Cryogenic Technology: Ongoing Developments for the Next Decade

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To obtain optimum sensitivity a submillimeter space observatory will require low temperature mirrors (~3K) and very low temperature detectors (</~ 0.1 K). Both of these temperatures have been achieved by space cryogenic systems, but neither for a 10 year duration. Past systems used superfluid helium to provide direct cooling in the 1 to 2 K range (IRAS, COBE, IRTS, ISO) or as an upper stage for an adiabatic demagnetization refrigerator to achieve temperatures down to 0.06K (Astro-E/XRS). Boiloff vapor may be used to cool an otherwise warm telescope as in the Space InfraRed Telescope Facility (SIRTF). In SIRTF a 0.85m telescope is cooled to 5.5K by absorbing about 6 mW in the cold vapor. This residual heat is due to both radiation from a helium vapor cooled outer shield at about 20 K and from conduction through a structure mounting the cold telescope and instruments to the warm spacecraft. The boil off rate required to cool the telescope results in a 2.6 to 5 year lifetime, depending on whether other parasitic heat sources such as thermoacoustic oscillations are also present. A helium dewar results in a very heavy system to achieve 2 to 5 year lifetimes. For example it takes roughly 400 kg for XRS to achieve 0.06K for two year life with a 250K boundary temperature, and ~300 kg (including thermal shielding) for SIRTF to achieve 1.3K for 5 year life with a 35 K boundary temperature. To go to longer duration and to lower the weight, active cooling methods are required combined with more aggressive passive cooling techniques. It is possible, with some development, to provide cooling for detectors to 0.05K and telescopes and instruments to <4 K for a 10 year mission with a 100 kg system including power sources, structural support, and vacuum enclosures for critical portions of the instruments.

Passive Radiators.

Passive radiators to achieve temperatures below 40K have been built for SIRTF and to achieve temperatures down to 30K are under development for the Next Generation Space Telescope (NGST). Parasitic heat leaks and size place practical limits of about T > 25K on passive radiation cooling. Several critical issues have been identified. Exposure to hot surfaces must be severely limited. Parasitics are critical and hard to control. There are many uncertainties with any modeling including the assumed material properties such as absorptance and reflectance. Testing will be critical. Thermal/mechanical isolation and efficient cryogenic heat transport techniques will be required.

The NGST thermal models currently predicts 80-90 K on the backside of the sunshield and approximately 35K on the primary mirror. This sunshield performance is achievable but with many hurdles. The issues being worked by NGST include: deployment/stability, lifetime (meteroid damage, degradation of material and optical properties), and analytical predictions of thermal performance accounting for all degrading factors. NGST's sunshield concept consists of 4-6 separated Kapton membranes approximately 32 x 14 meters across. Heat is rejected from between layers before reaching the cold backside of the sunshield. Shield performance is dependent on shield spacing, the optical properties, and number of layers. One must balance thermal performance with deployability, packaging and mass.

One interesting thing to note is that as the mirror mass starts to dominate the warm spacecraft mass, the structural support cross section will tend toward a constant. That is, to obtain a given minimum resonant frequency, the support stiffness will depend on the spacecraft mass rather than the mirror mass. Since the thermal conductance of the support depends on its cross sectional area, this implies that conducted parasitics into a large telescope will level off as the telescope gets larger.

For a submillimeter mission a 10 degree shield (allowing for up to 10 degrees of off-normal sun angle) has a size which varies with truss length. For a 15 meter truss length the shield size would be slightly smaller than the NGST shield. This appears to be the optimal size to shield a 3m diameter mirror. See Figure A.

