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A 100 mK BOLOMETER SYSTEM FOR SIRTF

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Abstract

Progress toward a prototype 100 mK bolometric detection system for SIRTF is described. Two adiabatic demagnetization refrigerators (ADR's) have been constructed, and used to investigate the capabilities necessary for orbital operation. The first, a laboratory ADR, has demonstrated a hold time at 0.1 K of over 12 hours, with temperature stability ~3 μK RMS achieved by controlling the magnetic field. A durable salt pill and an efficient support system have been demonstrated. A second ADR, the SIRTF flight prototype, has been built and will be flown on a balloon. Techniques for magnetic shielding, low heat leak current leads, and a mechanical heat switch are being developed in this ADR. Plans for construction of 100 mK bolometers are discussed. Three important cosmological investigations which will be carried out by these longest wavelength SIRTF detectors are described.

Introduction

The Space Infrared Telescope Facility (SIRTF) will require detectors in the 200 μm - 700 μm range with NEP's of order 10^{-17}W/√Hz for background limited or confusion limited observations [1]. To meet these specifications, bolometers must be cooled below temperatures attainable with He^3 refrigerators. The Multiband Imaging Photometer (MIPS) will use bolometers cooled to 0.1 K by an adiabatic demagnetization refrigerator (ADR). Although ADR's have been in use for over 50 years [2], only in the past few years has rapid progress been made toward implementation of ADR cooled detectors in astronomical observations. Ground-based observations have been made at mountain top observatories [3] and at the South Pole [4]. Balloon-borne ADR's will be flown this year, and both the SIRTF and AXAF satellites are planned to include ADR's. The focus of this report will be recent work at Berkeley on construction of a prototype for the SIRTF refrigerator; its design addresses all of the relevant issues for operation in the orbital environment. This prototype will be used on a balloon-borne telescope.

We will also discuss the progress towards construction of high performance 100 mK bolometers, and three exciting cosmological observations which are possible using such bolometers on SIRTF. These observations would benefit greatly from an extension of the SIRTF capability to 1500 μm.

Principles of Adiabatic Demagnetization

The refrigeration cycle of an ADR exploits the interaction between the atomic magnetic moments in a paramagnetic salt and an externally applied magnetic field. This process is fully discussed elsewhere [5,6]. The cycle can be described in terms of the entropy of the paramagnetic salt, S(T,H), where T is its temperature and H is the applied field. Fig. 1 displays the dependence of the entropy on temperature and field for the paramagnetic salt, ferric ammonium alum ($Fe(NH_4)(SO_4)_2 \cdot 12H_2O$), which is used in this work. The refrigeration cycle begins at point A; the entropy is reduced by increasing the magnetic field, thus ordering the spins. At point B, thermal contact to the helium bath is broken, and as the

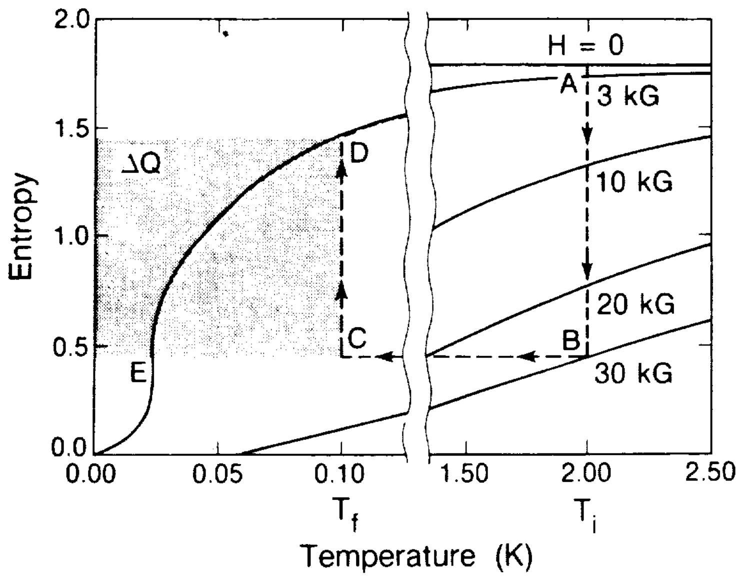

Figure 1. Entropy vs. temperature for ferric ammonium alum for several different applied magnetic fields (kG). The vertical axis is in units of R=8.31 J/moleK. The refrigeration cycle follows the path A-B-C-D (see text). Starting from T_i=2K and H=30 kG, the temperature of the salt pill is reduced to T_f=0.1K when H is reduced to ≈1.5 kG. The shaded area is equal to the energy the salt can absorb at 0.1K.

