Cryogenic Technology for CMB-Pol: Sub-Kelvin Cooling

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Abstract. Sub-Kelvin refrigeration is a critical technology for a wide range of future astronomy and cosmology missions. For fundamental reasons, microcalorimeters and bolometers must be cooled to extremely low temperature to achieve their ultimate resolution and, eventually, background-limited detection. This paper summarizes the performance capabilities of technologies that have been developed specifically for use in space, and concludes with an assessment of future trends and possibilities for increasing the performance and utility of these systems.

1. Background

Cooling to sub-Kelvin temperatures – typically below 300 mK, but increasingly to 50 mK or below – is needed for many detector technologies to reach their measurement goals. The trend for future missions is to use progressively larger detector arrays, with a correspondingly larger heat lift requirement. From the modest array size of the XRS instrument on Astro-E/2 of 32 pixels, which required a cooling power of only 0.3 μW at 60 mK, future missions will implement 1000+ pixel arrays. Even with multiplexing techniques, cooling powers of several μW at 50 mK will be needed.[1]

A number of methods exist for cooling to temperatures below 1 K, and considerable effort has been devoted over the last two decades to adapt them for use in space. These include both solid state (e.g., Adiabatic Demagnetization Refrigerators (ADRs)[2] and Normal-Insulator-Superconductor (NIS) tunnel-junction coolers[3]) and fluid-based systems (e.g., ^{3}He sorption[4] and dilution refrigerators[5]). These techniques vary considerably in their cooling capacities, operating temperature range, heat sink temperature range, and requirements for inclusion with various detector and instrument components. In some cases, they are viable over only part of the necessary temperature range – between the detector and heat sink – and therefore must be used as part of a larger cooling chain. In this paper we present a basic description of each technology that has been demonstrated for use in space, with a goal of identifying each one's capabilities, advantages and challenges. We conclude with a discussion of future development and cooler architectures that could significantly improve performance (cooling power, mass, size, input power, etc.)

One of the most significant constraints on the design and operation of any cooler is the heat sink to which it rejects heat. At least in their early development, the majority of sub-kelvin refrigerators staged their operation from a superfluid helium bath. Superfluid helium dewars were readily available, and the low, ~1 K, starting temperature was convenient for minimizing parasitic heat inputs. Moreover, the development of helium dewars for missions like IRAS[6] and COBE[7] extended that capability, and that of sub-Kelvin coolers, into space instruments. For a variety of reasons, cryocoolers are being developed to replace stored cryogen dewars for future missions. Offsetting the (significant) advantages of these coolers are their generally higher operating temperature and limited cooling power. For sub-Kelvin coolers, this is providing a bias away from single-shot coolers and toward those that operate continuously, to provide a better match between their peak heat rejection rates and the cryocoolers cycle. Since this has an inherent advantage in lowering the power requirements for the cryocooler, and therefore system mass, it is likely that continuous coolers will become more prevalent in future mission designs.

2. Flight-Capable Sub-Kelvin Cooling Technologies

Table 1 provides a summary of the sub-Kelvin coolers that are detailed in the following section. These are systems that 1) have flight heritage, 2) are currently being readied for flight instrument, or 3) are maturing to the point that they could be considered for future instrument. Cooling powers that have been demonstrated in flight or flight-like coolers are shown in figure 1 over the temperature ranges where these coolers are optimized for use.

Table 1. Demonstrated Performance and Heritage of Flight-Capable Sub-Kelvin Coolers

Technology	Configuration	Operating Temperature	Cooling Power	Heat Sink	Avg. Heat Rejection	TRL	Heritage
Sorption Cooling	^{3}He, single-stage	300 mK	10 μW	1.5 K	3.7 mW	9	IRTS [6], Herschel [4]
	^{3}He, two-stage	300 mK, 240 mK		2.5 K		6	
	^{3}He/^{4}He three-stage	2.5 K, 300 mK, 240 mK		5 K		6	
ADR	Single-stage	60 mK	0.3 μW	1.3 K	0.15mW	9	Astro-E2 [7]
	Two-stage	50 mK	0.4 μW	1.8 K	0.12 mW	5	SRG, Astro-H
	Continuous, Four-stage [8]	50 mK	6 μW	5 K	3.0 mW	4	
Dilution Refrigeration	Open-cycle	100 mK	0.1 μW	4.5 K	2.0 mW	7	Planck [5]
NIS Coolers		190 mK		0.3 K			

