mechanical coolers will be needed to prolong mission life by minimizing boil- off and providing stable pressurization of the cryogen tank. Large scale refrigeration on the order of 10s of watts may be needed at 25K for hydrogen and at 90K for oxygen. Planetary or lunar in situ oxygen production may also require large scale refrigerators.

Lockheed Martin is working on a several programs for large scale coolers. One cooler program is for a zero boil-off of propellant tanks that has demonstrated 30W @ 95K [18]. This cooler has also been suggested as a lunar LOX liquefier that can provide 40W@95K. Lockheed Martin is in the build phase of another cooler that will provide 25W of refrigeration at 70K [19]. Both coolers are presently in the build phase.

NASA has had a Small Business Innovative Research (SBIR) Subtopic call for Zero Boil-Off Cryocoolers capable of providing 10W of refrigeration at 20K. Creare, in a Phase 1 SBIR effort, has provided some initial design work for a 10W @ 20K reverse turbo-Brayton cooler [20].

Thales Cryogenics (Eindhoven) is developing a 18W @ 80K (or 5W @ 50K) pulse tube cooler for future ESA projects [21]. Thales has redesigned their military tactical coolers into long-life coolers for space applications.

5. Cooler performance summary

The table below summarizes most of the cryocoolers that have been discussed above, and in addition includes some of the larger capacity cryocoolers that have flown or that are in development. The Compressor Power is the input power to the cooler compressor from the drive electronics; the System

Table. Summary of performance characteristics for selected cryocoolers.

Cooler [Ref]	Type	Cold Stage	Upper stages	Input Power (W) Compressor	Input Power (W) System	Mass (Kg)	TRL
JEM/SMILES [5]	JT/Stirling	.030W @ 4.5K	200mW @ 20K, 1W @ 100K		140	65 TMU	8
JAXA/ SPICA [16,17]	JT/Stirling	.050W@4.5K	N/A		145		5
U of Twente DARWIN [14,15]	He/H_2 sorption	.005W at 4.5K	N/A	4 at 50K		8.3 TMU	4
LM Hypres [13]	4-stage pulse tube	.035W @ 4.5K	50mW@10K, 160mW@25K, 5.2W@66K	725		21 TMU	5
MIRI [6]	JT/ pulse tube	.070W@6K	70mW@18K	320	400	79 TMU + elec	6
LM 10K [22]	3-stage pulse tube	.260W@10K	10.4W@85K	600		16 TMU	4
NGST 10K [23]	3-stage pulse tube	.250W@10K, or .525W@15K	1W@51K	370		18.7 TMU	6
JPL Planck Sorption [8]	JT/ H2 sorption	.963W@18K	Heat rejected to radiator <60K	426			7
JAXA AKARI [4]	2-stage Stirling	.200W@20K	N/A		90		9
LM SBIRS Low [24]	2-stage pulse tube	1.7W@35K	17W@85K	610		23.8 TMU	5
Creare [25]	1-stage reverse turbo-Brayton	3W @ 35K		350		10 TMU	4
Creare HCC [25]	2-stage reverse turbo-Brayton	2W @ 35K	20 W @ 85K	490		18 TMU	4
Ball 35K HCC [26]	2-stage Stirling	1.5W@35K	8.5W@85K	200		14.4 TMU	4
NGST 35K HCC [27,28]	2-stage linear pulse tube	2.25W@35K	17.4W@85K	500		14.3 TMU	6
Raytheon RSP2 [29]	2-stage Stirling/ pulse tube	2.6W @ 35K	16.2W @ 85K	513		20 TMU	4
NGST ABI [10]	2 parallel pulse tube stages	2.3W@53K	6.7W@183K		170	5.5 TMU, 3.8 elec	7
LM GIFTS [9]	2-stage pulse tube	1.5W@53K	8W@140K		180	6.3 TMU, 4.2 elec	8
LM DARPA 10W [30]	1-stage pulse tube	9.6W@ 77K			220	12 TMU	4
Thales [22]	1 stage Stirling	5W@50K or 18W@80K		350			4
Creare NICMOS [31]	1-stage reverse turbo-Brayton	7W@72K			375	18.5 TMU	9
NGST HEC [32]	1-stage pulse tube	10W@95K		123		4.1 TMU, 3.3 elec	9

