Measurement of the Dipole Moment of the Cosmic Background Radiation at mm and Sub-mm Wavelengths

Mark Halpern
Department of Physics, UBC, Vancouver, Canada

Abstract

Sensitive measurements of a dipole anisotropy of the Cosmic Background Radiation at wavelengths of 1.7 and 0.8 mm are presented. Under the assumption that the dipole moment is caused by a doppler shift, these measurements are of sufficient precision to constrain spectral distortions of the CBR at short wavelengths. Measurements of the brightness and shape of diffuse galactic emission are also presented.

Introduction

This report contains some of the results of a balloon borne observing program undertaken at MIT to measure large angular scale anisotropy of the Cosmic Background Radiation.[1] The program started in 1974 and has included six flights of differential radiometers which operate at mm and sub-mm wavelengths. They are sensitive to the bulk of the energy in the CBR, well into the Wein tail. At these wavelengths atmospheric emission seen from the surface of the earth is brighter than the CBR and sensitive measurements, even differential measurements, are not possible from the ground. Therefore, we have used scientific balloons to carry our radiometers to an altitude of roughly 40km., above 99% of the atmosphere.

The Experiment

The sophistication of the radiometers has improved over the years as allowed by improvements in detector technology and as demanded by our deepening understanding of emission by competing sources, primarily diffuse galactic emission. The early radiometers were all two channel instruments. One channel extended from λ =1cm to λ =1mm, embracing the peak of the CBR. The second channel was sensitive to wavelengths as short as 330 μm and was included to monitor atmospheric emission. However, thermal emission by dust lying in the galactic plane was clearly evident in the short wavelength channel and we understood that better spectral resolution and galactic modelling were both needed in order to interpret our results. The final version of the radiometer had four channels centered at λ = 1.7mm, 830μm, 380μm and 290μm respectively.

All of the radiometers involved in this program measure the difference in brightness of two regions in the sky 45° from the vertical and 180° apart in azimuth. The radiometers are set into constant rotation about their vertical axis after launch, thus surveying a circle on the sky. This circle "drift scans" as the earth turns and as the package moves across the earth. The field of view varied slightly from flight to flight but was always quite large, approximately 17° FWHM. The data stream, consisting of detector signals, the output of an instrumented bubble level and three axis magnetometer to determine package orientation, and several temperatures and other housekeeping data, were tape recorded on board as well as being telemetered to the ground station. All of the flights were launched from the NSBF in Palestine, Texas, so our sky coverage is limited to the region $-20° \leq \delta \leq 85°$.

A. Hewitt et al. (eds.), Observational Cosmology, 63–68.

Because of our differential geometry, we do not measure brightness as a function of position on the sky directly. To make physical sense of our data we have fit the measured brightness differences to the model of sky brightness given in Table 1. The dipolar (T_n) and quadrupolar (Q_n) terms have become standard in expressing measurements of anisotropy of the CBR. The galactic model, G(b), is appropriate if the galaxy looks like a translucent disk with little dependence of brightness on longitude.

TABLE (1)

Model Components:

α is right ascension, δ is declination and b is galactic lattitude.

$$T_x\cos\alpha\cos\delta \quad T_y\sin\alpha\cos\delta \quad T_z\sin\delta \quad Q_1\left(\tfrac{3}{2}\sin^2\delta - \tfrac{1}{2}\right)$$

$$Q_2\sin 2\delta\cos\alpha \quad Q_3\sin 2\delta\sin\alpha \quad Q_4\cos^2\delta\cos 2\alpha \quad Q_5\cos^2\delta\sin 2\alpha$$

$$G(b){:}\frac{1}{\sin(b)} \text{ convolved with our beam profile, for } b \geq 1^\circ$$

Galactic Emission

The galactic polar antenna temperature inferred from our four channel data is plotted in Figure 1. Also shown are the estimates obtained by others at both higher and lower frequencies. There are two features of this graph which have a bearing on continued measurements of the CBR. First, there is no frequency at which one should expect to find a spot in the sky from which galactic emission is less than several times 10^{-6} of the CBR. Second, at the most promissing wavelengths from the point of view of low galactic signal, $\lambda \approx$ several mm, measured galactic brightness lies above reasonable extrapolations from higher and lower frequencies, making proper subtraction difficult. We have made maps of sky brightness which seem to show that this excess emission does not have the same spatial distribution as the dust seen at shorter wavelengths, compounding the problem.