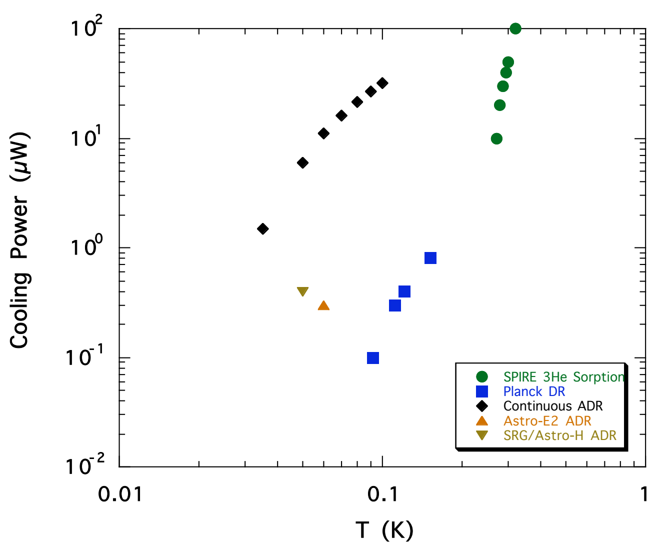

Figure 1. Demonstrated cooling power and operating temperatures for selected coolers.

2.1. ^{3}He Sorption Refrigeration

Sorption refrigerators produce cooling by evaporating liquid from an evaporator using a sorption pump. The sorption pump contains a quantity of material that has a large surface area and large binding energy for, in this case, ^{3}He. When this "getter" is cold, ^{3}He is strongly attracted to its surface, resulting in a very low equilibrium vapor pressure above the material. This allows it to act as a pump, and thereby drive large-scale evaporation of liquid from the evaporator. The remaining liquid is cooled until the evaporation rate balances the heat load. In principle, that point can be varied by changing the surface area and material (binding energy), but in practice it is necessary for the surface area to be so large that the helium, when fully adsorbed, occupies only a fraction of an atomic layer so that the equilibrium pressure remains low throughout the pumping phase. Consequently, the evaporator is typically pumped close to or moderately below the limiting temperature of 300 mK for ^{3}He (1 K for ^{4}He refrigerators). The base temperature can be stabilized over long time scales by regulating the sorption pump temperature, but short-term control is accomplished by heater control of loads coupled to the evaporator. By careful design (or the use of multiple stages) to minimize parasitic heat loads and ensuring a low impedance pumping path, ultimate temperatures of 200 mK or slightly lower have been demonstrated.

During the hold time of the refrigerator, liquid is evaporated as heat is absorbed. When the liquid is depleted, the sorption pump is warmed to desorb and re-condense the ^{3}He gas. For a typical sorption pump made using charcoal, the temperature must be raised to about 50 K to desorb the gas. In ground-based coolers, one can use a condenser anchored to the heat sink, from which the liquid drips back into the evaporator; for space coolers it is necessary to re-condense it in the evaporator. The inside of the evaporator is designed so that surface tension will confine the liquid and ensure it makes thermal contact with the walls. A heat switch is used to thermally connect the evaporator to the heat sink during the condensation phase and thermally isolate it during the cooldown and operational phase. The heat sink can be as warm as the critical point of ^{3}He (3.2 K), but this requires the sorption pump to be heated to high temperature to raise the ^{3}He pressure above the critical value – at a considerable cost in waste heat. Instead, heat sinks are typically 2.5 K or lower to reduce the power needed and to reduce the amount of helium that must be evaporated to cool to the operating point.

