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A Progress Report on using Bolometers Cooled by Adiabatic Demagnetization Refrigeration

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For sensitive detection of astronomical continuum radiation in the 200 μm - 3 mm wavelength range, bolometers are presently the detectors of choice. In order to approach the limits imposed by photon noise in a cryogenically cooled telescope in space, bolometers must be operated at temperatures near 0.1 K. We report our progress in building and using bolometers that operate at these temperatures. Our most sensitive bolometer had an estimated NEP of 7×10^{-17} W $\text{Hz}^{-1/2}$. We also briefly discuss the durability of paramagnetic salts used to cool our bolometers.

Theory

The noise equivalent power ($NEP_{optical}$) of a bolometer will be the quadrature sum of noise due to absorbed photons and noise components intrinsic to the detector. The $NEP_{optical}$ of a bolometer limited by photon induced noise from a thermal background is given by the following expression [1]:

$$NEP^2_{photon} = \frac{4\,A\,\Omega\,(kT_b)^5\,\varepsilon\,f}{\eta\,c^2\,h^3} \int \frac{x^4}{e^x - 1}\left(1 + \frac{\eta\,\varepsilon\,f}{e^x - 1}\right) dx$$

The corresponding expression for the absorbed background power is:

$$Q = \frac{2 A \Omega T_b^4 k^4}{c^2 h^3} \int \frac{x^3}{e^x - 1} \eta \varepsilon f \, dx$$

$$x \equiv \frac{h \nu}{k T_b}$$

where $A\Omega$ is the optical throughput, T_b is the background temperature, ε is the background emissivity, f is the optical system transmission, η is the bolometer absorptivity, k is the Boltzmann constant, c is the speed of light, and h is the Planck constant.

Bolometer optimization depends strongly upon the character of the background radiation [2]. For a bolometer exposed only to T_b = 2.7 K cosmic background in the 400 μm - 700 μm wavelength range by a diffraction limited telescope, and assuming that ε=1, f=0.5, η=1, we find $NEP_{photon} = 5 \times 10^{-18}$ W $Hz^{-1/2}$ and Q = 44 fW. The contribution of other astrophysical backgrounds [3], and telescope self-emission will raise both NEP_{photon} and Q. The Multiband Imaging Photometer for SIRTF (MIPS) has a sensitivity goal of $NEP_{optical}$ = 5×10^{-17} W $Hz^{-1/2}$ in the 200 μm - 700 μm wavelength range [4]. As another example, ground based observations in the 1.0 - 1.4 mm range (assuming ε = 0.5 and T_b = 273 K) imply $NEP_{photon} = 1.4 \times 10^{-15}$ W $Hz^{-1/2}$ and Q = 870 pW.

Detector induced noise cannot be less than the noise due to thermal fluctuations; its contribution to $NEP_{optical}$ is $NEP_{thermal} = \eta^{-1}(4kT^2G)^{1/2}$, where G is the thermal conductance, and T is the bolometer temperature. We desire $NEP_{photon} >> NEP_{thermal}$ for background limited performance. Most bolometers heat up, and become slower and less sensitive as the background power is increased from zero. It becomes a bolometer design challenge to maintain the above inequality, while the bolometer absorbs the appropriate background power. The best bolometers operating at 0.3 K have $NEP_{optical}$ of about 4×10^{-16} W $Hz^{-1/2}$ [5]; to reach lower NEPs, a bolometer operating at 0.1 K is required.

Experiment

Useful materials for bolometers operating at 0.1 K that meet the more stringent low background requirements appear to exist. We have adopted a design shown in Figure 1. Our bolometer component selections were motivated by our desire to keep the total heat capacity, C, as low as possible. For our bolometers, the astronomical radiation is absorbed by a 120 nm Bi film [6] deposited onto a sapphire substrate. The temperature change induced by the heating of the Bi film is measured with a Ge:Ga thermistor [7]. The thermistor is maintained near 0.1 K by 25 μm brass wires, which also serve to provide electronic conduction paths to measure the induced impedance changes.

The bolometer is mounted on the work surface of our adiabatic demagnetization refrigerator (ADR). Our ADR system can reach temperatures of less than 0.05 K, and can maintain temperatures of 0.1 K to within 14 μK, for periods of time in excess of 12 hours. Additional details of the refrigerator system and its performance are described in detail elsewhere [8,9].