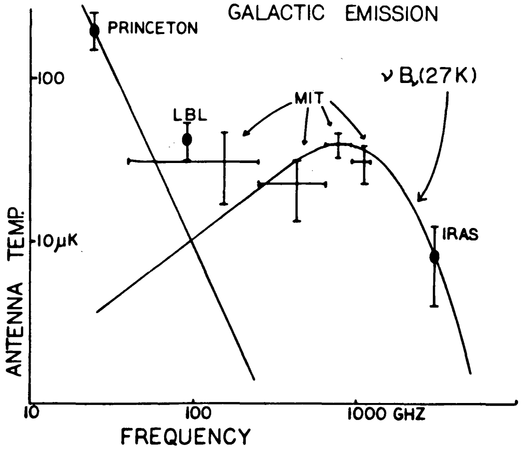


Figure 1. Galactic Polar Antenna Temperature, G(b). The thermal curve at high frequencies has been constrained to pass through our data at 380 μm and the IRAS data at 100 μm reported by Hauser *et al.* The straight line passing through the Princeton data at 25 GHz falls as $1/\nu^2$. Reasonable emission processes fall more rapidly than this with increasing frequency.

The Dipole Moment

The best fit dipole moment for each of the two low frequency channels is listed in Table 2. The higher frequency fit uses data from the only flight of the four channel radiometer whereas the lower frequency fit includes data from all but one of the six balloon flights. In the flight excluded the sky coverage is such that galactic emission is very strong, rendering the flight useless for determining properties of the CBR.

TABLE (2)
Dipole Moment in m°K

	1-8cm.$^{-1}$		5-18cm.$^{-1}$	
	ΔT_{RJ}	ΔT_{CBR}	ΔT_{RJ}	ΔT_{CBR}
T_x	-1.41±.19	-3.13±.41	-.25±.11	-3.14±1.43
T_y	-.03±.09	-.06±.20	.15±.09	1.96±1.13
T_z	-.59±.13	-1.32±.29	-.22±.11	-2.85±1.33
$G(b)$	.053±.013		.022±.009	
	χ^2_ν=.9571 (4167/4354)		χ^2_ν=.9809 (1155/1178)	

The stated errors include a 10% uncertainty in calibration.

The data are listed as antenna temperatures and also as equivalent thermal perturbations of the CBR assuming a temperature of 2.74°K. Under the assumption that the dipole moment is due to a doppler shift (or in fact any other mechanism which gives rise to a *thermal* perturbation), the brightness of the dipole moment is given by

$$\Delta I(\nu) = \frac{dB_\nu(T)}{dT} \Delta T_{dipole} = \frac{1.72 \times 10^{-12}\, \nu^4\, e^{hc\nu/kT}}{T^2\, (e^{hc\nu/kT} - 1)^2} \Delta T_{dipole} \frac{watts}{cm.^2\, str.cm^{-1}} \qquad (1)$$

At short wavelenghts this expression depends very strongly upon the temperature of the CBR. A proper comparison of our measurements to low frequency results[2,3,4] requires using Equation 1 to determine ΔT_{dipole} and T_{CBR} simultaneously from the data. The result is:

$$\Delta T_{dipole} = 3.35 \pm .12 mK \qquad T_{CBR} = 2.87 \pm .28° K \qquad 2 to 8 cm^{-1} \qquad (2)$$

$$\Delta T_{dipole} = 3.34 \pm .11 mK \qquad T_{CBR} = 2.97 \pm .24° K \qquad 5 to 18 cm^{-1} \qquad (3)$$

The inferred vaules of T_{CBR} are plotted in Figure 2, along with some recent direct measurements of the brightness of the CBR[5,6,7] and the indirect measurements obtained from the temperature of CN clouds. [8,9]