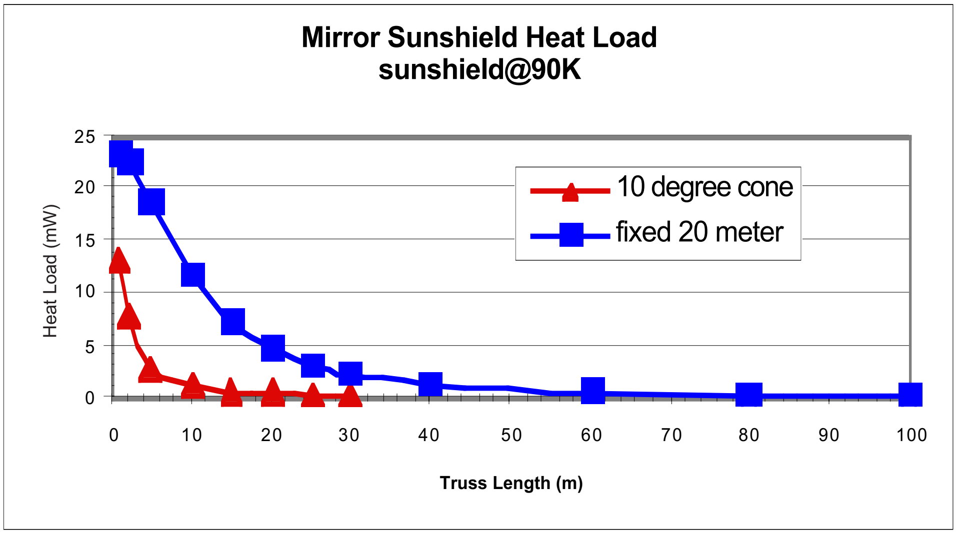

Figure A. Triangles are for sun shield diameter necessary to allow 10 degrees of telescope tilt relative to the sun. Squares represent the effect of distance from a fixed 20 meter diameter sun shield.

Cryogenic Capillary Pumped Loop (CCPL).

Capillary Pumped Loops (CPLs) are capable of transporting large amounts of heat and providing tight temperature control utilizing capillary pumping forces (no moving parts). The CCPL provides a very efficient heat transport path at low temperature. This allows cooling of remote or distributed systems with minimal temperature gradients even in the presence of a large heat flow. A CCPL can be used in a cryogenic thermal bus or as a temperature control device for cryogenic detectors. CCPLs use simple construction from copper or aluminum. They are highly flexible and suitable for miniaturization, as would be required for the low heat flows in the 2 to 4K range.

A liquid nitrogen CCPL was successfully demonstrated on STS-95 in October, 1998 tranporting 2W at 80K. Several ground demonstrations have been performed with liquid nitrogen (transporting 0.5 to 12 W in the 80 to 100K range) and liquid neon (transporting 0.25 to 3.5 W in the 35 to 40K range). The basic two-phase technology is established, the remaining questions concern operating fluid properties and parasitics. A hydrogen loop breadboard which transfers 0.5W - 5W over a 1.5 meter distance at around 20K was recently demonstrated in the lab. The loop has a quick start-up within a couple hours and very robust continuous operation for over 10 hours. An improved prototype unit is being built.

For a future submillimeter mission CCPLs could be used to cool distributed heat sources for the cold optics (liquid helium CCPL, 2-4 K) or to provide cooling to structures remote from a cryocooler or low temperature radiator (liquid neon CCPL). Development is needed for the liquid helium CCPL.

Mechanical Cryocoolers.

Space qualified cryocoolers currently achieve a low temperature of about 20K. Laboratory coolers with a reasonable thermodynamic efficiency (a few % of Carnot) and limited input power to the compressor of 200 watts or less have recently demonstrated cooling to below 10 K.. The Advanced Cryocooler Technology Development Program (ACTDP) will fund the development of cryocoolers producing 7.5 mW of cooling at 6 K and 0.25 W of cooling at 18 K for an input power of less than 150 W with a mass of less than 40 kg systems including control electronics. The first engineering units of such coolers will be ready in 2005.

Stirling/J-T Coolers. There are 3 versions of the Ball Aerospace multi-stage Stirling cycle cooler. The two-stage version, capable of producing 0.45 watts at 30 Kelvin for 70 watts of input power, has been qualified for flight. A protoflight model two-stage cooler has completed a life test at Goddard. Ball has proposed adding a Joule-Thomson expander stage to this cooler to achieve temperatures to 6K. Matra Marconi Aerospace has produced a high power Gifford-McMahon with a J-T stage that achieves ~4K. Unfortunately the input power required for this cooler is greater than 2kW.

