

MEASUREMENTS OF THE COSMIC BACKGROUND RADIATION

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ABSTRACT

Maps of the large scale structure ($\theta > 6^\circ$) of the cosmic background radiation covering 90% of the sky are now available. The data show a very strong 50-100 σ (statistical error) dipole component, interpreted as being due to our motion, with a direction of $\alpha = 11.25 \pm 0.15$ hours, $\delta = -5.6 \pm 2.0^\circ$. The inferred direction of the velocity of our galaxy relative to the cosmic background radiation is $\alpha = 10.6 \pm 0.3$ hours, $\delta = -23 \pm 5^\circ$ ($l^{\text{II}} = 287^\circ$, $b^{\text{II}} = 31^\circ$). This is 44° from the center of the Virgo cluster. After removing the dipole component the data show a Galactic signature but no apparent residual structure. An autocorrelation of the residual data, after subtraction of the Galactic component from a combined Berkeley (3 mm) and Princeton (12 mm) data set, shows no apparent structure from 10° to 180° with a rms of 0.01 mK^2 . A 90% confidence level limit of 7×10^{-3} is placed on a quadrupole component.

INTRODUCTION

It has now been twenty years since the discovery of the cosmic background radiation. In these twenty years numerous experiments have been carried out to study the spectrum, angular structure and polarization. Our current knowledge of the radiation can be summarized by paraphrasing the original 1965 article of Penzias and Wilson namely that the radiation is consistent with a blackbody of temperature of about 3 K, is isotropic and unpolarized. So far, we have learned a great deal but discovered very little. Our prized relic of the early universe is frustratingly simple to describe.

Of course the radiation is slightly anisotropic due to our motion ($\beta \approx 10^{-3}$) but on cosmological scales this is just a local phenomenon. Another local effect is the seasonal difference due to the motion of the Earth around the Sun ($\beta \approx 10^{-4}$) which is observed in both the Berkeley 3 mm and Princeton 12 mm data from flights separated by 6 months.

On scales from arc seconds to a hundred eighty degrees, experiments have been performed with no intrinsic structure being found. The current measurements are summarized in Figure 1. Large scale measurements have reached a sensitivity where the dipole is measurable in real time, as shown in Figure 2, and can be used as a low level calibration source as well as providing us with a convenient way to test if our instrument is working in flight. The dipole has become a "background" to be subtracted away. A much more problematic background is the emission due to our galaxy. With synchrotron and bremsstrahlung radiation decreasing and dust emission increasing with frequency, a natural minimum occurs somewhere around 90 GHz, as shown in

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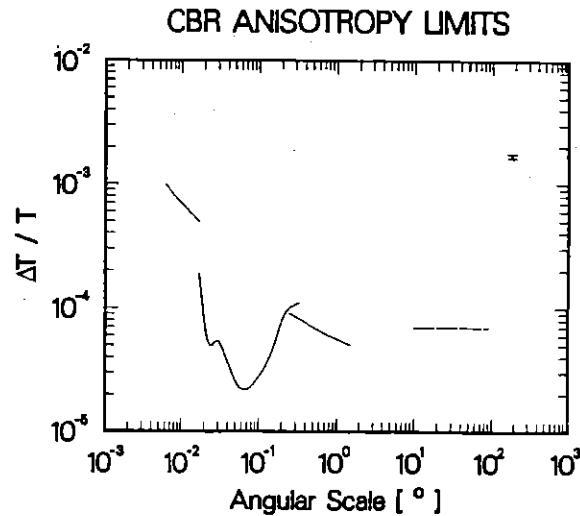


Figure 1 - Anisotropy Measurements at Various Angular Scales.

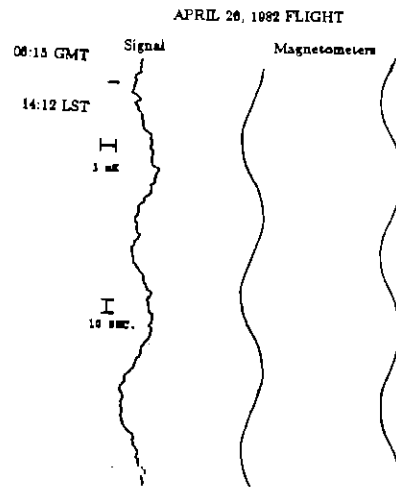


Figure 2 - Real Time Dipole Measurement.