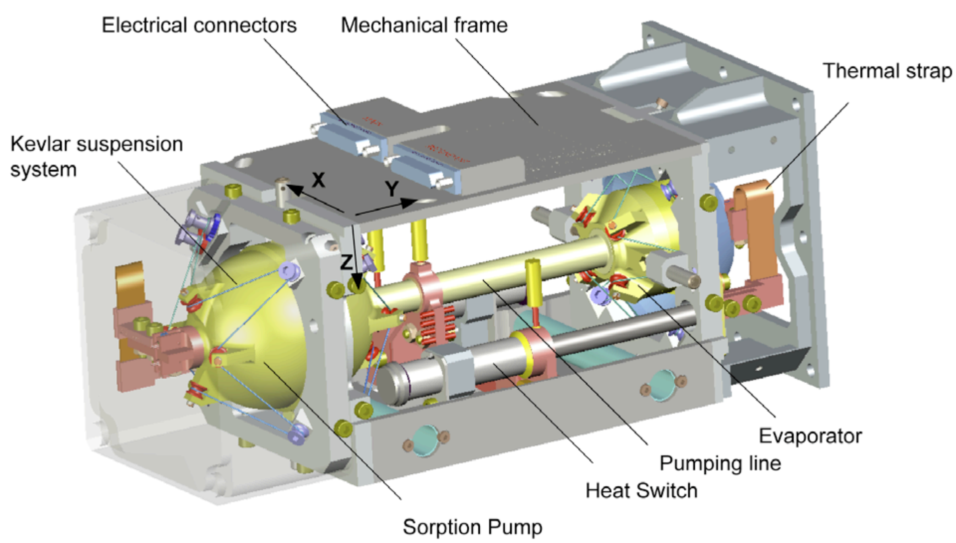

Figure 2. A single-stage ^{3}He cooler will be use to cool the SPIRE instrument on the Herschel mission.

The hold time of a sorption cooler is determined by the detector heat load and the volume of liquid remaining after pumping to the operating point. The design values for Herschel [4] (Figure 2) are 10 μW at 290 mK, and a hold time of 70 hours. The cooler generates waste heat during operation due to the heat of adsorption in the pump, and during recycling due to the heat of condensation of the ^{3}He charge, the heat required to warm the sorption bed, and heat required to operate the heat switch. For the Herschel cooler, operating at 277 mK with a 10 μW load, the total heat rejected is 927 J into the superfluid helium at ~1.5 K. From this, one can see that one of the main disadvantages of sorption refrigerators is their low overall efficiency (~1.5% of Carnot).

2.2. Adiabatic Demagnetization Refrigeration

ADRs make use of the magnetocaloric effect: an increasing magnetic field in a paramagnetic material causes the magnetic moments to increasingly align with the field, decreasing their entropy. This appears as heat in the lattice, causing the material to warm. Conversely, a descreasing field produces cooling in the material. What is notable about this process is that the heating and cooling are essentially reversible, leading to extremely high efficiencies. A typical single-shot ADR consists of a capsule of paramagnetic material (usually called a "salt pill"), a superconducting magnet, and a heat switch. The heat switch is used to thermally connect the salt pill to a heat sink while it is being magnetized, and to thermally isolate it after reaching full field. Subsequent demagnetization then causes the salt pill to cool to its operating temperature. Depending on starting and ending temperatures, and the peak field, this point will be reached with some magnetic field remaining. This provides a means of regulating temperature – with no waste heat input – as the salt pill absorbs heat both from the load (detectors or other experiment components) and parasitic sources. As heat is absorbed, the field is continually reduced until it reaches zero. The ADR must then be recycled. For space missions, the hold time requirement is typically 24 hours, followed by a recycling period of no more than 1 hour.

While the magnetocaloric effect is usable over a very wide range of temperatures (high and low), there are practical limitations for a single stage device. First, for a single stage to reach very low temperature the magnetic field applied must be roughly proportional to the heat sink temperature (1 T for a 1 K sink, and 4 T for a 4 K sink for operation at 100 mK). At present, high field to current ratio magnet technology is limited to NbTi, and practically limited to heat sinks at 5 K or lower and fileds of 4 T or lower. Single-stage ADRs operating at, for example, 50 mK are therefore limited to heat sinks up to perhaps 2 K. With colder heat sinks, temperatures as low as 20 mK are readily achievable. However, ADRs are easily adaptable to multi-stage configurations which also provide size and mass benefits. As an example, the single-stage ADR on Astro-E2 [[7] (Figure 3) operating at 60 mK used 920 g of ferric ammonium alum refrigerant, a 2 T NbTi magnet and a 1.3 K superfluid helium bath as a heat sink. Its net (detector) cooling power was 0.3 microwatts, and the total mass was 15 kg. For the upcoming Astro-H [9] mission with a 1.8 K heat sink, a two-stage design was chosen (240 g chrome potassium alum with a 2 T NbTi magnet, and 72 g gadolinium lithium fluoride with a 3 T NbTi magnet) that will provide 0.4 μW of detector cooling at 50 mK with a mass of only 8 kg.

