Cryogenic Technology for CMB-Pol: Passive Cooling and Stored Cryogen Systems

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Abstract. Staged cooling is the most efficient means of achieving low temperature in an observatory or instrument with the least cost and mass. The first stage is usually passive radiators taking advantage of views to deep space. This area is under active development for many space missions and takes the form of blackbody radiators and lightweight sunshields. Stored cryogens have been extensively used to achieve temperatures below 10 K (solid hydrogen) and below 2 K (superfluid helium). While this technology is very mature in the general sense, each implementation is significantly different to the extent that the technology readiness level is usually TRL 5. Ground tests demonstrating the thermal performance of large cryogenic systems is problematic due to the presence of warm spacecraft components in the same thermal vacuum chamber. Methods to increase the thermal modelling confidence while decreasing the costs of these tests are also presented.

1. Passive Cooling
When designing a low temperature system for an instrument or an observatory it is most efficient to use multiple stage of cooling – both for thermodynamic efficiency and to utilize optimal cooling techniques for the various temperature ranges. The first (warmest) stage of cooling is usually passive. Passive cooling systems block parasitic heat inputs from the Sun, Earth, spacecraft and other warm components from reaching the low temperature stages. Passive cooling systems also take advantage of the biggest heat sink in the universe to radiate heat to deep space. V-Groove radiators provide one or more stages of radiation in an optimal direction defined by the “V” while blocking radiated heat from the other directions[1]. Planck is a good example of a multi-stage, fixed V-groove radiator[2]. A larger, very lightweight, deployable version of a V groove radiator can be found in the James Webb Space Telescope (JWST) sunshield[3]. (See Figure 2.) The shield is made up of 5 layers of aluminized or Si coated Kapton to provide more than 40 dB of attenuation of the incident sunlight power while radiating to space out the gaps between layers. The size and mass limitations limit the membrane shape and layer separation that can be achieved on the ground. This, in turn, limits the testability of the design.

Because of the proximity, angular coverage and varying direction of thermal radiation and reflected sunlight from the Earth, low Earth orbit (LEO) is thermally inferior to a deep space orbit like the Earth-Sun L2 Lagrange point or a drift-away orbit. L2 was used by the Wilkinson Microwave Anisotropy Probe (WMAP) which radiatively achieved 90 K[4], and will be used by Herschel[5] and Planck, followed by JWST (27 K on the instrument radiators). With a very simple fixed shield and
radiator, Spitzer has achieved 34 K in a drift-away solar orbit[6], while the outer shell of the COBE dewar in LEO reached 138 K.

Note that while the cosmic microwave background temperature is 2.73 K, deep space is effectively 7 K due to inner solar system dust[7]. This difference is not a practical limitation, however, due to the $T^4$ dependence of radiation and the other practical limitation on radiators, such as conductive supports. The difference between the two space temperatures on the radiation from the Spitzer outer shell at 34 K is only 0.2%.

The Spitzer observatory consists of a 0.85 m diameter telescope cooled to 5.5 K by the boil-off gas from a superfluid helium dewar. The telescope is mounted directly to the dewar and supported from a radiative cooled outer shell with a vapor cooled shield in between. See Figure 1. The helium dewar is described in the next section. The outer shell, which is cooled entirely by radiation, is silvered on the side facing the solar array and the sun and is painted with Ball InfraRed Black (BIRB) on the deep space facing side. The radiative performance turned out to be as predicted based on heat load from the solar array, the conduction of the outer shell and the emissivity of the BIRB[6].

The thermal testing of passive cooling systems is problematic not only due to the size and gravity effects, but also due to the difficulty of achieving and measuring milliwatt heat loads in the presence of kilowatts of thermal radiation from room temperature spacecraft components within the same thermal/vacuum chamber. A very big thermal driver is the difference between real chamber walls and empty space. The warm spacecraft and any solar simulator can be seen by the cold portions of the instrument through reflections off these walls. The chamber also needs to be cold enough so that radiation from the wall itself is not significant. Even a great observatory like Spitzer could not afford a test that would adequately simulate the thermal environment of space. The “inexpensive” compromise test that was run on Spitzer resulted in a heat load to the instrument that was 10 times the actual on-orbit value, so was of little use in predicting on orbit behavior.

