LARGE-SCALE ANISOTROPY AT CENTIMETER WAVELENGTHS

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Scientific interest in large-scale anisotropy measurements is now focused on intrinsic effects, which could tell us much about the early Universe. Current experimental precision of better than 10^{-4} K begins to probe for interesting physical processes. However, at these levels of precision systematic effects and foreground sources present serious difficulties. Some recent results from balloon flights of a maser radiometer (λ 1.2 cm) and a cooled mixer (λ 3 mm) are discussed and interpreted. The dipole effect gives a velocity for the Local Group in the general direction of the Virgo cluster. The Earth's motion is clearly seen. There is no quadrupole detected at a level of $\Delta T/T \sim 5 \times 10^{-5}$.

1. INTRODUCTION

Precision observations of the large-scale anisotropy of the 2.7K cosmic microwave background radiation have demonstrated the extragalactic origin[1] of the radiation, and have measured the Earth's velocity[2,3] with respect to the radiation - presumably the co-moving reference frame of the Universe. As experimental accuracy improves, the scientific focus for this work has become intrinsic effects that might have originated in the very early Universe, or been caused by interactions with anisotropic matter at the time of decoupling of radiation and matter. Several possible effects with $\Delta T/T \lesssim$ few x 10^{-4} have been theoretically discussed[4], and two groups[3] have reported tentative detections of a quadrupole effect in the 2.7K radiation. However, recent results from two measurements show no quadrupole distribution larger than $\Delta T/T \sim 5 \times 10^{-5}$. Apparently, even better measurements are needed to see the imprints of early processes on the 2.7K radiation.

This paper discusses the recent experimental work at centimeter wavelengths, and some implications of the latest results. But first, to put the results into perspective, some techniques and experimental difficulties are discussed.

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2. TECHNIQUES AND PROBLEMS FOR CENTIMETER WAVELENGTHS

The basic problem is to measure the difference in the radiation temperature from two directions in the sky with an accuracy of better than 10^{-4} K. Carefully designed room-temperature Dicke radiometers integrate their random noise down to this level in about a day; the best cooled radiometers require about 10^3 sec of integration per pair of points. Radiometer front-ends for large-scale anisotropy measurements have evolved from tube-type, room-temperature, mixers to maser amplifiers[5] and mixers[6] cooled to liquid helium temperature. However, system noise is not the main problem with these instruments. Instabilities of 10^{-5} in reference sources, Dicke switch balance, and antenna wall radiation cause serious systematic errors at sensitivity levels of 10^{-4} K. Differential (two horn) techniques, mechanical and electrical symmetry, temperature control, and magnetic shielding are all essential. In addition, rotation of the instrument[7] (secondary Dicke switching) is necessary because such a high degree of instrument symmetry cannot be maintained for longer than a few minutes.

Local radiation sources present another difficult problem at centimeter wavelengths. Ground radiation ($\sim$ 300 K) must be excluded to an extraordinary level (10^{-6}) by special antennas and shielding. Nonuniform atmospheric emission has forced all recent experiments onto balloons or high-flying aircraft. Plans are being made for satellite experiments to fly in this decade.

It now appears that foreground Galactic radiation (synchrotron and bremsstrahlung) will limit the accuracy of large-scale anisotropy measurements at wavelengths longer than 5 mm. Synchrotron emission has been mapped at longer wavelengths[8], but must be extrapolated over more than a factor of 50 in wavelength to reach the 1 cm to 3 mm wavelength. Spectral index variations with wavelength or position on the sky cannot be modeled. Bremsstrahlung radiation presents even more serious problems. It is not mapped on large angular scales, because at long wavelengths Galactic synchrotron emission dominates the bremsstrahlung emission. H II regions and intense emission near the Galactic plane have been mapped at centimeter wavelengths, but weak diffuse emission off the plane can be a problem for anisotropy measurements, and little is known about this. Sensitive maps of Hα emission[9] give lower limits on emission-measure along some lines of sight, but unknown extinction corrections prevent accurate predictions of bremsstrahlung radiation, even if the plasma temperature is known.