field is reduced the temperature drops, until point E is reached at zero field. As heat leaks into the salt, the system follows the H=0 line to point D; during this time, the bolometers may be maintained at 100 mK by a heater.

A more efficient cycle, called isothermal demagnetization, halts demagnetization at point C, with T=0.1 K. The field H is gradually reduced to compensate for the heat leak, maintaining T=0.1 K along path CD. In this case, the cooling power of the refrigerator is nearly doubled - the total heat absorbed per cycle is proportional to the shaded area in Figure 1, rather than just the area to the left of curve ED. Our ADR's take this approach, regulating the cold stage to 100 mK by controlling the magnetic field on the salt.

Apparatus

Two ADRs are discussed in this paper. One is a complete operating refrigerator designed for testing bolometers in the laboratory. The second, which will serve as a prototype for the SIRTF flight refrigerator, is being tested. It is designed to cool bolometers on a balloon-borne astronomical telescope.

The laboratory refrigerator is shown in Fig. 2. The paramagnetic salt pill is suspended inside a vacuum space by Kevlar cords from walls cooled to ~1.4K by a pumped He^4 bath. The magnetic field is provided by a superconducting magnet immersed in this bath. Thermal contact between the salt pill and the 1.4K walls is achieved by a He^4 exchange gas heat switch. The bolometers being tested and the thermometer that is used for temperature regulation are mounted on a cold stage connected to the salt pill.

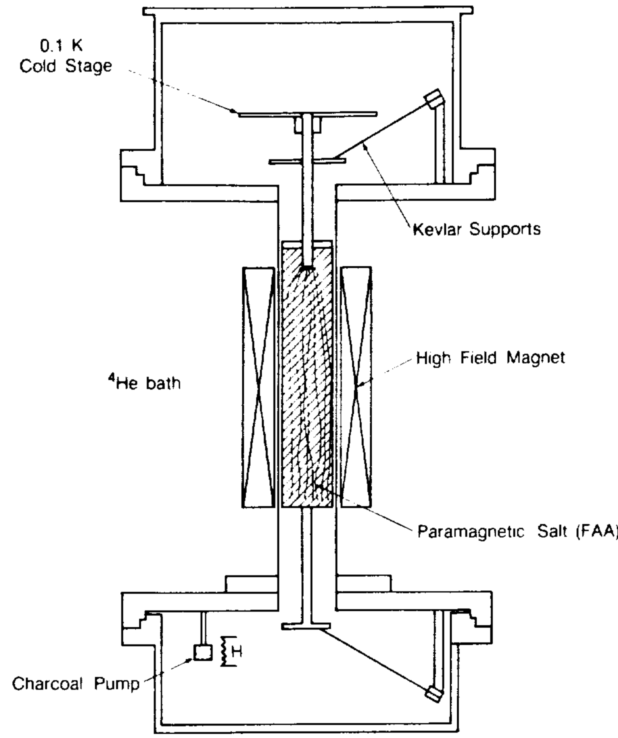

Figure 2. The laboratory adiabatic demagnetization refrigerator. The entire assembly is surrounded by a He^4 bath. The charcoal pump is part of the He^4 gas heat switch.

The flight refrigerator shown in Fig. 3 is similar to the laboratory refrigerator in the design of the salt pill, suspension system, and the cold stage. It uses a pumped He^4 bath as a 2K reservoir, but the entire refrigerator, including the superconducting magnet, is conduction-cooled through a thermal bus that is attached to the cold plate of a liquid He dewar [7]. It has a magnetic shield and an electro-mechanical heat switch. The flight prototype refrigerator is a compact structure that will bolt to a cold plate. The total mass of 3.4 kg is dominated by the 1.9 kg magnetic shield. Both of these refrigerators will be discussed further in terms of the issues of concern for use on balloons and in space.