To overcome this limitation it is proposed that the problem be attacked in two ways: make and test a subscale hardware model of the thermal system of a realistic large space telescope and perform a thermal model on this subscale model and test conditions; and outfit the test chamber with the appropriate thermal baffling and cold black body surfaces to achieve a more space-like thermal environment. The first enables use of a smaller chamber, which lowers the cost and increases the opportunities for test. It also helps with the one-g problem – in general, the smaller the system, the less effect gravity has on it. The second requires a careful design of a chamber/experiment baffle. This is also aided by making the test article smaller. One can vary the boundary conditions on the resulting test article to simulate conditions like LEO or deep space. JWST will test its sunshield design...
on a one third scale model. The size was chosen to make use of existing thermal vacuum chambers, and to provide the proper scaling. That is, too small a model will be dominated by conduction and boundary effects while too large a model will be affected by gravity and facility availability.

To demonstrate the feasibility of this scheme, an 18% scale (the largest diameter shield was 1.5 m) version of the SPIRIT Origins Probe telescope shield was tested in a low cost helium shroud within a LN2 shrouded vacuum chamber. See Figure 3. Performance data showed that less than 10 microwatts of radiative heat leaked from the warm to cold sides of the shields during the test implying that the boundary conditions were well understood. Excellent agreement was obtained between the data and the thermal models[8].

2. Stored Cryogen Cooling

Several cryogens, solid and liquid, have been used as consumables to cool instruments and observatories. Volumes have ranged from 36 liters (Astro-H) to over 2500 liters (Herschel). See Figure 4. Most were great successes, but there have been some notable failures. IRAS, COBE, CLAES, IRTS, ISO[9], GP-B[10], and Spitzer[6] are in the latter category. The Hubble Near Infrared Camera and MultiObject Spectrograph (NICMOS) which used solid nitrogen had a much shorter on-orbit lifetime due to a thermal short caused by the solid nitrogen itself. The Wide field InfraRed Explorer (WIRE) which was cooled by two stages of solid hydrogen had a premature release of its aperture cover which enabled sunlight to enter the cold volume and exhausted the hydrogen within one day. The Suzaku XRS2 instrument, cooled by a combination of mechanical cooler at 100 K, solid neon at 16 K and superfluid helium, suffered a complete loss of helium four weeks into the mission when vented gas reentered the dewar vacuum space. It is noted that all of these failures were peculiar to using stored cryogens, and would not have happened to a mechanical cryocooler system. In fact, NICMOS was brought back into service by attaching a cryocooler to the dewar in 2002 and is still successfully operating[11].

The successor to the Japanese Suzaku xray mission is Astro-H. The current thinking on the cryogenic system is to use both a superfluid helium tank and a Joule-Thomson cryocooler to achieve technological redundancy. While this does provide redundancy, it has a distinct mass disadvantage to either of the two cooling systems alone.

The Spitzer cryogenic system approaches the optimum engineered solution for stored helium systems. The combination of excellent passive cooling and careful thermal design produced a cryogenic system whose lifetime is expected to exceed its 5 year goal using only 360 liters of superfluid helium. The Spitzer mirror is cooled to 5.5 K by the boil off vapor from a superfluid helium tank that operates at 1.2 K. A heat load to the superfluid helium of 6 mW coincidently
produces about 6 mW of cooling by the vapor at 5.5 K, the enthalpy difference of the gas from 1.2 K to 5.5 K being approximately equal to the latent heat at 1.2 K. The average instrument dissipation is about 3 mW which is directly deposited into the liquid. The outside shell of the dewar is itself cooled by the boil-off, resulting in a negligible parasitic heat load to the superfluid. The remainder of the 6 mW is generated by a heater (2.5 mW average) and by excess superfluid film flow (0.5 mW).