We digress to discuss an important issue affecting the reliability of ADRs used for cooling detectors: the lifetime of the magnetic refrigerant. Paramagnetic salts useful for cooling bolometers in ADRs are often chemically active and can deteriorate when stored at room temperature. Chemical reactions may occur that alter their low temperature magnetic properties and degrade or render them useless for ADR applications. We have achieved considerable success using chromic potassium sulfate (CPS) as our working paramagnetic salt. We encapsulate the CPS within a brass cylinder, with epoxy end caps to hermetically seal the CPS from the atmosphere. We have used one such salt pill over a period of three years without noticeable degradation of refrigeration performance. This result suggests that CPS is a very suitable magnetic refrigerant for reliable long-term use in ADRs.

Returning to our discussion of detectors, we designed our bolometers to have a thermal conductance, G equal to 2×10^{-8} W/K, so that they could effectively function in the presence of background power up to 400 pW. Thermodynamic induced noise places a minimum contribution to $NEP_{optical}$ of $\eta^{-1}(4kT^2G)^{1/2}$, hence $NEP_{optical} > 1 \times 10^{-16}$ W Hz$^{-1/2}$. This value is higher than that required for a cosmic background limited bolometer, but is less than NEP_{photon} for the ground-based application mentior .d above. In order for the bolometer to respond to modulated power at chopping frequencies of 10 Hz and higher, we desired a bolometer heat capacity $C < 10^{-10}$ J/K. This requirement was achieved, and the estimated contributions to the heat capacity of the materials we used are listed in Table 1.

We estimated $NEP_{optical}$ of our bolometer by measuring the current, I, and voltage noise v_n, as a function of electrical bias across the bolometer, to infer an electrically determined value of the bolometer NEP (NEP_{elec}). We then applied the relation $NEP_{optical} = \eta^{-1}\ NEP_{elec}$ [1], assuming a value of $\eta=1$, as is appropriate for a bolometer in an integrating cavity. Our bolometers were biased through a Eltek Model 106 metal film resistor, having an impedance of 250 MΩ at 2 K. A cold J230 JFET source-follower circuit was coupled to the bolometer, to match the bolometer impedance and to minimize microphonic and electrical interference. The current-voltage relationship for our most sensitive bolometer is shown in Figure 2. Our measured electrical parameters are listed in Table 2. From these data, we estimate a responsivity of 6.4×10^{8} V/W and $NEP_{optical}$ of 6.7×10^{-17} W $Hz^{-1/2}$ at the bias point marked by an arrow in Figure 2. This value of the NEP is the lowest recorded for infrared and submillimeter bolometers, and represents a significant advance in sensitivity.

We have measured the optical response of our bolometer, to modulated power variations (Figure 3), to infer a time constant of 3 ms for the detector. This value provides useful, fast response for chopping radiometric applications. Further description of the bolometer and measurements made of it are reported elsewhere [9].

The bias point was selected to be such that the electrical power dissipated in the bolometer is greater than that of a hypothetical background power for 44 fW (as may be appropriate for a low background spacecraft application). This choice of electrical bias is close to optimal for this radiometric application [2]. In Table 3, we list the theoretical contributions to the NEP; the total contribution is equal to our measured NEP_{elec} to within experimental error.

However, we have observed a discrepancy in the value of the thermal conductance of our bolometer and the value we expected. An independent measurement of the thermistor yields a resistance-temperature relation, $R = 2.87\ \Omega \cdot \exp(4.58\ K^{1/2}\ T^{-1/2})$; we use this expression to calibrate the temperature of the bolometer, as a function of bias from Figure 2. From this temperature and bias power data, we infer a thermal conductance of our bolometer, $G = 1.6 \times 10^{-9}$ W/K, which is one order of magnitude lower than the value we would expect from published brass thermal conductivity data [10]. It is possible that boundary resistance effects induced by the electrical contacts, and compositional differences in the brass wire [11] used account for the differences in measured values; we do not fully understand the origin of this discrepancy. The low G value does not affect the accuracy of the electrical self-calibration procedure to estimate NEP_{elec}, but does limit the maximum background power the bolometer can accept.

It has been suggested that non-ohmic behavior of bulk thermistor material may be partially responsible for the nonlinearity shown in Figure 2, and may affect the accuracy of the self-calibration procedure we used to infer NEP_{elec} [12]. We do not believe this to be the case for our bolometers. The amount of bias power per unit volume necessary to reduce the resistance in 0.1 K Ge by 30% is 4×10^{-2} W/m^3 [13]. For our 0.1 K bolometer, the bias power density was 4×10^{-4} W/m^3, which suggests that non-ohmic behavior is a less than 1% effect, and has a negligible effect on NEP_{elec}.