Figure 3, which gives the measured large scale Galactic contribution from recent experiments versus frequency, using a cosecant (b^H) Galactic model flattened near the plane. The top plot of Figure 3 gives the ratio of the amplitude of the cosecant (b^H) model (pole value) to the dipole amplitude versus frequency. The dipole flux (in antenna temperature) decreases at high frequencies due to the change in slope of the spectrum. At 3 mm wavelength, where we made our measurements, the pole value amplitude is $44 \pm 11 \mu\text{K}$ and hence the Galactic contribution to the dipole ($\approx 3 \text{ mK}$) is at the 1-2% level near the Galactic pole and rises to about 20% at the Galactic plane.

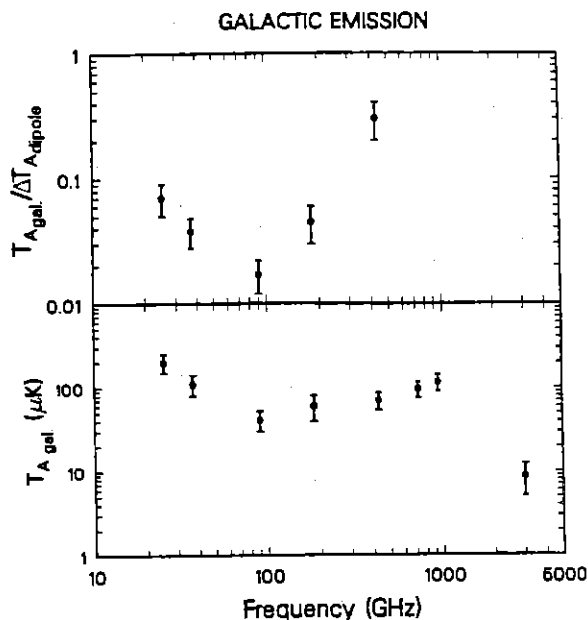


Figure 3 - Measured Galactic Emission Versus Frequency.

A more detailed analysis implies that the pole may be less and the plane more (Lubin and Vilella 1985). Inclusion of the Galactic plane only changes the 3 mm dipole and quadrupole fits by 1σ . In searching for higher order anisotropies (quadrupole, etc.), proper modeling of the Galaxy is crucial since even at 3 mm where the Galactic emission is very small, it is comparable to errors in the quadrupole components, which are 50-80 μK . Future experiments will need to pay particular attention to this problem.

MEASUREMENTS

The data presented here are the result of independent measurements at 12 mm using a maser (Princeton) and 3 mm using a Schottky diode mixer (Berkeley). Both instruments are cooled to liquid helium temperature. The experiments are described in detail in Fixsen, Cheng, and Wilkinson (1983) and Fixsen (1982) for the 12 mm experiment and Lubin, Epstein, and Smoot (1983), Epstein (1983), and Lubin and Vilella (1985) for the 3 mm experiment. The combined results we describe here are based on collaborative work to be published (Vilella, Walker, Wilkinson, and Lubin 1986). The 12 mm and 3 mm data sets have been combined to cross check the results of each and to produce a combined map which is better connected (see Lubin and Vilella 1985) than either, as well as has increased sky coverage. The 12 mm experiment uses a more sensitive detector than the 3 mm experiment but observes in a region of higher Galactic emission, so ultimately both experiments have nearly identical sensitivities to large scale structures (dipole, quadrupole, etc.) as shown in the fits given in Table I. Both experiments have had three data flights, two from Palestine (lat.

TABLE I

COMPARISON BETWEEN 3 MM AND 12 MM FITS			
Values in thermodynamic temperature for T=2.7 K			
FIT	COEFFICIENTS	3 MM ¹ DATA	12 MM ² DATA
Dipole only	T_x	-3.35 ± 0.17	-3.01 ± 0.17
	T_y	0.71 ± 0.10	0.56 ± 0.09
	T_z	-0.35 ± 0.08	-0.28 ± 0.09
Dipole and Quadrupole	T_x	-3.37 ± 0.17	-3.07 ± 0.17
	T_y	0.69 ± 0.09	0.67 ± 0.09
	T_z	-0.42 ± 0.09	-0.45 ± 0.09
	Q_1	0.10 ± 0.09	0.15 ± 0.08
	Q_2	0.15 ± 0.10	0.15 ± 0.11
	Q_3	0.12 ± 0.11	0.14 ± 0.07
	Q_4	-0.09 ± 0.09	0.06 ± 0.11
	Q_5	0.08 ± 0.08	-0.01 ± 0.07

¹Excludes data within 5° of the galactic plane.
²Fixsen, Cheng and Wilkinson (1983).
 Errors include calibration.