Power is the input power to the cooler drive electronics. The cooler mass is provided when known. TMU refers to the thermal mechanical unit. The estimated TRL level is also given for the coolers under development. As is often the case, the cooler customer (particularly NASA or the DoD) will fund several cooler manufacturers simultaneously to develop coolers up to a TRL level of 4 or 5, readying the coolers for selection to a particular flight program. Once selected, the flight program will carry the cooler development through a final design modification as necessary to meet the flight program cooling requirements, build the cooler flight electronics and flight qualify the cooler subsystem.

Figures 1 and 2 show the performance characteristics of a variety of coolers that have been developed and reported on over the years. Attempts have been made to include only the most recent and best data for each of the coolers. The data points/curves generally represent published data, although a few data points were provided through private communication. Labeling of the data points with the identification of the coolers manufacturers were not included to help keep the plot uncluttered. Figure 1 shows the specific power (the compressor input power required to provide a watt of cooling) for the cold stage only, even if the cooler has multiple stages. The Specific Power curve fit has been biased towards the low values to reflect this. The specific power for multi-stage coolers is generally higher because a significant fraction of the compressor power may be used to provide additional heat lift at the upper stages. It needs to be pointed out that the specific power refers to the power into the cooler compressor itself, and not the power into the cooler drive electronics. Unless the cooler is carried into a flight build, there is generally only laboratory electronics to drive the cooler. To get an estimate of the system level specific power one can assume the cooler flight electronics is 80-85% efficient, with a few additional watts of overhead (or tare) power to power the control circuits.