Observational Tests

We have used our adiabatic demagnetization refrigerator system to perform one millimeter continuum observations using the Hale 5 m telescope at Palomar Mountain. During our observing run during November 1985, we used an unoptimized bolometer operating at 0.2 K. Construction materials were similar to our 0.1 K bolometer described earlier, except that thermistor material was selected with a lower dopant density, to provide a bolometer resistance of 1 MΩ at 0.2 K. In addition, brass wire of diameter 50 μm was used, to design this bolometer for the high background expected for our ground-based observing location. A non-optimal Bi film thickness of 30 nm was applied to the sapphire substrate. NEP_{elec} of this bolometer was estimated to be 2×10^{-15} W $Hz^{-1/2}$.

We estimated a noise equivalent flux density (NEFD) of 10 Jy $Hz^{-1/2}$ for our ADR bolometer system, based upon one millimeter wavelength measurements of the planet Jupiter and the radio galaxy 3C84. The ADR system NEFD was higher than the 6 Jy $Hz^{-1/2}$ of an optimized helium-three cooled system [14], which was placed onto the telescope after the ADR. The relatively high NEP_{elec} , low absorptivity of the detector, and optical mismatch to atmospheric transmission windows precluded the ultimate in NEFD to be realized with the ADR system. We expect that bolometer optimization, and improved optical filtering will lower the ADR NEFD substantially.

As bolometers are thermal detectors, we expect them to be affected by temperature variations in the refrigeration system. In order to investigate the magnitude of this effect, we monitored the NEFD during temperature regulation of the ADR at the telescope. Regulation effects did not introduce significant amounts of excess noise into our radiometric observations. This result is consistent with our expectations, as the effect on the responsivity induced by bolometer heat sink temperature variations is given by the following expressions [9]:

$$\frac{\Delta S}{S} = \frac{1}{1 - I^2 \alpha} \frac{\Delta \alpha}{\alpha}$$

$$\alpha \equiv \frac{1}{G} \frac{dR}{dT}$$

where S is the responsivity, and $\Delta\alpha$ is calculated over the regulated temperature range. For our 0.2 K bolometer operated at Palomar, responsivity variations were calculated from the above equations to be less than 1%. For our 0.1 K bolometer, we estimate $\Delta S / S = 0.2\%$, for 14 μK temperature variations. Thus, temperature regulation effects would not be expected to degrade the bolometer system sensitivity to a significant degree.

Conclusions

We have successfully constructed and used bolometers cooled by ADR at an astronomical observatory to perform sensitive radiometric measurements. We have achieved NEP_{elec} as low as 7×10^{-17} W $Hz^{-1/2}$, for bolometers operating at 0.1 K . We expect that bolometers can be made more sensitive by decreasing the thermal conductance further and by cooling the load resistor below 2 K; such changes should readily achieve $NEP_{optical}$ of less than 5×10^{-17} W $Hz^{-1/2}$ as required for SIRTF and other low background applications.

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Table 1

Bolometer Thermal Data at 0.1 K

Material	Volume	Est. Heat Capacity, C	Ref.
Bismuth Film	1.1×10^{-3} mm^3	1.3×10^{-13} J/K	[15]
Sapphire Substrate	2.2 mm^3	8.4×10^{-13} J/K	[16]
Ge:Ga Thermistor	1.0 mm^3	3.5×10^{-12} J/K	[16]
Epoxy	0.01 mm^3	7.0×10^{-12} J/K	[16]
Brass Wires	3.0×10^{-3} mm^3	$1/3 \times 3.4 \times 10^{-11}$ J/K	[17]
In Solder	4.2×10^{-3} mm^3	5.5×10^{-13} J/K	[16]

	Theoretical	Experimental
Total heat capacity	2.3×10^{-11} J/K	6×10^{-12} J/K
Thermal conductance of brass wire	2.0×10^{-8} W/K	2×10^{-9} W/K
Time constant	1.1 ms	3 ms

Table 2

Measured bolometer electrical parameters

(Using notation of reference [1])

Z, dynamic impedance	36 MΩ
R, resistance	42 MΩ
I, current	9.8×10^{-11} A
v_n, voltage noise	43 nV $Hz^{-1/2}$ at 20 Hz
T_S, bolometer sink temperature	0.0725 K
R_L, load resistance	250 MΩ
T_L, load resistor temperature	2 K
S, responsivity	6.4×10^{8} V/W
NEP_{elec}	6.7×10^{-17} W $Hz^{-1/2}$