At shorter wavelengths ($\sim$ 3 mm) the foreground radiation problem becomes dust emission. Even less is known about this than about synchrotron and bremsstrahlung radiation. The distribution of dust is poorly known, and the spectral index is uncertain by at least a factor of 2. However, the radiation intensity is much lower than at $\lambda \sim 1$ cm.

In principle, the foreground radiation problem can be overcome by anisotropy measurements at several frequencies, using spectral signatures

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to separate foreground from background components. If foreground sources can be understood, the experimental accuracy will be limited by systematic errors.[7] The most worrisome systematic effects are those that are synchronous with instrument rotation such as, coupling to the Earth's magnetic field, asymmetric ground radiation entering antenna side lobes, radio interference, and instrument heating from asymmetric infrared sources.

3. RECENT RESULTS

3.1 Dipole Distribution

The largest anisotropy in the 2.7K background radiation is a dipole (cos θ) distribution, most of which is due to the Sun's velocity with respect to the radiation frame. This effect was anticipated from the beginning[1], but ten years of instrument and technique development were needed before the dipole was clearly seen. A number of dipole measurements have now been reported[2,3] at wavelengths between 1.2 cm and 1 mm. All are in reasonable agreement on the magnitude and direction of the effect. Furthermore, the spectrum of the dipole is approximately blackbody, as expected for the velocity effect. The spectrum rules out Galactic radio sources for the dipole.

Two very recent results also show good agreement with older dipole results. The Berkeley group has flown, in balloons, a cooled 3 mm mixer radiometer with system noise 125K. The Princeton group has flown a 1.2 cm maser radiometer with a system noise of 33K. Data from two northern hemisphere flights of each instrument cover over 60% of the sky. At 3 mm, corrections for Galactic radiation are small, but the dust contribution is unknown. At 1.2 cm, Galactic radiation is important, and uncertainties in the model limit the accuracy of the results, especially with the very low instrumental noise of the maser. The preliminary dipole results of these two experiments are shown in the following table.

λ (cm)	T_x (mK)	T_y (mK)	T_z (mK)	Group
0.33	-3.48 ± 0.08	0.61 ± 0.08	-0.32 ± 0.08	Berkeley[6]
1.2	-3.02 ± 0.04	0.85 ± 0.04	-0.41 ± 0.03	Princeton[5]

The temperatures given in the table are thermodynamic temperatures, assuming that the cosmic background is a 2.7K blackbody; errors are statistical only. The reference frame is the Sun.

The velocities of the Sun and the Local group are easily derived from the dipole anisotropy by assuming that all of the effect is due to motion through the radiation, and that the radiation temperature is 2.7K. Averaging the two results above, and estimating the error from the

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difference, gives

$$v_{SUN} = (372 \pm 25)^{km}/sec, \text{ towards } \alpha = 11^h.2 \pm 0^h.2, \ \delta = -6^\circ \pm 3^\circ.$$

Taking the canonical value for solar motion with respect to the local group (300 km/sec towards $\ell = 90^\circ$, $b = 0^\circ$) gives,

$$v_{LG} = (610 \pm 50)^{km}/sec, \text{ towards } \alpha = 10^h.5 \pm 0^h.4, \ \delta = -26^\circ \pm 5^\circ.$$

These should be regarded as preliminary results, as the data are still being analyzed for systematic errors and sensitivity to Galactic radiation corrections. However, it is particularly interesting to note that this direction of $\vec{v}_{LG}$ is only 17° from the direction of $\vec{v}_{LG}$ found by Hart and Davies[10] from HI observations of Sbc galaxies with redshifts between 1000 km/sec and 5500 km/sec. The magnitude of the velocity from that work is (436 ± 55) km/sec, substantially smaller than the cosmic background result. The $\vec{v}_{LG}$ direction is 49° away from the Virgo cluster.