Space Flight Issues

Several critical issues must be addressed in designing an ADR for operation in a satellite [8]. SIRTF will have three major instruments which share the cooled telescope and the liquid He^4 reservoir. The ADR is used for the longest wavelength detectors of one instrument, the MIPS. The length of the SIRTF mission is determined by the lifetime of the cryogen and is planned to be ≈5 years. The ADR must be reliable, must not interfere with the other instruments, and must not place excessive demands on the cryogen. The specific issues addressed below are:

- paramagnetic salt pill reliability
- salt pill suspension and hold time
- cold stage temperature stability
- magnetic shielding

- low heat load magnet leads
- reliable heat switch
- low mass, compact size

Paramagnetic Salt Pill

For space applications there are several concerns about the salt pill. First, commonly used paramagnetic salts like ferric ammonium alum (FAA) and chromic potassium alum (CPA) are mildly corrosive. Secondly, they dehydrate when exposed to air or vacuum. Finally, they decompose at moderate temperatures: 40°C for FAA and 89°C for CPA.

To establish good thermal contact between the paramagnetic salt and the cold stage and to prevent corrosion the salt is grown directly onto gold wires. The wires are silver-soldered to a copper post that in turn is bolted to a copper cold stage. The solder joint is gold-plated. The salt pill is 2.2 cm in diameter × 10 cm long and contains ≈40 grams of ferric ammonium alum and 200 gold wires. The wires are 250 μm in diameter. This salt pill is sealed in a stainless steel can to

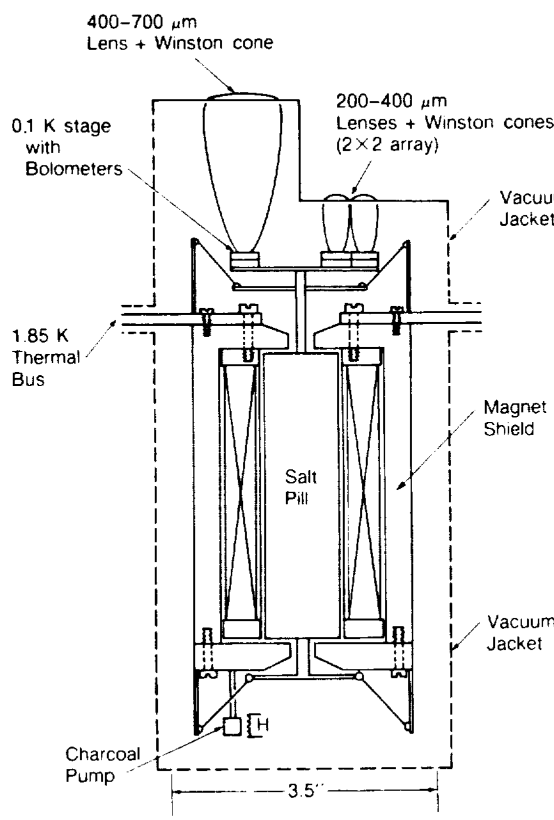

Figure 3. The flight prototype refrigerator now being tested. The refrigerator and superconducting magnet are cooled by conduction through the thermal bus. The He^4 gas heat switch may be replaced by a mechanical heat switch; the vacuum jacket then becomes unnecessary. The magnetic shield is to prevent stray magnetic fields from disturbing the bolometers or other instruments, both during normal operation and in the event of a magnet quench.

prevent the salt from dehydrating. Stainless steel end caps are sealed in place with epoxy [9].

The FAA salt pills made in this manner show no degradation in performance, even when stored at room temperature for several months. CPA salt pills will be used for SIRTF because their higher decomposition temperature is more compatible with the expected bake-out temperatures of the cryostat. A shake test of a CPA salt pill is planned to check the effects of launch vibrations on the salt pill.