Table 3

Theoretical Estimates of Bolometer NEP_{elec} contributions [1]

$NEP_{thermal}$	2.3×10^{-17} W $Hz^{-1/2}$
$NEP_{Johnson, R}$	1.6×10^{-17} W $Hz^{-1/2}$
$NEP_{Johnson, load}$	3.3×10^{-17} W $Hz^{-1/2}$
$NEP_{amplifier}$	2.3×10^{-17} W $Hz^{-1/2}$
NEP_{elec}	4.9×10^{-17} W $Hz^{-1/2}$

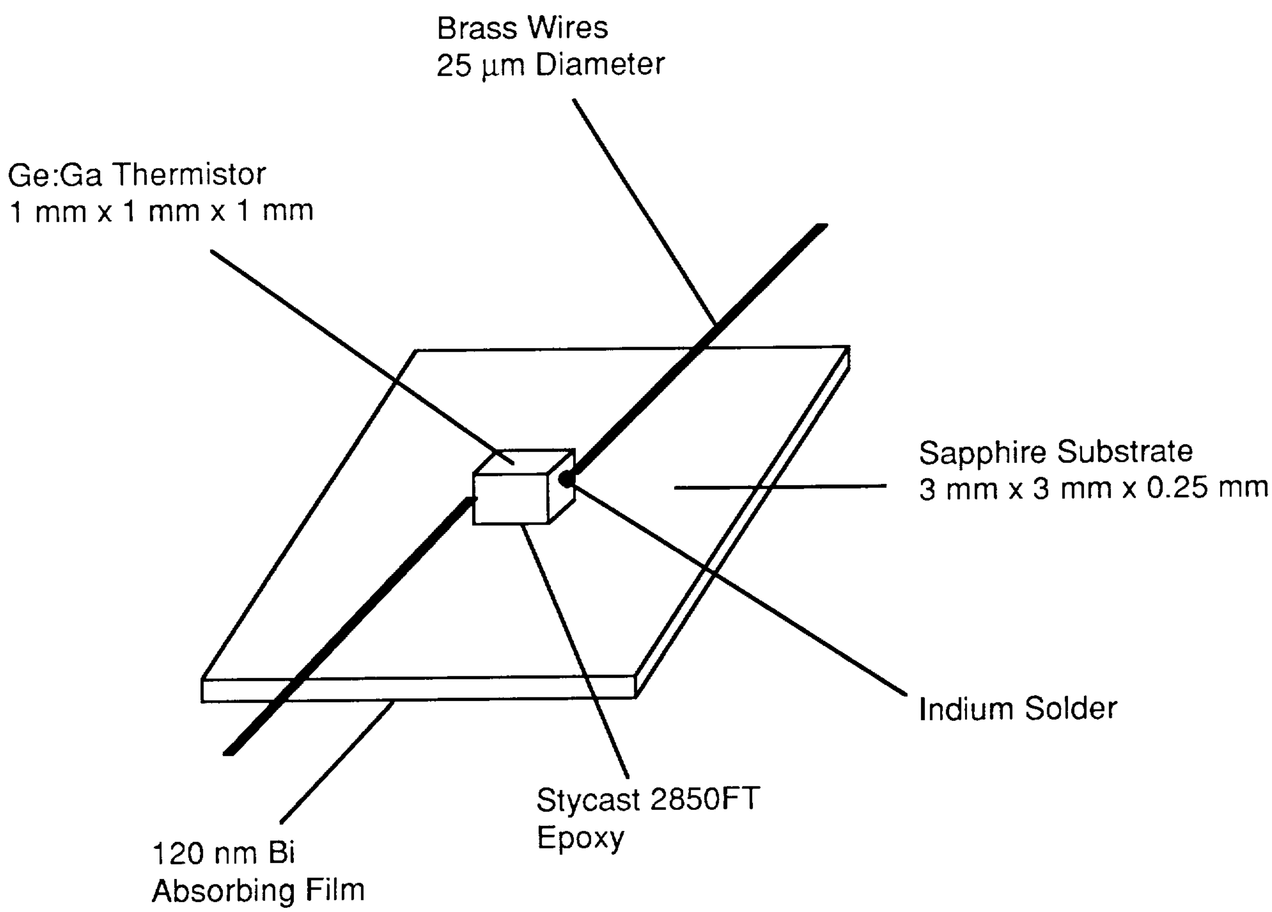

Figure 1

Bolometer Materials and Dimensions

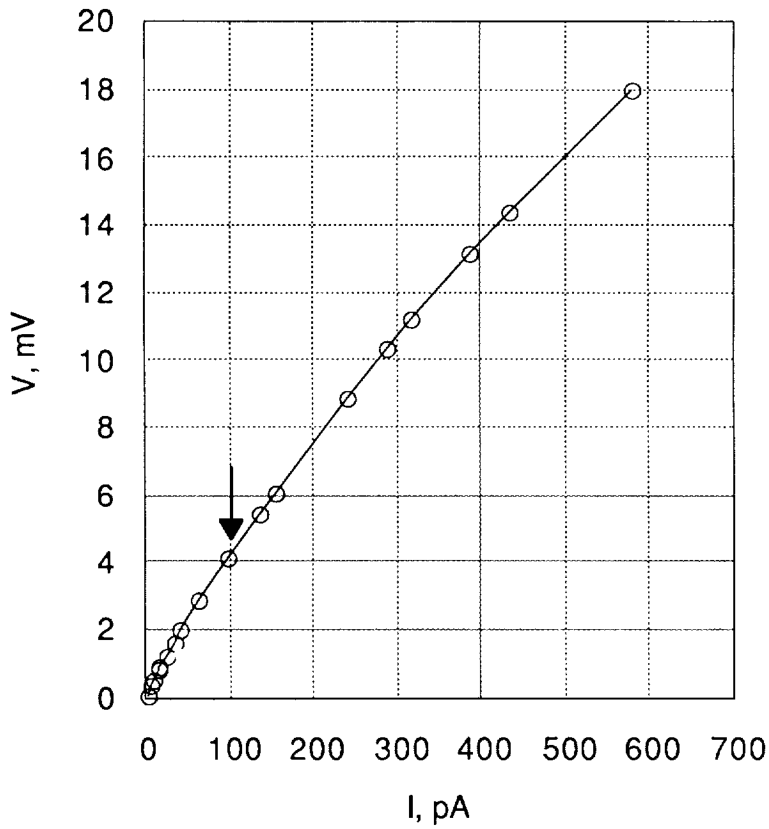

Figure 2

Bolometer Load Curve

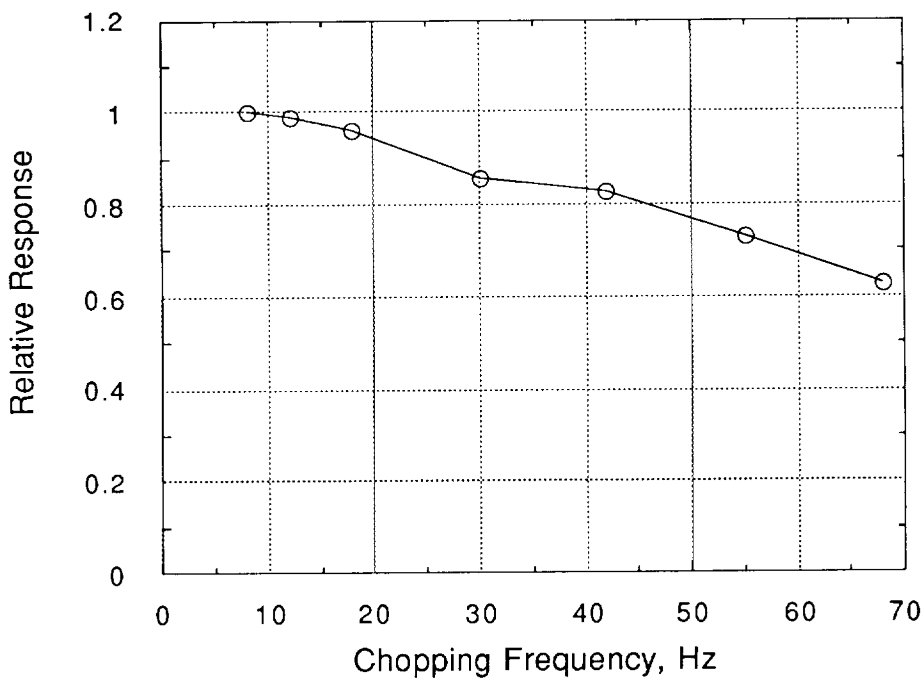

Figure 3

Bolometer Response to Modulated Radiation