Table I - Spherical Harmonics Fits.

= 32°), Texas, and one from near São José dos Campos (lat. = -23°), São Paulo, Brazil, for each. Both experiments have nearly identical sky coverage of 85% with a combined sky coverage of 90%.

Corrugated scalar horn antennas with a beam of 6° FWHM and an opening angle of 90° symmetrically placed 45° with respect to the zenith are used in each experiment to measure the temperature difference between the two beams. Both experiments are flown from a balloon platform at an altitude of 25 to 30 km at night. Atmospheric emission is typically 5 to 25 mK but since the instruments only measure temperature differences the atmospheric contribution cancels out to first order. Both instruments have inflight calibration sources which currently limit the error on the dipole amplitude to 5% accuracy while the statistical errors are at the 1% to 2% level.

RESULTS

The dipole and quadrupole fits are summarized in Table 1. Both experiments have dipole directions which agree within 1.6°, with an average of $\alpha = 11.25 \pm 0.15$ hours and $\delta = -5.6 \pm 2.0^\circ$ for the Solar velocity. The effect of the Earth's orbital velocity around the Sun, which was measured in both experiments, in flights separated by six months, was corrected for. There is still some discrepancy in dipole amplitudes presumably due to calibration errors with a dipole amplitude of 3.45 ± 0.17 mK for the 3 mm data (Lubin, Villela, Epstein, and Smoot 1985) and 3.07 ± 0.17 mK for the 12 mm data (Fixsen, Cheng, and Wilkinson 1983). This calibration error does not affect the dipole direction significantly but does affect the Solar and hence inferred Galactic and Local Group velocities. Taking an average Solar velocity direction of $\alpha = 11.25 \pm 0.15$ hours and $\delta = -5.6 \pm 2.0^\circ$ with an average dipole amplitude of 3.26 ± 0.23 mK and correcting for the Galactic Solar velocity of 230 km s^{-1} toward $l^{\text{II}} = 90^\circ$, $b^{\text{II}} = 0^\circ$, gives a Galactic velocity of $V_G = 540 \pm 50 \text{ km s}^{-1}$ towards $\alpha = 10.6 \pm 0.3$ hours, $\delta = -23 \pm 5^\circ$ or $l^{\text{II}} = 267 \pm 5^\circ$, $b^{\text{II}} = 31 \pm 5^\circ$. This gives an angle of 44° between the center of the Virgo

cluster (M87, $l'' = 284^\circ$, $b'' = 75^\circ$) and \bar{V}_G . Assuming that the velocity of the Sun relative to the Local Group is 295 km s^{-1} toward $l'' = 97.2^\circ$, $b'' = -5.6^\circ$, (Sandage 1986) gives a Local Group velocity of $\bar{V}_{LG} = 610 \pm 50 \text{ km s}^{-1}$ towards $\alpha = 10.8 \pm 0.3$ hours, $\delta = -25 \pm 5^\circ$ or $l'' = 272 \pm 5^\circ$, $b'' = 30 \pm 5^\circ$. This gives an angle of 45° between the center of the Virgo cluster and \bar{V}_{LG} .

The quadrupole limits of both data sets are 7×10^{-5} as a 90% confidence level upper limit. A combined map made from both data sets is given in Figure 4 and the residual map after subtraction of the dipole is given in Figure 5. An autocorrelation of the residual map shows no obvious structure from 10° to 180° giving a rms of 0.01 mK^2 .

Recently, several groups have looked at the IRAS data set and for $60 \mu\text{m}$ data have found a "dipole" (Yahil, Walker, and Rowan-Robinson 1985). The "dipole" direction is found to be $l'' = 248 \pm 9^\circ$, $b'' = 40 \pm 8^\circ$ ($\alpha = 10.2 \pm 0.6$ hours, $\delta = -5.4 \pm 8^\circ$). This "dipole" direction is $21 \pm 11^\circ$ from \bar{V}_{LG} . It's not clear precisely what significance should be given to this. A "quadrupole" has also been reported in the X-ray background (Fabian, Warwick, and Pye 1980) with an axis direction similar to the dipole direction.