Salt Pill Suspension

The salt pill and cold stage of the flight ADR are suspended from 2 K walls by 50 lb. test Kevlar cords as illustrated in Figure 4. A miniature pulley at each vertex of the star configuration allows for convenient and uniform tensioning. A drop of oil on each pulley freezes at liquid helium temperatures, locking the suspension into place. The lowest resonant frequency of the system, with the support warm, is measured to be 240 Hz, whereas the signal frequencies and the bulk of the launch vibrational energy will be below 100 Hz. The support should withstand a static load of over 150 g's. A complete vibration test of the system will be conducted shortly.

In the laboratory ADR, the heat leak from 1.4 K to 0.1 K for this support has been measured to be ~0.25μW. This will scale roughly as the cube of the temperature at the hot end; the hold time is inversely proportional to the heat leak.

Hold Time

The hold time of the laboratory ADR stage at 0.1 K easily exceeds the 12 hour hold time of the He^4 dewar. The achieved cooling power of the laboratory ADR is 50-70% of its theoretical capacity; this shortfall is probably attributable to the fact that the field in the solenoid achieves its rated 3 T only near the center of

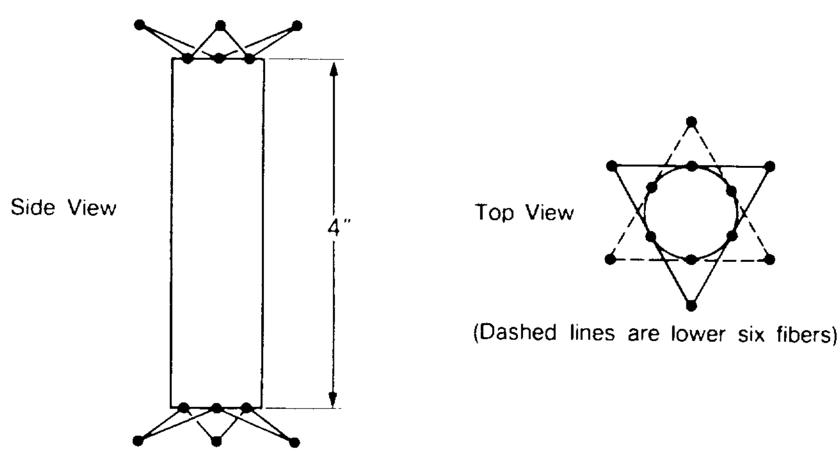

Figure 4. Schematic diagram of the suspension of the salt pill. The fibers are Kevlar cord. The black dots represent small pulleys which ensure uniform tension in the fibers.

the bore, whereas the salt fills the bore. The magnetic shield in the SIRTF prototype acts as a flux return which makes the field uniform over the entire salt pill. We project a hold time of order 24 hours for the SIRTF ADR, using a CPA salt pill and a 2.0 K helium bath. Since the time required to recycle is less than 30 minutes, the duty cycle of the ADR will be 98%, which is more than sufficient for proposed modes of observation.

Temperature Stability

In order to operate thermal detectors such as bolometers on the cold stage, the temperature must be very carefully regulated. For ideal refrigeration efficiency, one would like to regulate the temperature solely by controlling the magnetic field, following the vertical line CD in Figure 1 as closely as possible. In our laboratory ADR, the temperature is read out with commercial equipment - a Lakeshore Cryotronics GR-200A-30 thermistor [10] and a BTI Model 1000 potentiometric conductance bridge [11]. A personal computer reads the bridge and determines the desired magnet current, which is implemented by a custom built, digitally controlled, 16 bit, low ripple current supply. The system stabilizes the temperature readout to 2.8 μK RMS for several hours.

This level of stability is sufficient for our current work; a firm determination of the SIRTF requirement must await measurements on actual bolometers. The stability requirement also is dependent upon the observing mode of the SIRTF bolometers. Since the 2.8 μK variance is consistent with the noise specification of the BTI bridge, a lower noise bridge preamp is the obvious first step to obtain higher stability, should it be required.

A smaller and lighter version of all of the electronics necessary to operate the laboratory ADR is under construction for use on the balloon flight of the SIRTF prototype ADR.