The liquid is phase separated from the gas by a porous plug in the vent line. For low flow rates, the superfluid film flow leaking past the porous plug is a substantial fraction of the total flow of gas vented. In Spitzer this was controlled by instituting a 3.5 mm diameter tube immediately downstream of the porous plug, which limited the film flow to a calculated 0.5 mW equivalent. More drastic measures were used to eliminate the film from the XRS instrument on Astro-E and Suzaku[12].

From the Spitzer example one can see that cooling by vapor alone would not be efficient for a CMB-Pol telescope operating at 2.7 K. Some of the cooling would be generated by a weak thermal link directly from the telescope/instrument into the superfluid helium tank.

At these low flow rates the vapor cooling is also small. The inner vapor cooled shield just outside the telescope settles at 24 K. This implies a vapor cooling of only 27.5 mW at this shield.

Figure 4. The large and the small. On the left is the Herschel observatory with its 2560 liter helium tank in black in the center. On the right is the Suzaku observatory with the 32 liter shiny helium tank near the bottom. The pictures are roughly to scale. Herschel is expected to last over 5 years while Suzaku was designed for a 2-3 year cryogen lifetime. By using very low temperature cryocoolers, the successor to Suzaku, Astro-H, is expected to have a lifetime in excess of 5 years using only 36 liters of helium.
It is useful to estimate the realistic heat loads for a system like CMB-Pol. Assume a 3 m diameter primary mirror operating at 2.7 K. One can get a handle on the expected heat loads by scaling from Spitzer. The Spitzer primary is 0.85 meter in diameter. The cooled mass includes the entire helium dewar including the vacuum shell, and is 240 kg. Of this about 140 kg is the dewar and helium itself. Roughly one third of the cold surface area is due to the dewar. The parasitic heat loads come from conduction in structural supports and electrical leads and radiation from the surrounding 24 K shield which is cooled by the boil-off vapor. The mirror and instrument mass is roughly 100 kg. The total heat load at 5.5 K for Spitzer is 6 mW. The structural support may be scaled linearly with mass and with the square of the shield temperature that is used to intercept conducted heat. The radiation may be scaled linearly with surface area and as the 4th power of the shield temperature, and the electrical leads which feed the instruments and telescope mechanisms will be roughly the same. The mass of the instrument will be assumed to be constant at 75 kg, and the mirror and structure will scale as the cube of the dimension. The outside surface area will scale with the square of the linear dimension. If one arbitrarily assigns 2 mW each to the structure conduction, lead conduction, and the radiation for Spitzer, then the values expected for CMB-Pol are: 17 mW conduction and 25 mW from radiation for a total of 44 mW. For a 5 year mission this would lead to a 2700 liter dewar - on the order of the size of the ISO, Herschel and GP-B dewars. Such a large dewar would probably force the observatory into the heavy lift category of rockets.

Note that it is not necessary for the stored cryogen system (or mechanical cooler for that matter) to reach the telescope/instrument operating temperature of 2.7 K. A closed cycle JT expander and sorption cooler or an Adiabatic Demagnetization Refrigerator (ADR) could provide the final stage of cooling from 10 K or so. In that case a SH₂ dewar could be used with its higher latent heat, and consequently, lower mass.

3. General Comments

Large uncertainties exist in the thermal designs for space flight cryogenic systems. To accommodate these uncertainties the AIAA Spacecraft Thermal Control Handbook recommends design margins for cryogenic systems of 50% at project start, falling to 35% at the critical design review, and 25% at launch[13]. Here margin is defined as the predicted heat load subtracted from the cooling capability divided by the cooling capability. These margins have been derived from flight project experience. It is noted that the last preflight predictions for lifetimes of both IRAS and COBE were 25% above the actual lifetime achieved on orbit.