OTHER EXPERIMENTS

Recently, the Soviet Union completed a satellite-borne cosmology mission known as Prognoz 9. Only very preliminary results (Strukov and Skulachev 1984) have been released from this experiment. The instrument consisted of a 8 mm (37 GHz) parametric amplifier and similar corrugated scalar horn antennas to ours, also with a 90° opening angle. Sensitivity should be excellent given the long integration time available for the mission, however Galactic emission, because of the relatively long wavelength, will have to be modeled very carefully. Because neither the Princeton 12 mm data nor the Berkeley 3 mm data are sensitivity (statistics) limited for the dipole measurement, it is unlikely that the Prognoz 9 results will significantly change our understanding of the dipole. Current limitations on the dipole are due to inflight calibration errors ($\approx 5\%$) and pointing errors ($\approx 1^\circ$). The Prognoz 9 data will significantly increase our understanding of the Galactic emission and may provide more sensitive measurements of intrinsic fluctuations. Recent dipole measurements are summarized in Figure 6 as a function of frequency. The 12 mm (25 GHz) and 3 mm (90 GHz) data are also plotted. The broad band higher frequency measurements are from bolometric systems of the M.I.T. (Halpern 1983) and University of Rome (Fabbri, Guidi, Melchiorri, and Natale 1980) groups.

CONCLUSIONS

In the twenty years since the discovery of the background radiation no intrinsic structure has been convincingly measured. The dipole anisotropy, apparently due to our motion, has been measured sufficiently well to determine our direction of motion within 2° . Our galaxy is moving in a direction that is about 44° from the center of the Virgo cluster. The dipole is now a background to be subtracted to get measurements of intrinsic anisotropies. Large scale measurements are now becoming limited by Galactic backgrounds particularly at centimeter wavelengths and even at the best wavelengths around 3 mm an order of magnitude improvement will be difficult without a detailed knowledge of Galactic emission.

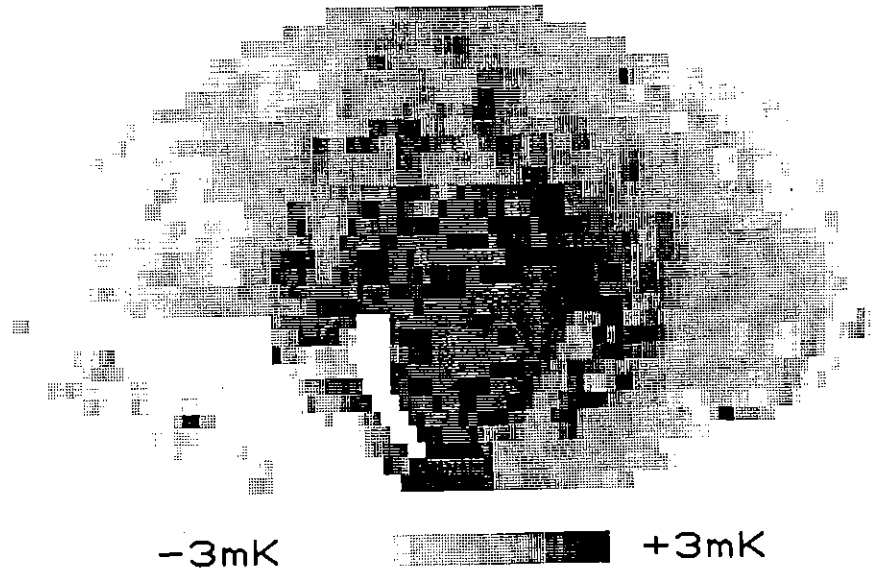


Figure 4 - Combined Dipole Map.