Pulse Tube Cryocoolers. Long life, high reliability pulse tube cryocoolers for space applications have been space qualified to temperatures as low as 35 K. The primary advantage of the pulse tube cryocooler, compared to a Stirling cycle cryocooler, is that the pulse tube does not have any moving parts at the cold end which improves reliability and reduces induced vibration at the cold tip. Also, system weight and development costs are reduced. The thermodynamic efficiency of pulse tubes has been shown to be as good or better than Stirling cycles at the same operating conditions. Thermodynamic efficiency can be improved by operating the compressor at a low temperature (down to 35 K) but additional radiator area (and therefore mass) will be required to reject heat from the compressor at this low temperature.

Exported vibration from the compressor is minimized by the opposed motion of the pistons in conjunction with an electronic feed back control loop to cancel the net momentum of the moving masses. The residual vibration levels are 0.1 N in the lateral direction since the current control schemes only control the axial vibration levels. It is possible to reduce this level of vibration but additional development is needed. Some potential areas to improve the induce vibration are: improved alignment and balancing of the opposing pistons to reduce the lateral forces, improved closed loop control of the pistons in the drive direction, and innovative techniques such as 3-axis dynamic balancing.

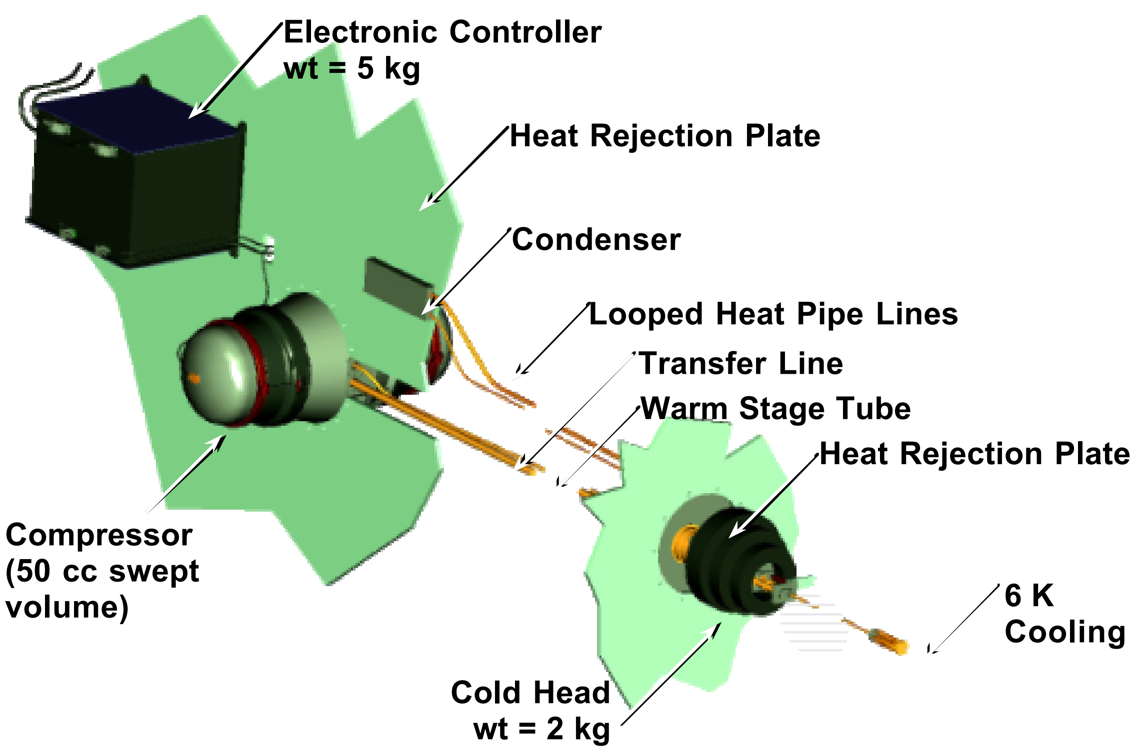

Figure B. Lockheed Miniature Low Temperature Pulse Tube Cryocooler.