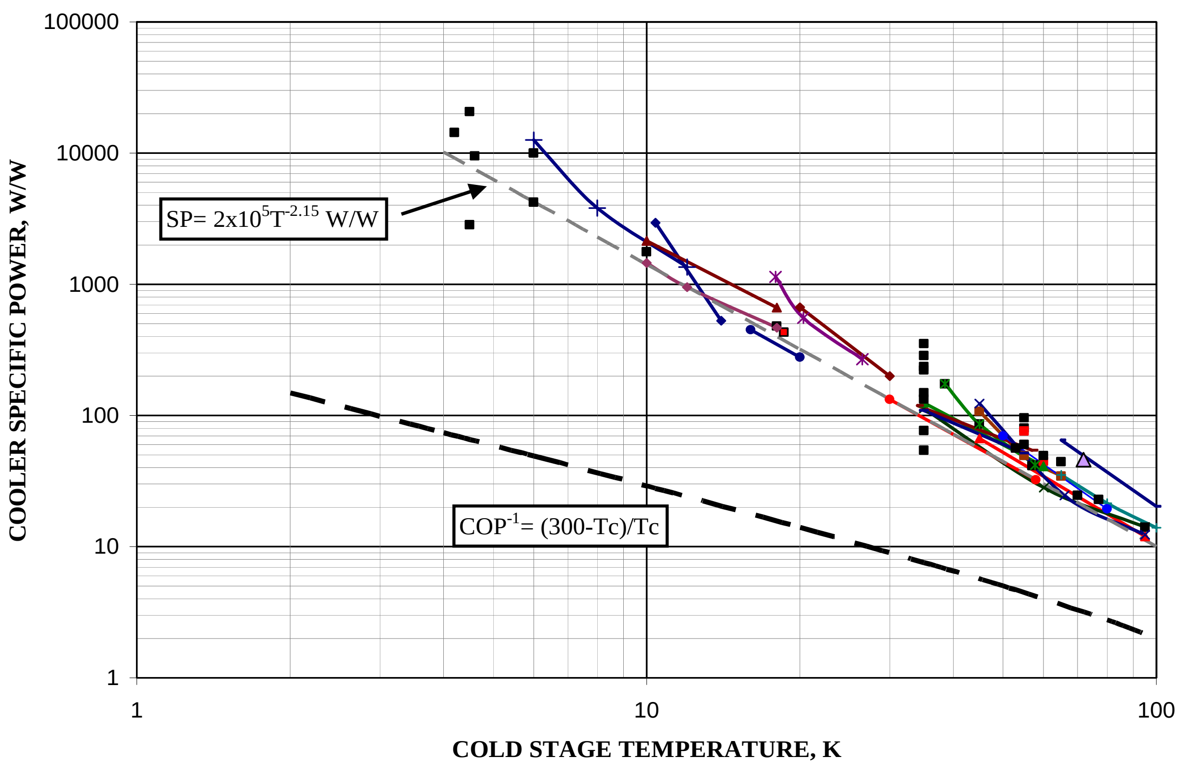

Figure 1. Specific power of single and multi-stage coolers based on the total power into the cooler but only on the heat lift at the cold stage. The ideal Coefficient of Performance (COP) is shown for comparison.

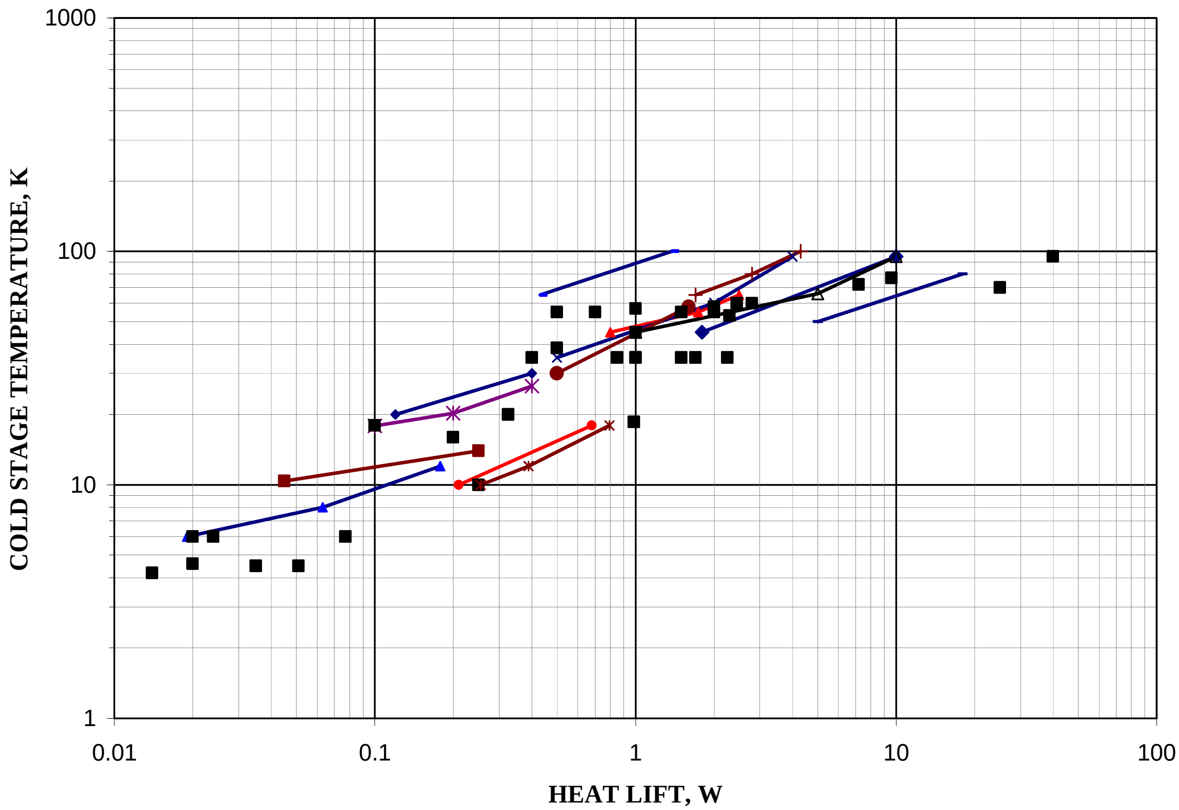

Figure 2. Heat lift capacity of the coldest stage of selected single and multi-stage coolers.