Mechanical cryocoolers provide the competition for stored cryogen systems over the range from room temperature to a few K. The trade-off between the two usually comes down to cost, mass (which can equate to launch cost), technology readiness level (TRL), reliability and redundancy, servicing, and operational flexibility. A stored cryogen is a large potential cooling capacity: it is equivalent to energy. To compare with continuously produced cooling, from a passive radiator or mechanical cooler, for instance, it is necessary to know the requirement and goal for mission lifetime. In general, for missions expected to last more than one year, a mechanical cryocooler will be the more cost effective solution.

The total mass of a cryocooler system must include the power system (solar arrays, power conditioning electronics, batteries, and cryocooler controllers, the radiators to dissipate the cryocooler power, as well as the cryocooler components itself. Even so, the overall mass trade came down in favor of a cryocooler system for JWST (240 kg vs. 50 kg). In addition, the dewar mass and volume must all be absorbed in the cold section of the instrument or observatory. Mass here is at a premium due to the need to limit parasitic heat loads through the structure.

An assessment of the maturity of a technology is usually made through the use of its Technology Readiness Level (TRL). The TRL of a component or subsystem is defined on a numerical score of 1-9 with 1 being the least mature (the device exists as a concept only) through TRL 9 (the device has flown in its present form). See Table 1. It is generally assumed that stored cryogen systems have a TRL of 7-9 because many dewars have flown before. In fact helium dewar systems are generally TRL
5 at best, because the design is always somewhat different. As a case in point, the COBE dewar was supposed to be a rebuild of the successful IRAS dewar, but in fact 50% of the drawings were changed including the cryogen tank size.

A stored cryogen system in general is single string. It is extremely cumbersome for a dewar system to include redundancy without providing a completely separate cryostat. Even components such as valves have limited redundancy due to increased mass and size. Most helium dewars’ boil off rates have been dominated by parasitic heat loads which does not allow a dewar to be held back for use later

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<td>Final product in mission configuration qualified through test and evaluation</td>
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**Table 1. Definitions of Technology Readiness Levels (TRLs).**
in the mission. In contrast, most cryocooler systems can be made fully or partly redundant. A spare cryocooler can remain off or in use with limited power with only a small penalty in parasitic heat load on the primary cooler. Joule Thomson expanders are usually isolated by long lengths of low conductivity material and thus have a negligible extra parasitic. One can make the electronics part of the cryocooler system redundant (the path that JWST has taken with its cryocooler) since there are no cold moving parts and the warm moving components in the compressors have very high reliability and have been successfully used on many missions.

One must consider the ground operations up to launch that a cryogenic system must go through. Stored cryogen systems need constant care and are more vulnerable to leaks, vent line plugs, and ground support equipment failures. Before launch the servicing equipment that maintains the dewar close to its operating temperature in space must be removed. This limits the length of time that the dewar may sit on the launch pad before servicing must be reinitiated, thus limited the launch schedule flexibility.

During the mission one must consider the parasitic load on the cryogen when scheduling events. Decontaminating optics or detectors is difficult or impossible given the much larger heat leaks to the cryogen. With a known or estimated end date, on orbit check out and mission planning has an extra level of urgency. One need only look at the WIRE and Astro-E2 (Suzaku) dewar failures to see that one mistake can lead to the end of a mission or instrument.

4. Summary
A number of far infrared/submillimeter/CMB missions are enabled by advancing the state of the art in efficiently designed space flight cooling systems. Multi-stage stroed cryogen-free cooling systems have been developed by Planck and JWST. Verification of the thermal performance of these high performance systems with an open geometry operating over a large temperature range is difficult and potentially expensive. A combination of conservative design subscale tests to validate the thermal models is warranted. Trades for use of active coolers versus stored cryogen systems have been made. Over the last several years significant advances have been made in mechanical cryocoolers operating below 10 K and these look to be the choice over stored cryogens for the future.

5. References