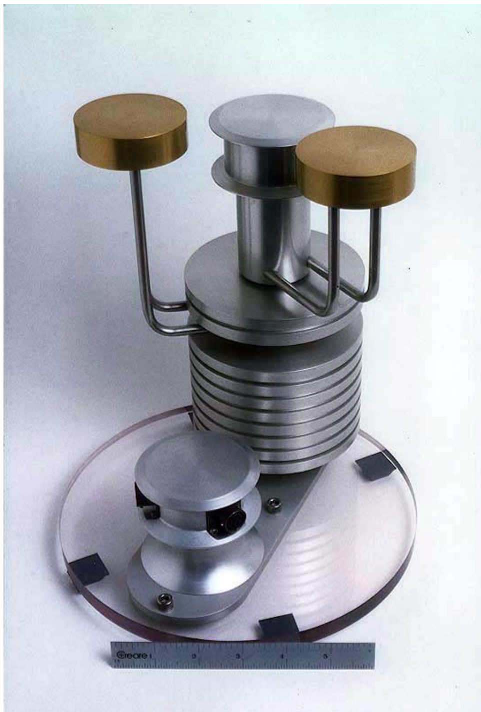

Figure C. Miniature Turbo Reverse Brayton Cooler. 35K model.

Recent data from the Lockheed miniature pulse tube cryocooler program has shown that the pulse tube can be staged allowing access to low temperatures. Component tests combined with simulations have shown cooling down to 5.2 K under no load, or a cooling power of about 60 mW at 10K, for a compressor input power of only 100 W.

Miniature Reverse Brayton Cooler. Turbo-Brayton cooler technology has many excellent features, including essentially vibration free operation, large cooling power per unit mass and volume, high thermodynamic efficiency at low temperatures, and ease of integration. Unfortunately, it has historically not been possible to adequately miniaturize the technology for use in space.

Technical breakthroughs by Creare, Inc. have enabled this technology to be miniaturized while maintaining high thermodynamic efficiency. The cooler consists of three major components, a compressor, a counterflow heat exchanger and a turboalternator (expander). The compressor and the turboalternator use identical technology, namely high speed miniature turbines supported by gas bearings. Miniature high speed turbomachines with self acting gas bearings and low mass shafts will provide the compression and expansion functions without vibration. Rotors of approximately 2 mm - 5 mm diameter are typical and rotational speeds are between 1,000 rev/s and 10,000 rev/s. The compressor turbine typically rotates at up to 1,000,000 RPM. A 70K version of this cooler is currently in use on the NICMOS instrument on the Hubble Space Telescope.

In order to reduce the number of compression stages and the complexity of the machines, the cryocooler must operate at relatively low pressure ratios. These conditions require very high performance recuperative heat exchangers in order to keep system input power at acceptable levels. The use of an efficient counterflow heat exchanger, instead of a regenerative heat exchanger as required by Stirling cycle coolers and pulse tube coolers, enables reverse Brayton cycle coolers to achieve extraordinary thermodynamic efficiency in the 4 to 10 Kelvin temperature range. It is the high thermodynamic efficiency of the turbo-Brayton cooler, along with its very small mass and size, that make this cooler technology so appealing for space missions with detectors and other hardware operating at or below 10 Kelvin. . For cooling loads in the range of 5 mW to 100 mW at temperatures between 4 K and 10 K, cycle power levels are expected to be between 15 W and 200 W.

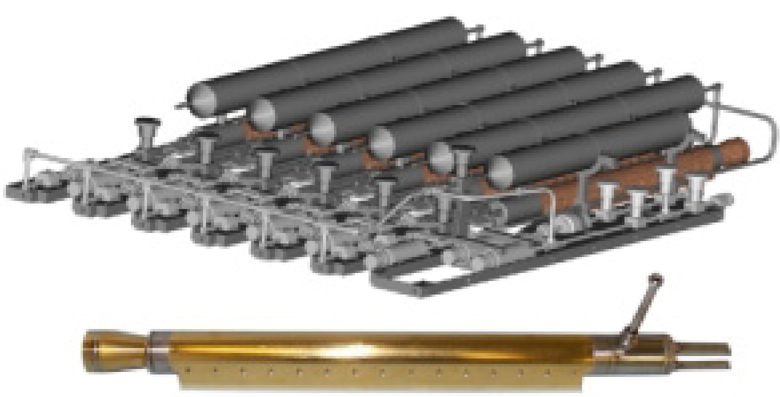

Figure D. 18 K Sorption Cooler for Planck Mission. The drawing shows a number of the sorption bed compressors and condensers that make up a multistage system.