Figure 2 shows the cold stage refrigeration capacity as a function of operating temperature for a number of the coolers. There has been a general trend towards larger heat lift capability as the cooler efficiencies have improved.

6. Interfacing active coolers with passive cryocoolers

Cooling chains have long been the subject of study for all future astronomical missions. The requirement for the spacecraft to provide kilowatts of electrical power to handle the cooling of bolometers necessitates the use of passive cooling to ease the power burden. However passive cooling by itself is insufficient if temperatures below about 7K are desired, and so a combination of active and passive cooling must be used. The improved efficiency and reliability of the coolers are providing more options to ease the decision making process. The mechanical coolers can be used to cool telescopes and sunshades in addition to the detectors. And vice versa, the sunshades can be used as passive radiators to enhance the cold-end performance of mechanical cooler.

6.1. Heat Intercept

A cryocooler's refrigeration capacity and operating temperature can be enhanced significantly by using passive cooling to remove heat from the coldfinger of the cooler. The intermediate-temperature radiator is attached to a point partway down the length of the coldfinger regenerator, for example at one of the upper stages of a multi-stage coldfinger, to carry away a large fraction of the heat that comes from the warm end of the coldfinger. The location of the coldfinger intercept point, and the temperature of the radiator, determines the performance improvements realized. Early laboratory heat intercept tests with single stage coolers demonstrated a doubling of the cooler performance, either by doubling the heat life capability or by halving the input requirement for the original heat lift, if the coldfinger were tied to an intermediate-temperature radiator at ~120-160K [23-26]. The Planck hydrogen sorption cooler relies on this technique to remove heat at temperatures of 170K, 100K and 60K to enable it to produce the necessary 18-K refrigeration for the Planck mission.

Two independent studies have been conducted on the effect of a heat interceptor on a two-stage cooler. RAL studies on a 2-stage BAe (now Astrium) Stirling cooler found they were able to increase the 20K refrigeration from 140mW to 220K when intercepting heat at the 1st stage of the coldfinger [27]. They were also able to simultaneously reduce the compressor power by 11%. However they found little performance improvement in reducing the 1st stage temperature below 100K from its nominal temperature of 130K without the intercept. In the other study, CEA/SBT studied the effects of using passive radiators at 50K and 80K for heat intercepts on a 20K 2-stage pulse tube [28]. A G-M cooler was used in laboratory tests to simulate the radiators. The G-M cooler was able to remove 1.7W of heat from the pulse tube regenerator at 80K, or 2.7W at 50K, which resulted in lowering the ultimate no-load temperature of the coldtip (to 13.5K with the 50K heat intercept), but there was little net improvement in refrigeration capacity at the 20K coldtip temperature. This seems to corroborate the RAL results that state there is little improvement in trying to cool the 1st stage below 100K. Further studies are needed to better understand and characterize the cooler performance results.

6.2. Distributed cooling

The need to cool broad areas of sensor arrays, multi-segmented telescopes or sunshades will require the need for distributed cooling either through heat spreading with high conduction materials or by using the helium fluid flow circulation techniques. Development of distributed cooling techniques has been getting much attention from the cryocooler community as they work to satisfy the needs of future space missions. Several different techniques are being pursued which deliver a rectified flow gas stream to the device being cooled. Both single phase and two-phase fluid flows are being considered. Ball Aerospace uses a neon J-T circuit at the base of their 2-stage Stirling cooler to provide 2-phase flow to cool a remotely located device [26]. This circulating flow loop also utilizes a thermal storage unit in the JT circuit to enable extra cooling during peak load periods. Creare and Raytheon teamed together to place a Reverse Turbo Brayton cooler at the cold end of the 2-stage Raytheon cooler to provide either a cold circulating flow loop and/or an additional stage of refrigeration [39]. U of Wisc, in collaboration with Atlas Scientific, is developing a cold rectified-flow loop that siphons part of the cold helium gas from the end of a 2-stage pulse tube to provide cold circulating gas [40]. These uni-directional fluid flow loops can deliver refrigeration over long distances to allow a vibration-free environment where required, keeping the mechanical cooler far removed from the sensor area. The fluid loops can adsorb the heat either via long heat exchanger lengths or through multiple parallel flow paths to minimize the temperature gradients in the object being cooled.