Magnetic Shield

We have constructed and tested a ferromagnetic shield, necessary to avoid disturbing other SIRTF instruments, especially in the event of a magnet quench. The shield also improves the uniformity of the magnetic field inside the salt pill, and thus the efficiency of the refrigerator. The shield was designed using a computer program described elsewhere [12]. The shield is made of vanadium permendur, an alloy of iron, cobalt and vanadium with a high saturation induction.

Tests of this shield show that with the magnetic field inside the shield at its maximum value of 30 kG, the field more than 3 cm outside the shield is <1 G. Since the time constant for the decay of the field after a quench of the superconducting magnet is ~0.2s, the rate of change of the magnetic field outside the shield will be less than 5 G/s. The largest e.m.f. that could be induced in any single loop of wire in SIRTF would be less than 15 μV.

Magnet Leads

The superconducting solenoid [13] selected for the flight prototype requires 6 A to develop 30 kG. The magnet is quite compact; it has a 2.5 cm diameter bore, 5.7 cm outside diameter, and a 10 cm length and uses 140 μm diameter NbTi windings. Finer wire could be used to build a 3 A, 30 kG magnet [13] with the same dimensions. Copper leads can carry 6 A in typical cryogenic systems with modest loading (Joule heating and thermal conduction) on the cryogens. In SIRTF the combination of thermal conduction and Joule heating from 6 A leads would give an average dissipation of ~10 mW in the 2K cryogen. The thermal and electrical properties of superconductors can be used to minimize this dissipation. Leads of Nb_3Sn from 2 K to ~12 K would almost eliminate the dissipation in the 2 K cryogen. The new high-T_c superconductors can potentially be used up to ~60 K.

Heat Switch

The He^4 gas heat switch used in the laboratory refrigerator is reliable and dissipates little heat (~30 mW when the charcoal heater is on). The duty cycle is <1% but requires a gas tight container around the ADR to isolate it from the thermal vacuum of the rest of the satellite. In particular, a vacuum window is required in the optical path (see Fig. 3). The solenoid-actuated heat switch shown in Fig. 5 has been developed to avoid these complications. The switch uses a commercial solenoid [14] to squeeze together a pair of copper jaws which contact a copper tab attached to the salt pill. The contacts are gold plated. The switch has a thermal conductivity of 0.015 W/K at 1.7 K when activated with 100 mA of current. This conductivity is sufficient to allow the isothermal magnetization step in the refrigeration cycle to occur in less than 5 minutes. When the solenoid current is off, the contacts fully disengage so the thermal conductivity is zero. The energy imparted to the salt pill when the jaws release the tab is $\sim 3\times10^{-3}$J. This energy is

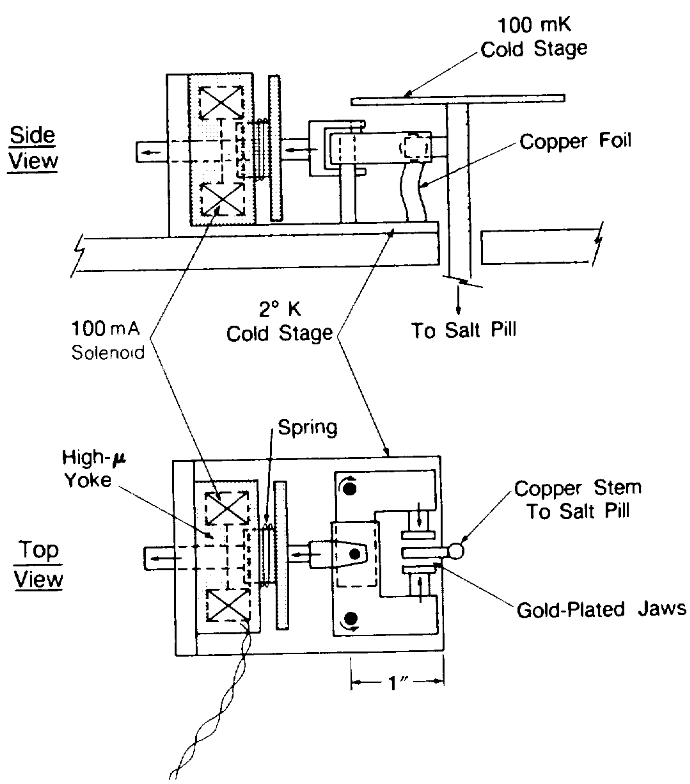

Figure 5. The solenoid-actuated heat switch. When activated with 100 mA, the solenoid forces the jaws together with ≈230 N of force. The spring pulls the jaws apart again when the current is off. The thermal conduction in the "off" state is zero.