Sorption Cooler. Sorption coolers, like the turbo-Brayton cooler, use a recuperative cycle. That is, they take advantage of the returning gas to precool the warm compressed gas. They do not rely on a regenerator which must have a high heat capacity. Unlike the turbo-Brayton cooler, compression is done by an absorber, not a moving turbine. The sorption cooler can be sized for very small heat loads. The only moving parts in the refrigerator are check valves, thus the system also has little vibration. A 20K sorption cooler is under development by JPL for the Herschel/Planck mission. (See Figure D.) A breadboard unit has been tested and flight units will be produced by 2004. Development of a 6K version is under consideration for NGST. The final goal is for 10 to 20 mW of cooling power at 6 to 8 K.

Coolers for Very Low Temperature.

Dilution Refrigerator. A helium dilution refrigerator (DR) is the most common method for reaching temperatures between 0.010 and 0.300 K on the ground. The DR relies on the unique properties of liquid He-3 and He-4. Cooling is produced when He-3 atoms cross the phase boundary that exists between liquid He-3 and liquid He-4 at low temperatures. (Essentially, He-3 'evaporates' into the liquid He-4.) The principal advantages of a dilution refrigerator when operated with sorption pumps are: it is small and light, it has no moving parts to wear out, and it produces no vibration. On the ground, gravity provides the force that keeps the two helium liquids in their required places so that the cooling can happen when and where it is needed. In space this force must be replaced with weaker capillary forces that arise when the liquids are confined in porous sponges. It was found, however, that the small pores needed to control large heights of liquid on the ground are too small to allow sufficient liquid flow for effective cooling. It has been shown that it should be possible to develop a helium dilution refrigerator that will confine the liquids with capillary forces and still provide the cooling that makes the dilution refrigerator so valuable. This approach should work even better in microgravity. A shallow single-cycle version of the refrigerator that does not require large heights of liquid to be supported by capillary forces has been built tested.

Herschel/Planck will use a single shot dilution refrigerator currently under development by ESA. Models already produced have about 0.1 microwatt of cooling at 100 mK and require a 10 K cryocooler stage for precooling. These prototypes require large tanks for helium gas storage.

NASA/Ames is working on a concept for a continuously running dilution refrigerator that will produce a few microwatts of cooling at 50 mK for less weight. A 4 K cryocooler stage is required for this design. A zero g demonstration of a prototype is desirable. Figure E shows the NASA/Ames configuration to be tested on the ground. The dilute He-3 flows out of the mixing chamber into the still as before. But the He-3 gas, instead of being pumped from the still into a charcoal pump, now goes to a new chamber, the condenser, at 0.4 K, where it condenses back to a liquid and pure He-3 returns to the mixing chamber. Thus this He-3 never leaves the low-temperature region. As long as the still is heated to maintain its temperature at 0.6 K and the condenser is cooled to maintain its temperature at 0.4 K, He-3 will be continuously pumped from the still into the condenser and forced back into the mixing

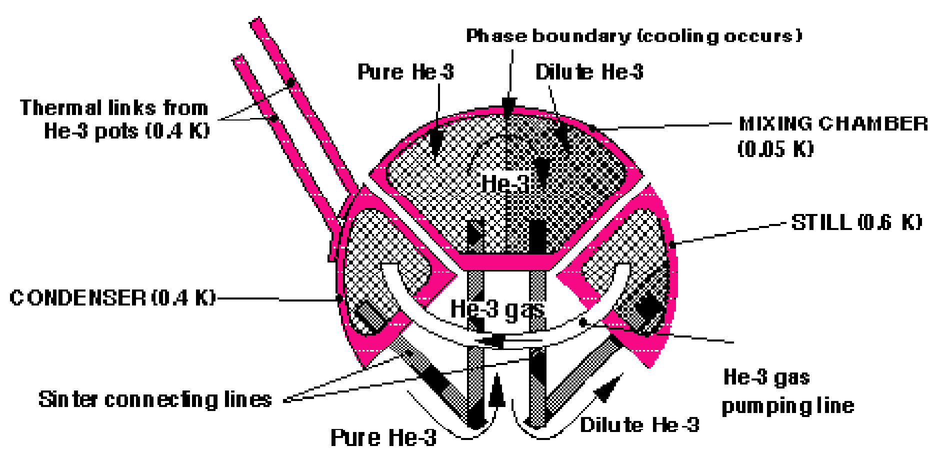

Figure E. Details of the low-temperature chambers of the continuously-operating dilution refrigerator.