7. Summary

There are a variety of cryogenic cooling techniques available that span a wide range of temperatures and heat lift capabilities from which to select the cryocooler architecture best suited for astrophysics missions. The large, yet incomplete, list of mechanical cryocoolers mentioned above provides an abundance of possibilities. The coolers will be able to cool sunshades to maintain low and steady temperatures, to cool telescopes, and to provide the pre-cooling necessary for the sub-Kelvin coolers. The readiness of these cryocoolers to fit into the particular mission's cooling architecture will depend on the mission's refrigeration requirements; these requirements will determine whether the coolers are ready for flight qualification or whether additional modifications of the cryocoolers may be required for varying the heat lift capability or the temperatures at which the cooling is provided. Closely related to the cooler development for a specific mission will be the need to validate the integration technology readiness for interfacing the coolers with large sensor arrays, telescopes and/or sunshades.

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9. References

[1] Ross R G, Jr 2007 Aerospace coolers: a 50-year quest for long-life cryogenic cooling in Space *Cryogenic Engineering: Fifty Years of Progress* ed K Timmerhaus and R Reed (New York: Springer Publishers) chapter 11 pp 225-84

[2] Ross R G Jr. and Boyle R F 2007 An overview of NASA space cryocooler programs – 2006," *Cryocoolers 14* ed S. Miller and R G Ross, Jr (Boulder, CO: ICC Press) pp 1-10

[3] Gibson A F, Bradshaw T W and Linder M 2008 Heritage overview: 20 years of commercial production of cryocoolers for space *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference - CEC*, Vol. 53 (Chattanooga, TN, 16-20 July 2007) (*AIP Conference Proceedings* vol 985) ed J G Weisband, et al (New York: Amer. Inst. of Physics) pp 493 --505

[4] Hirabashi M, et al 2008 Thermal design and it on-orbit performance of the AKARI cryostat *Cryogenics* **48** 189 -97

[5] Narasaki K, et al 2004 Development of cryogenic system for SMILES *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC*, Vol. 49 (Anchorage, AK, 22-26 September 2003) (*AIP Conference Proceedings* vol 710) ed J Waynert, et al (New York: American Institute of Physics) pp 1785--94

[6] Durand D, Colbert R, Jaco C, Michaelian M, Nguyen T, Petach M and Tward E 2007 NGST Advanced Cryocooler Technology Development Program (ACTDP) cooler system *Cryocoolers 14* ed S Miller and R G Ross, Jr (Boulder, CO: ICC Press) pp 21 -5

[7] Ross R G, Jr and Johnson D L 2006 NASA's advanced cryocooler technology development program (ACTDP) *Adv. in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC,:* Vol. 51 (Keystone, CO, 28 Aug-2 Sept, 2005) (*AIP Conference Proceedings* vol 823) ed J G Weisend, et al (New York: American Institute of Physics) pp 607 --14

[8] Pearson D, Zhang B, Prina M, Paine C, Morgante G, Bhandari P, Bowman R and Nash A 2007 Flight acceptance testing of the two JPL Planck sorption coolers *Cryocoolers 14* ed S Miller and R G Ross, Jr (Boulder, CO: ICC Press) pp 497-504

[9] Jensen S M, Hansen G, Nast T, Roth E and Clappier R 2007 Thermal/mechanical system level test results of the GIFTS 2-stage pulse tube cryocooler *Cryocoolers 14* ed S Miller and R G Ross, Jr (Boulder, CO: ICC Press) pp 65-74

[10] Colbert R, Pruitt G, Nguyen T, Raab J, Clark S and Ramsey P 2009 ABI cooler system protoflight performance *Cryocoolers 15 (Long Beach, CA, 9-12 June 2008)* ed S Miller and R G Ross,Jr (Boulder, CO: ICC Press) (In Press).