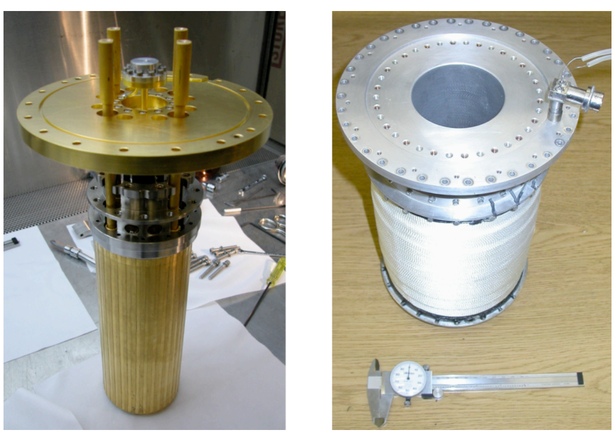

Figure 3. A single-stage ADR (salt pill/heat switch assembly at left; magnet at right) was flown on the Suzaku (Astro-E2) mission to cool the X-Ray Spectrometer detector array to 60 mK.

The heat rejected by the ADR comes from two main sources – the heat of magnetization of the spins and hysteresis heating in the superconducting magnet. However, as in the sorption cooler, significant heating can come from operation of the heat switches, especially active gas-gap switches. Generally, though, magnet hysteresis and heat switch dissipation are at most comparable to the heat of magnetization, giving overall efficiencies that are only about half of the efficiency of the salt pills in absorbing heat, which can be as high as 70% (of Carnot) at 50 mK.

ADRs have the disadvantage of needing current leads for the magnets – on the order of a few amps – but recent development in high-Tc materials allows these currents to be introduced to low temperature with a quite manageable impact on the thermal design. Materials such as MgB_2 and YBCO deposited on low conductance tape can be heat sunk to cryocooler stages or vapor cooled with venting cryogen to reduce heat loads on the cold stage to a small fraction of a mW.

2.3. Dilution Refrigeration

Dilution refrigerators (DRs) were developed in the 1960s and quickly became the standard laboratory sub-Kelvin cooling. In comparison to other techniques (principally ADR and ^3He sorption), DRs operated continuously, had very large cooling power, and could reach temperatures of a few mK. These systems relied critically on gravity for phase separation of the two helium isotopes, and it is this fact that has precluded their direct application in space, as no other mechanism has yet succeeded in providing the required $^3He/^4He$ phase separation and liquid confinement.

The Planck mission [5], however, developed an open-cycle DR (Figure 4) that has achieved cooling to 100 mK. The system feeds gaseous ^3He and ^4He from external storage tanks, condenses them at 4.5 K with a sequence of radiative and Joule-Thomson (JT) coolers, and pre-cools the individual streams to 1.6 K with a JT cooler which uses the exiting $^3He/^4He$ mixture as its expansion fluid. The two streams are further pre-cooled in counterflow heat exchangers with the exiting mixture. When the two streams are finally mixed, they cool as the pure ^3He dilutes the ^4He. Because the ^4He flow must be cooled by the dilution process, the net cooling is much less than for a conventional DR cycle where (ideally) only ^3He is circulated. Nevertheless, by careful minimization of parasitic heat loads, the 100 nW cooling power is sufficient to cool the bolometers to 100 mK. The external tanks contain enough ^3He and ^4He to achieve a lifetime of 24 months.

The pre-cooling requirement from auxiliary cryocoolers for the dilution unit is 2 mW at 4.5 K. Like sorption coolers, this results in a low overall efficiency, less than 1% of Carnot. To improve on this performance, plans are underway to convert the operation to a closed-cycle. This has the potential to increase the cooling power to into the range of 1 μW at 50 mK, and remove the lifetime limitation.