chamber. This continuous circulation of He-3 will produce continuous cooling in the mixing chamber where He-3 crosses the phase boundary from pure He-3 into the He-4. The condenser can be cooled by two single-cycle He-3 refrigerators, each with its own charcoal pump, and each thermally linked to the condenser by a heat switch. It also can be cooled by a continuous ADR stage running at about 0.4 K. The amount of heat dissipated in this stage is about 800 microwatts for 3 microwatts of cooling at 0.05 K.

If He-3 refrigerators are used, the charcoal pumps for the He-3 pots need to be cooled below 8 K to achieve good pumping. However, the He-3 pots need to be cooled to 2 K or below to efficiently condense He-3. If a temperature this low is not otherwise available, then a pair of He-4 pots and charcoal pumps would be added. These would condense He-4 and reject heat at 4 K, and then be pumped down to 1 K to provide a heat sink for condensing He-3 into the He-3 pots. They would be operated alternately, like the He-3 pots, to provide continuous cooling to a 1 K heat sink.

<u>Adiabatic Demagnetization Refrigerator (ADR)</u>. An ADR uses a magnetic refrigeration cycle and consists basically of a high-field magnet, a paramagnetic material (called a "salt pill") and a heat switch. The salt pill is located in the bore of the magnet, occupying the highest field region, and the heat switch allows it to be thermally connected to or isolated from the higher temperature heat sink

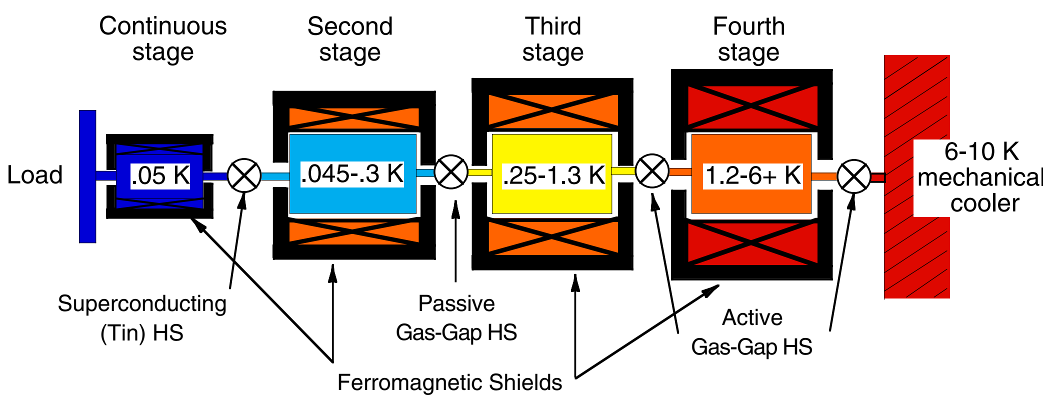

Figure F. Schematic of a CADR. A fifth stage may be inserted between the third and fourth stages to maintain a 1.3K thermal shield and to maintain the second and third stage magnets at low temperature.

depending on which part of the thermodynamic cycle the refrigerator is in.
The continuous ADR technology being developed at GSFC under the Cross Enterprise Technology Development Program (CETDP) has currently demonstrated 1.5 microwatts of cooling at 0.035 K rising to 15 microwatts of cooling at 0.100 K dumping heat to a SFHe reservoir at 1.3 K. Development during the next two years will allow the heat to be dumped at up to 10 K as well as increase the cooling power by about a factor of 2. See Figure G. Overall efficiency of greater than 25% of Carnot is expected for a system operating between 0.05 and 10 K.

Advantages of an ADR for very low temperature cooling include: no moving parts, high thermodynamic efficiency, and simple operation. It also can be fully demonstrated on the ground; gravity plays no role in its operation. It is however, somewhat heavier than an equivalent dilution refrigerator and it may produce stray magnetic fields from which many detectors must be shielded.