[11] Breon S R, Shirey K A, Banks I S, Warner B A, Boyle R F andMustafi S 2003 Operation of a Sunpower M87 cryocooler in a magnetic field *Cryocoolers 12* ed R G Ross, Jr (New York: Plenum Publishers) pp 761-9

[12] Banks S, Breon S and Shirey K 2004 AMS-02 cryocooler baseline configuration and EM qualification program *Cryogenics* **44** 551 -7

[13] Nast T, Olson J, Champagne P, Mix J, Evtimov B, Roth E and Collaco A 2008 Development of a 4.5K pulse tube cryocooler for superconducting electronics *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC*, Vol. 53 (Chattanooga, TN, 16-20 July 2007) (*AIP Conference Proceedings* vol 985) ed J G Weisband, et al (New York: American Institute of Physics) pp 881 – 6

[14] Doornink D J, Burger J F and ter Brake H J M 2008 Sorption cooling: a valid extension to passive cooling," *Cryogenics* **48** 272-9

[15] Burger J, Holland H, Meijer R, ter Brake H J M, Doornink J and Sirbi A 2009 Further developments on a vibration-free helium-hydrogen sorption cooler *Cryocoolers 15* (Long Beach, CA, 9-12 June 2008) ed S. Miller and R G Ross, Jr (Boulder, CO: ICC Press) (in press)

[16] Sugita H et al 2006 Cryogenic infrared mission “JAXA/SPICA” with advanced cryocoolers *Cryogenics* **46** 149-157
[17] Sugita H et al 2008 Development of mechanical cryocoolers for the Japanese IR space telescope SPICA *Cryogenics* 48 258-66
[18] Frank D, Roth E, Olson J, Evtimov B, Nast T, Sompayrac B and Clark L D 2007 Development of a cryocooler to provide zero boil-off of a cryogenic propellant tank *Cryocoolers 14* ed S Miller and R G Ross, Jr (Boulder, CO: ICC Press) pp 583-8
[19] Nast T C, private communication, 2008.
[20] Zagorola M V, private communication, 2008.
[21] van de Groep W, Mullie J, Willems D and Benschop T 2009 Development of a 15W coaxial pulse tube cooler *Cryocoolers 15* (Long Beach, CA, 9-12 June 2008) ed S. Miller and R G Ross, Jr (Boulder, CO: ICC Press) (in press)
[22] Olson J R and Davis T 2006 Development of a 3-Stage pulse tube cryocooler for cooling at 10K and 75K *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC*, Vol 51 (Keystone, CO, 28 Aug-2 Sept, 2005) (*AIP Conference Proceedings* vol 823) ed J G Weisend, et al (New York: Amer. Inst. of Physics) pp 1885-92
[23] Jaco C, Nguyen T and Raab J 2009 10K Pulse tube cooler performance data *Cryocoolers 15* (Long Beach, CA, 9-12 June 2008) ed S. Miller and R G Ross, Jr (Boulder, CO: ICC Press) (in press)
[24] Foster W G, Olson J, Champagne P, Evtimov B, Will E, Collaco A, Nast T, Clappier R, Mitchell A, Jungkman D, Radebaugh R and Curran D G T 2003 Development of a high capacity two-stage pulse tube cryocooler *Cryocoolers 12* ed R G Ross, Jr (New York: Kluwer Academic/Plenum Publishers) pp 225-32
[25] Zagarola M V, Dietz A J, Swift W L and Davis T M 2004 35K Turbo-Brayton cryocooler technology *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC*, Vol. 49 (Anchorage, AK, 22-26 September 2003) (*AIP Conference Proceedings* vol 710) ed J Waynert, et al (New York: American Institute of Physics) pp 1635-42
[26] Gully W, Glaister D, Hendershott P, Marquardt E, Lester J and Levenduski R 2009 Initial test results for a 35K *Cryocoolers 15*, *Cryocoolers 15* (Long Beach, CA, 9-12 June 2008) ed S Miller and R G Ross, Jr (Boulder, CO: ICC Press) (in press)
[27] Jaco C, Nguyen T, Colbert R, Pietrzak T, Chan C K. and Tward E 2004 High capacity staged pulse tube cooler *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC* Vol. 49 (Anchorage, AK, 22-26 September 2003) (*AIP Conference Proceedings* vol 710) ed J Waynert, et al (New York: American Institute of Physics) pp 1263-8
[28] Jaco C, Nguyen T and Tward E 2008 High capacity two-stage coaxial pulse tube cooler *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC*, Vol 53 (Chattanooga, TN, 16-20 July 2007) (*AIP Conference Proceedings* vol 985) ed J G Weisband, et al (New York: American Institute of Physics) pp 530 --7
[29] Kirkconnell C S, Hon R C and Roberts T 2009 Raytheon Stirling/pulse tube cryocooler maturation programs *Cryocoolers 15* (Long Beach, CA, 9-12 June 2008) ed S Miller and R G Ross, Jr (Boulder, CO: ICC Press) (in press).
[30] Kotsubo V, Olson J R, Champagne P, Williams B, Clappier B and Nast T C 1999 Development of pulse tube cryocoolers for HTS satellite communications *Cryocoolers 10* ed R G Ross, Jr (New York: Kluwer Academic/Plenum Publishers) pp 171-9
[31] Swift W L, Dolan F X and Zagorola M V 2008 The Nicmos cooling system – 5 years of successful on-orbit operation *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC*, Vol. 53 (Chattanooga, TN, 16-20 July 2007) (*AIP Conference Proceedings* vol 985) ed J G Weisband, et al (New York: American Institute of Physics) pp 799 --806