Conclusions

Notice that the resulting values of T_{CBR} are reasonable. This means that the dipole moment does in fact have the spectrum expected from the doppler shift of a 2.7°K blackbody. We are moving at $v = 1.2 \times 10^{-3} c$ with respect to a frame in which the CBR would appear to be isotropic. This velocity is 1000 times too large to be the remnant of a primordial peculiar velocity. Also notice that these results are competitive in accuracy with the direct

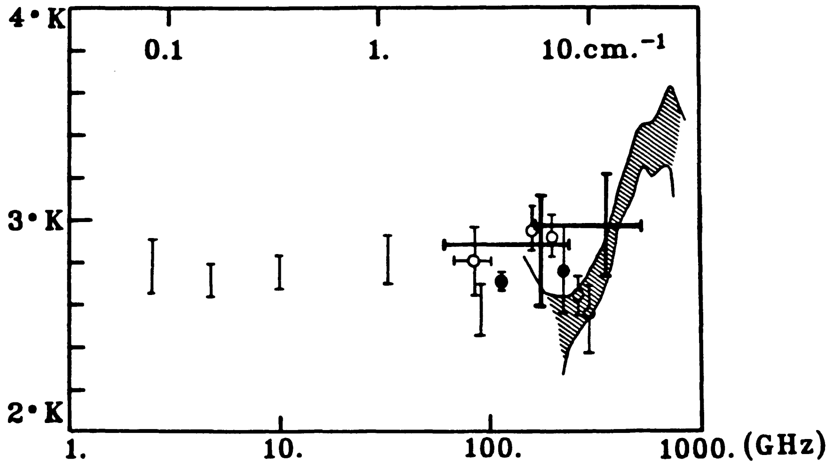


Figure 2. Inferred Temperature of the CBR as a function of frequency. Our data are plotted as bold crosses where the vertical bar shows the meaured value $\pm\sigma$ and the horizontal bar shows the spectral response. The vertical bars, open circles, shaded region and solid circles are direct and indirect measurements of the CBR spectrum taken from references 5,6,7 and 8 and 9 respectively.

measurements in this difficult spectral region even though we are only sensitive to 10^{-3} of the power in the CBR. This is because spatial chopping is easier than absolute radiometry and also because of the sensitivity of the dipole moment to T_{CBR} at short wavelengths. In fact, in the higher frequency channel a 30% measurement of a dipole moment has led to an 8% constraint on T_{CBR}, a pleasing shrinkage of uncertainty.

More measurements are needed to understand the spectrum of the CBR at high frequencies, especially since it is possible to imagine mechanisms which might distort the spectrum in this region. A new radiometer has been built at MIT using improved detectors which in turn allow higher spectral resolution. At the same time, an experiment is underway to measure the short wavelength spectrum directly. The Physics Department at the University of British Columbia has built a liquid helium cooled differential fourier transform spectrometer which will be carried aloft on a sounding rocket this spring.[10] If successful it will attain an accuracy of $\delta T/T = 1\%$ in the wavelength range from $\lambda = 3$ mm to 300 μm.

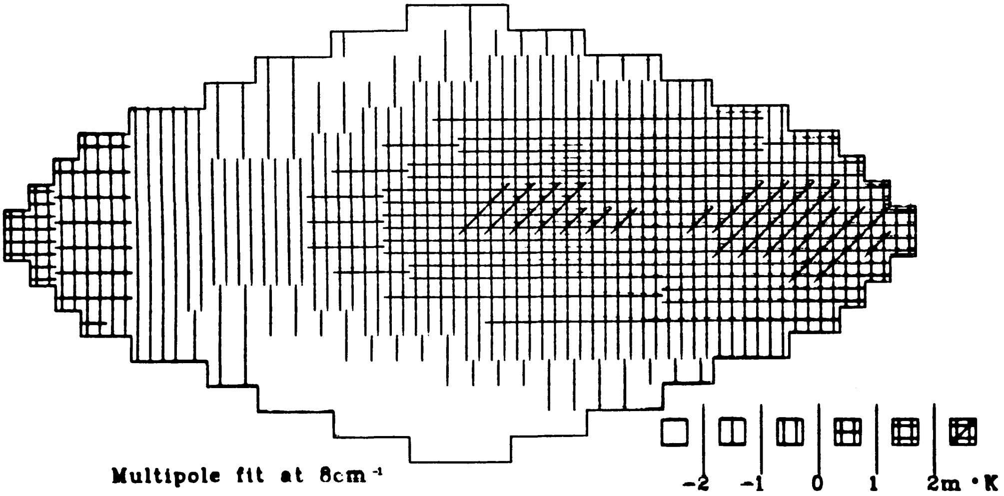
References.