Cooling a telescope to <4 K with a 6-10 K mechanical cooler may be achieved with high efficiciency by using the upper stage of an ADR and a continuous stage to maintain the low temperature. In fact, the overall efficiency of the system will improve greatly over a mechanical cooler alone due to the high efficiency of a CADR. A CADR operating from 10 K to 4 K could have an efficiency of

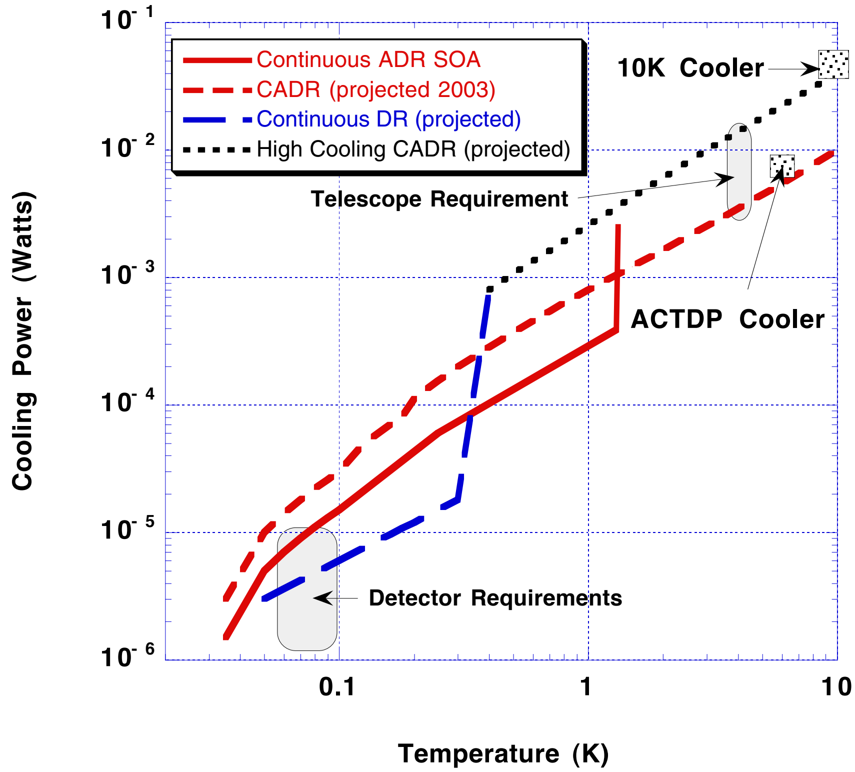

Figure G. Cooling power for continuous dilution refrigerators and continuous adiabatic demagnetization refrigerators currently under development. The heat rejection requirements are compared with the cooler to be developed under the ACTDP and for a higher power 10 K cooler. The cold mass of each of these technologies is less than 10 kg.

greater than 80% of Carnot, while a mechanical cooler's efficiency over this range decreases drastically due to the rapid change of thermodynamic properties of the helium gas working fluid.

Normal/Insulator/Superconductor (NIS) Cooling

A new technique using a superconducting analogue to thermoelectric cooling is being developed. By sweeping electrons in a normal conductor across an insulating voltage barrier and allowing the electrons to pair up in a superconductor one can achieve cooling on a small scale – large enough to be able to directly cool detectors from about 0.3 to 0.1K. In conjuction with an ADR or ^{3}He sorption cooler this could be attached to a mechanical cooler. This type of cooler for single pixels is being developed in Finland and for large arrays at Lawrence Livermore National Laboratory (LLNL) under CETDP funding. The larger LLNL NIS device will be able to cool 2 nanowatts at 0.1K while rejecting 20 nanowatts of heat at a temperature of 0.3 K. The development is expected to result in a laboratory demonstration of detector cooling by the end of 2003.

Cryo/Thermal Summary.

The cryogenic and thermal components necessary to accomplish a large long-life sub millimeter mission are currently in, or proposed for, development. If the funding is available, the necessary development will be completed in the next 10 years. Development of mechanical coolers, very low temperature coolers and improved thermal systems will significantly lower the system mass and make the mission more affordable. System level studies of how these components will work together and the optimization of various parameters like weight and complexity remain to be done.

ACKNOWLEGMENTS

The author thanks T. Nast, R. Boyle, J. Ku, P. Shirron, P. Roach, J. Ullom, and W. Swift for providing information included in this article.