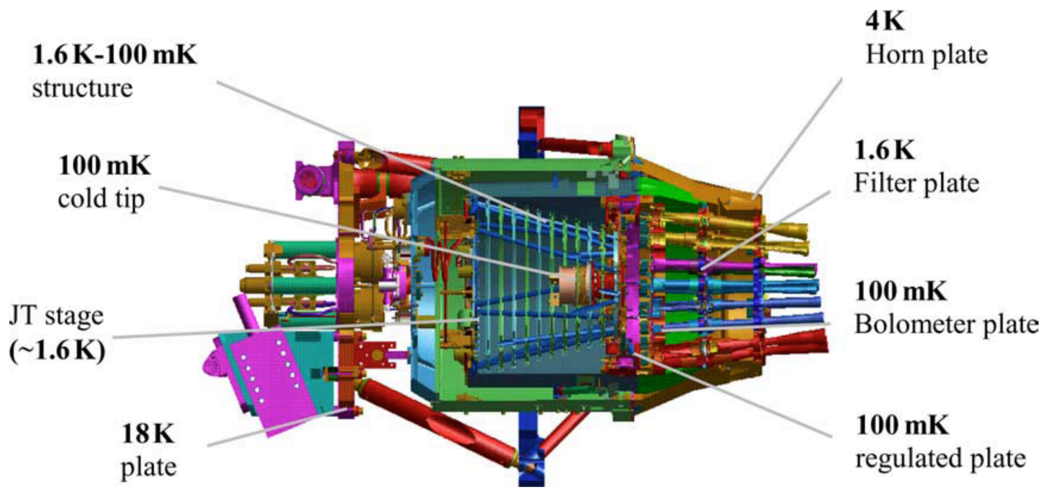

Figure 4. Schematic of the Planck focal plane with the dilution refrigerator.

2.4. NIS Coolers

The most recently developed technique, shown in figure 5, for cooling at low temperature is the concept of using NIS tunnel junctions [3], which have the potential to cool from 300 to 100 mK. Biasing an NIS junction causes the hottest electrons in the normal metal to tunnel across the insulator barrier into the superconductor, which cools the remaining normal-metal electrons. Extending the normal metal onto a membrane as a cold finger cools both the electrons and lattice of the electrically separate membrane. Although the magnitude of the cooling power is small, the virtue of this technique is that the cooler can be integrated directly with the detector pixels, and thus cool only the pixels suspended on insulating supports. This is done instead of cooling the frame surrounding the detector array and thus having to absorb parasitic heat from lead wires and other structures. Figure 5 shows a test device in which an NIS cooler being used to cool an x-ray transition-edge sensor (TES). The heat sink for the NIS cooler is an ADR stage that can provide base temperatures from 300 mK to below 50 mK. In this case, cooling from 300 mK to 190 mK was demonstrated. The technique is in principle capable of cooling into the 50 mK range from 300 mK.

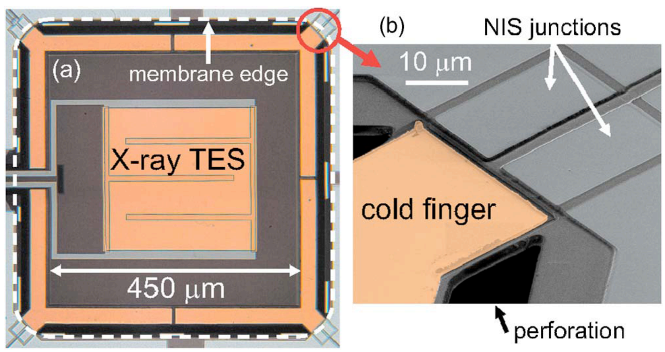

Figure 5. Micrograph of an NIS cooler integrated with a TES x-ray microcalorimeter.

3. Future Developments and Cooler Architectures

3.1. Single-Shot versus Continuous Coolers

Single-shot coolers are well-suited to operation with stored cryogens, since only the total heat transferred to the cryogen is a concern. However, for cryocooler-based operation, the peak rate at which heat is rejected during recycling becomes the most significant concern, although load-leveling techniques can be applied which refocus attention toward the average rate. Consequently, adapting single-shot coolers to operate continuously can be very beneficial (in reducing the mass and simplifying the requirements for both the sub-Kelvin refrigerator and the cryocooler) by removing the need to store heat for long periods of time and reject it quickly in a short recycle operation. DR and tunnel-junction coolers are inherently continuous techniques, so this conversion applies mainly applies to sorption refrigerators and ADRs. However, since continuously operating versions of the these coolers can be used, for example, as pre-coolers for DR or NIS coolers, there is potential benefit for a wide range of cooler combinations.

Sorption refrigerators and ADRs can employ multiple stages either in parallel or in series to accomplish continuous cooling. The simplest, but by no means most efficient or least complex, way is to use two separate coolers in parallel, using one to cool the load while the other is recycling. It requires two heat switches to couple the coolers to the load. Two key requirements for these switches are that they conduct well at the cooler's operating temperature, and have sufficiently low heat leak when one end is raised to the heat sink temperature. For ^{3}He sorption coolers at ~250 mK, gas-gap switches are suitable. For an ADR at 50 mK, only switches using metal as the conductive element will be functional, limiting the choices to mechanical, magnetoresistive, and superconducting switches. Each has significant limitations, making the series arrangement of stages preferable for a continuous ADR [8]. Such a system has been developed. Shown in figure 6, it uses 4 stages in which heat is cascaded from a stage that is essentially a thermal buffer, sequentially through the upper stages to a heat sink. It has demonstrated continuous cooling as low as 35 mK with a 4.2 K heat sink. With a mass of 8 kg, produces net cooling powers of 6 μW at 50 mK and more than 30 μW at 100 mK.