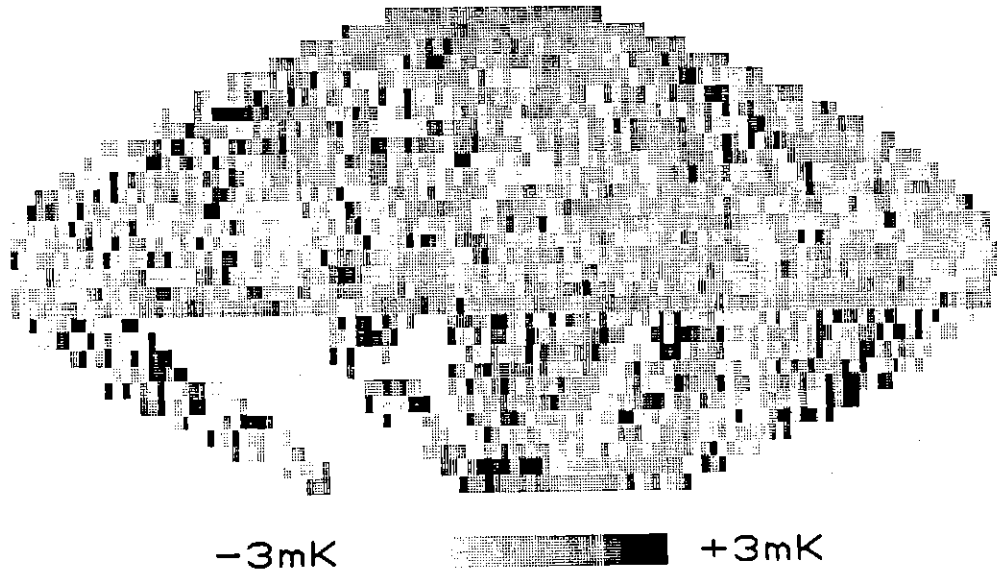


Figure 5 - Combined Residual Map.

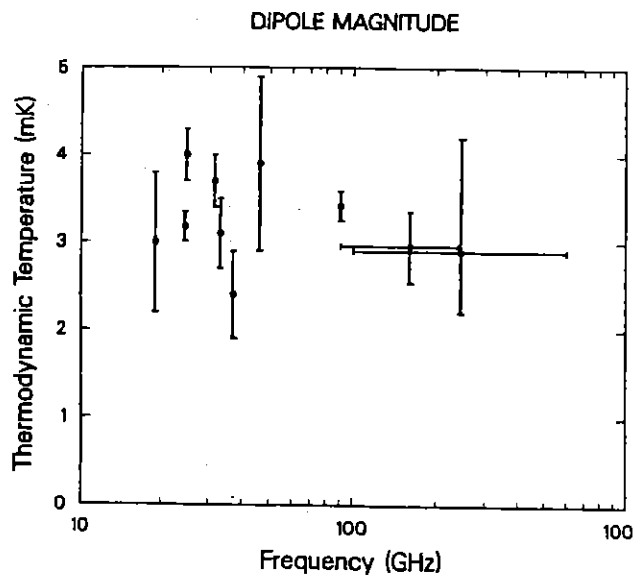


Figure 6 - Recent Dipole Anisotropy Measurements.

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REFERENCES

- Epstein, G. L. 1983, *Ph.D. Thesis*, University of California, Berkeley.
- Fabbri, R., Guidi, I., Melchiorri, F., and Natale, V. 1980, *Phys. Rev. Letters*, **44**, 1563.
- Fabian, A. C., Warwick, R. S., and Pye, J. P. 1980, *Physica Scripta*, **21**, 650.
- Fixsen, D. J. 1982, *Ph.D. Thesis*, Princeton University.
- Fixsen, D. J., Cheng, E. S., and Wilkinson, D. T. 1983, *Phys. Rev. Letters*, **50**, 620.
- Halpern, M. 1983, *Ph.D. Thesis*, Massachusetts Institute of Technology.
- Lubin, P., Epstein, G., and Smoot, G. 1983, *Phys. Rev. Letters*, **50**, 616.
- Lubin, P. and Villela, T. 1985, *Società Italiana di Fisica, Conference Proceedings, "The Cosmic Background Radiation and Fundamental Physics"*, **1**, 65.
- Lubin, P., Villela, T., Epstein, G., and Smoot, G. 1985, *Ap. J. (Letters)*, **298**, L1.
- Penzias, A. A. and Wilson, R. W. 1965, *Ap. J.*, **142**, 419.
- Sandage, A. 1986, *Private Communication*.
- Strukov, I. A. and Skulachev, D. P. 1984, *Sov. Astron. Letters*, **10**, 1.
- Villela, T., Walker, K., Wilkinson, D., and Lubin, P. 1986, *to be published*.
- Yahil, A., Walker, D., and Rowan-Robinson, M. 1985, *preprint*.