small compared to the heat capacity of the salt pill at 2 K (~1 J), so its temperature will rise only slightly upon release. The switch was tested for reliability; in 4000 cycles over 2 days the "on" thermal conductivity remained stable to ~5% and the jaws always released the contact to the salt pill in the "off" condition. This number of cycles is equivalent to one 5-year flight of SIRTF with the refrigerator cycled every 12 hours. A new heat switch is being developed that employs a superconducting solenoid.

100 mK Bolometers

We do not expect bolometers for use at 100 mK to look very different from those in use at 300 mK. We have measured the temperature dependence of the resistance R(T) for several samples of neutron transmutation doped germanium provided by Prof. Eugene Haller. These thermistors, as well as ion-implanted silicon thermistors, exhibit large non-thermal electrical non-linearities, perhaps due to an electric field dependent resistance or a hot electron effect. These non-linearities complicate the prediction and measurement of bolometer performance; we wish to have a satisfactory model, even if only phenomenological, of this behavior before attempting to optimize the SIRTF bolometers. Bolometers which are not optimal may of course be fabricated; we will do this shortly, and other groups have done so already, in order to gain information on the behavior of thermal links, absorbers, etc. Our laboratory ADR and regulation system are capable of attaining any temperature from 50 mK to 2 K within minutes, allowing rapid measurements of these properties.

Observations with SIRTF Bolometers

The bolometric channels on the MIPS will be able to observe numerous sources of submillimeter radiation, including the cosmic microwave background radiation (CBR) and the recently discovered submillimeter excess [15]. The MIPS will be ideally

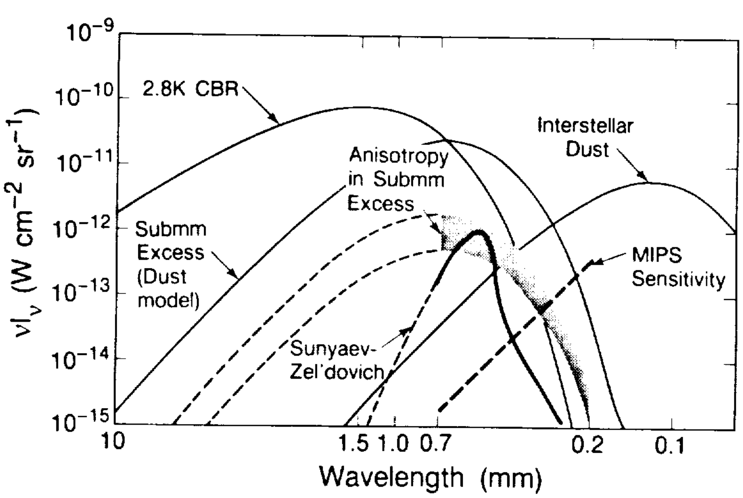

Figure 6. Sensitivity of the MIPS bolometer channels to submillimeter sources. The spectrum of the submillimeter excess is a fit to a dust model [16]. The predicted anisotropy in this excess is from Bond et al. 1986 [17]. The plotted signal from the Sunyaev-Zel'dovich effect is the expected enhancement in the CBR signal when viewed through the Coma cluster. The MIPS sensitivity is for a 500-second integration and includes detector and photon noise and confusion from galaxies and IR cirrus.

suited for searching for small scale (~arc minutes) anisotropy in the CBR and the submillimeter excess and for observing the Sunyaev-Zel'dovich effect (see Fig. 6). The possibility exists of extending the longest wavelength response of the bolometric channels beyond 700 μm; SIRTF would then have an even greater ability to detect these sources and to distinguish them from each other.

Acknowledgments

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