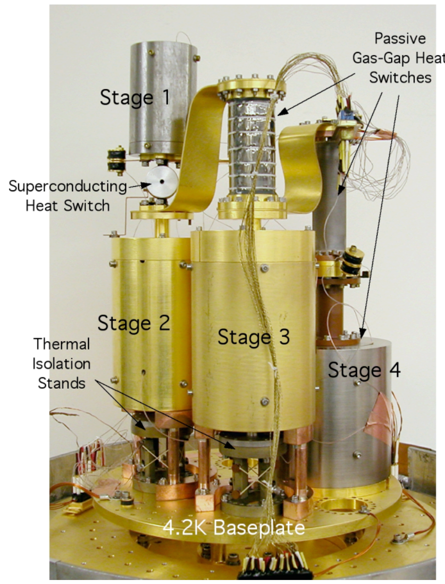

Figure 6. A continuous ADR capable of operating at 50 mK and below with a 5 K heat sink.

3.2. Sub-Kelvin Cooler Combinations

As seen in the companion papers on flight cryogen and cryocooler systems, one can choose from a rather wide range of pre-coolers as a basis for sub-Kelvin coolers. In the stored cryogen category are superfluid helium at 1.3-1.7 K, and solid hydrogen at 6 K. In the cryocooler category, pulse-tube and Stirling cycle coolers can reach temperatures near 4 K with cooling powers in the 10-100 mW range, and JT systems can cool below 2 K with up to 10 mW of cooling. This opens a large parameter space for optimizing system design, and/or for developing cooler systems that meet unique constraints such as low cold mass or low magnetic field requirements.

ADRs have the widest operating temperature range of the coolers discussed. Temperatures of 50 mK and below can be reached from heat sink of 4-5 K. At the warm end, one can in principle add stages to arbitrarily extend an ADR's operating range; the present limitation is NbTi magnet technology which requires temperatures below 6 K. Other magnet technologies are emerging, such as Nb_3Sn [10], which show promise for enabling low (<5 A) current, high (>3 T) field magnets to operate at temperatures up to 10 K. As this becomes a reality, it will enable the use of multi-stage ADRs with smaller, more efficient solid hydrogen dewars, or with simpler cryocoolers having fewer stages. An ADR is the only sub-Kelvin technology that can be extended for use above 5 K, and its high efficiency suggests that that there would be system-level advantages to doing so.

In the low temperature limit, there are combinations of coolers that could offer mass or size advantages, particularly in lowering the cold mass. For example, a ^{3}He refrigerator can produce substantial cooling at 250-300 mK. Attaching a single ADR stage would be a very simple way to extend cooling to 50 mK or below, and by adding two stages [11], continuous cooling at 50 mK could be realized. The advantage here is that these stages, like the ^{3}He cooler, would be relatively small and lightweight, as they would require magnetic fields of only a few tenths of a T. Such fields would be easy to shield from detectors and require low (<1 A) currents. The ^{3}He cooler could be a single-shot version and coupled to a ^{4}He single-shot refrigerator to operate from a 5 K sink.

A variation on this would be to couple a dilution unit to a ^{3}He sorption cooler. While a cooler using this concept [12] is already being developed for use in 1 g, the concept could improve the performance of the open-cycle DR by pre-cooling the mixture below 1.5 K, and reducing the fraction of dilution cooling used to cool the incoming mixture.

4. Summary

A variety of sub-Kelvin cooling technologies have been brought to flight-ready or flight-proven status in order to meet the demand for very low temperature detector cooling. There are still challenges to their use on future missions, including lower temperature operation and higher cooling power requirements for larger detector arrays, the need to interface these coolers with cryocoolers operating at higher temperature and with more limit cooling capacity, and longer mission lifetimes than has been demonstrated on any previous flight instrument. There are, however, coolers under development whose performance envelops the estimated requirements for these missions, and which can operate with existing cryocoolers. What they, and other promising technologies, need most is further investment to achieve sufficiently high TRLs in advance of proposing their use on future missions.

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