[32] Tward E, Chan C K, Colbert R, Jaco C, Nguyen T, Orsini R and Raab J 2002 High efficiency cryocooler *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC*, Vol. 47 (Madison, WI, 16-20 July 2001) (AIP Conference Proceedings 613) ed M Adams, et al (New York: American Institute of Physics) pp 1077 --84

[33] Johnson D L and Ross R G, Jr 1995 Cryocooler coldfinger heat interceptor *Cryocoolers 8* ed R G Ross, Jr (New York: Plenum Press) pp 709-17

[34] Johnson D L and Ross R G, Jr 1994 Spacecraft cryocooler thermal integration *Proc. of the Spacecraft Thermal Control Symposium* (Albuquerque, NM, November 1994) (Abuquerque, NM: AirForce Research Laboratory)

[35] Gillman D C 1997 Cryocooler heat interceptor test for the SMTS program *Cryocoolers 9* ed R G Ross, Jr (New York: Plenum Press) pp 783-93

[36] Gully Ph, Charles I, Durand J L and Briet R 2008 A new mini pulse tube with a heat interceptor *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC*, Vol. 53 (Chattanooga, TN, 16-20 July 2007) (*AIP Conference Proceedings* vol 985) ed J G Weisband, et al (New York: American Institute of Physics) pp 1651—58

[37] Bradshaw T W, Orlaska A H, Jewell C, Jones B G and Scull S 1997 Improvements to the cooling power of a space qualified two-stage stirling cycle cooler *Cryocoolers 9* ed R G Ross, Jr (New York: Plenum Press) pp 79-88

[38] Charles I, Golanski L, Gauthier A, Coynel A and Duval J M 2008 20K Coaxial pulse tube using passive pre-cooling *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC*, Vol. 53 (Chattanooga, TN, 16-20 July 2007) (*AIP Conference Proceedings* vol 985) ed J G Weisband, et al (New York: American Institute of Physics) pp 887--94

[39] Kirkconnell C S, Zagarola M V and Russo J T 2006 Hybrid Stirling/reverse Brayton and multi-stage Brayton cryocoolers for space applications *Adv. In Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference – CEC*, Vol 51 (Keystone, CO, 28 Aug-2 Sept, 2005) (*AIP Conference Proceedings* vol 823) ed J G Weisend, et al (New York: American Institute of Physics) pp 1489 -- 96

[40] Feller J, Salerno L, Maddocks J, Helvensteijn B, Kashani A, Nellis G and Gianchandani Y 2009 Distributed cooling techniques for space applications *Cryocoolers 15 (Long Beach, CA, 9 - 12 June 2008)* ed S Miller and R G Ross, Jr (Boulder CO: ICC Press) (in press).