1 M. Halpern, R. Benford, S. Meyer, D. Muehlner, and R. Weiss In Peparation.
2 D. Fixsen, E. Cheng, and D. Wilkinson Phys. Rev. Lett. **50**,620, 1983
3 P. Lubin, T. Villela, G. Epstein and G. Smoot Ap. J. **298**:L1, 1985
4 R. Weiss Ann. Rev. Astron. and Astrophys. **18**,489, 1980
5 G. Smoot *et alia* Soc. Ital. di Fisica Conf. Proc. **1**,27, 1985
6 J. Peterson, P. Richards and T. Timusk Phys. Rev. Lett. **55**,332, 1985
7 H. Gush Phys. Rev. Lett. **47**,745, 1981
8 D. Meyer and M. Jura Ap. J. **297**,119, 1985
9 P. Crane, D. Hegyi, N. Mandolesi and A. Danks Ap. J. 15 October 1986.
10 H. Gush Proc. of 1983 Space Helium Dewar Conference. Hendricks, Karr eds.p.99, 1984

BIRKINSHAW: What Quadrupole moment limits can you place from your measurements?

HALPERN: We can not place any interesting quadrupole moment limit. We have been unable to model diffuse galactic emission well enough to remove it from our signal. At lower frequencies as well as in our own data at high frequencies where the CBR no longer has any power, the necessary modelling is comparatively straightforward. This is what first convinced us that diffuse galactic emission has different shapes at different frequencies. When we include the quadrupolar terms in our model along with the dipole and the galaxy we get a significant non-zero result. However, this result looks like the galactic plane and therefore cannot be attributed to the CBR. Please see the figure.

As sensitivity increases there will certainly be reports of lumps in the sky. To attribute them to structure of the CBR they should be seen at several frequencies. One should ask if the spectrum is reasonable and if the shape is reasonable. Does it look like any competing sources? The dipole moment clearly passes these tests. The quadrupole moment clearly fails.



The brightness assigned to the Dipole (T_n) and Quadrupole (Q_n) terms when all of our data is fit to the model in Table 1. (Q_1 was not included in the fit.) The entire night sky is shown in a $cos(b)$ projection of galactic coordinates. The galactic center is at the center of the drawing. The galactic plane runs horizontally through the middle and the north and south poles are at the top and bottom respectively.

The galactic plane is evident. The plane does not appear to be uniformly bright because the effect of the dipole moment of the CBR has not been removed from the data.

Because of the strong galactic residue which is assigned to the Q_n terms in preference to the galactic model, $G(b)$, our search for a quadrupole moment of the CBR has not been successful.

ULMER: Do your measurements give the same direction as previous measurements of a dipole moment?

HALPERN: Yes, roughly. Our results are not as precise as the others. The directions of each of the dipole moments which we have measured are listed below along with those of Fixsen _et al._ and Lubin _et al._

Author	Frequency	Right Ascension	Declination
Fixsen et al.	25 GHz.	11.08 ± .04 Hours	$-8.1^{\circ} \pm .62$
Lubin et al.	90 GHz.	11.2 ± .1 Hours	$-6.^{\circ} \pm 1.5$
MIT CH.1	180 GHz.	12.1 ± .24 Hours	$-23^{\circ}\,{}^{+5}_{-4}$
MIT CH.2	360 GHz.	$9.9\,{}^{+1.7}_{-1.1}$ Hours	$-38^{\circ}\,{}^{+13}_{-21}$