The high sensitivity of the maser instrument makes possible a clear detection of the Earth's velocity with respect to the 2.7K radiation. The instrument was flown on Dec. 10-11, 1980 and again on June 29-30, 1981 - an interval of about 6 months. The difference of the Earth's velocity on those dates predicts a dipole difference of

$$\Delta T_x = -0.528 \text{ mK}, \ \Delta T_y = 0.016 \text{ mK}, \ \Delta T_z = 0.007 \text{ mK}.$$

The dipole results for the individual flights are

$$\text{Dec. 80: } T_x = -3.37 \pm 0.06 \text{ mK}, \ T_y = 0.80 \pm 0.05 \text{ mK}, \ T_z = -0.19 \pm 0.04 \text{ mK},$$

$$\text{June 81: } T_x = -2.71 \pm 0.07 \text{ mK}, \ T_y = 0.92 \pm 0.06 \text{ mK}, \ T_z = -0.33 \pm 0.05 \text{ mK}.$$

The measured dipole difference, due to the Earth's velocity is

$$\Delta T_x = -0.66 \pm 0.09 \text{ mK}, \ \Delta T_y = -0.02 \pm 0.08 \text{ mK}, \ \Delta T_z = 0.14 \pm 0.06 \text{ mK}.$$

Comparing the predicted and measured dipole differences shows that the Earth's velocity has been detected, and is about a 7σ effect in the maser data.

3.2 Quadrupole Distribution

The recent Berkeley and Princeton results have also been searched for evidence of a quadrupole distribution in the 2.7K radiation. No significant quadrupole effects are seen; the results are,

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λ(cm)	$Q_2{}^{11}$(mK)	Q_3(mK)	Q_4(mK)	Q_5(mK)	Group
0.33	0.23 ± 0.12	0.26 ± 0.10	-0.10 ± 0.08	0.06 ± 0.07	Berkeley[6]
1.2	0.06 ± 0.06	0.05 ± 0.04	0.16 ± 0.04	0.00 ± 0.03	Princeton[5]

Again, the quoted errors are only statistical and do not include calibration errors, uncertainties in the Galactic radiation model, or correlations introduced by incomplete sky coverage. The apparently large effects, such as Q_4 in the Princeton results, are not believable, because of the extreme sensitivity to systematic effects at this level. For example, if the Galactic radiaion model is perturbed by adding the term, (60 μK)cosec b, then Q_4 becomes 0.07 mK, and Q_2 becomes 0.19 mK. Since there is no independent way of detecting a Galactic component as small as this perturbation, we must assume that Q's less than $\sim$ 0.20 mK are due to inaccuracy of the Galactic radiation model.

The Princeton results can, however, be interpreted as an upper limit on possible quadrupole effects in the 2.7K background. Taking an rms of the Q values, integrated over the sky, gives an upper limit on Q_{rms} of 0.13 mK, with 90% confidence.[5] Clearly, the reported[4] quadrupole effects (e.g., $Q_5 = -0.54 \pm 0.14$ mK) are not in the 2.7K background. The centimeter work was done with radiometers having 10 times more noise than the maser; systematic errors were very hard to detect. Also, a much improved model for Galactic foreground radiation has been used for analyzing the maser data. The older data are being reanalyzed with the new model, and the instruments are being further tested for systematic effects. The millimeter observation of quadrupole-like effects could have been caused by large-scale dust emission. Little is known about the dust distribution at high Galactic latitudes, and no spectral information was obtained to look for dust emission.

4. FUTURE PROSPECTS

The preliminary results discussed above represent a substantial improvement over earlier results.[2,3] But the measurements are now reaching fundamental limits due to foreground sources, systematic errors, and instrument noise. Further improvements will require multiple frequency observations, with cooled radiometers, good sky coverage, and long integration times. More balloon work is planned at λ 0.65 cm and λ 0.33 cm, however, satellite[12] experiments planned for late in this decade hold the most promise for reaching the best possible accuracy.

REFERENCES

1. Partridge, R.B., and Wilkinson, D.T.: 1967, Phys. Rev. Letters, 18, p.557.
2. Smoot, G.F., and Lubin, P.M.: 1979, Ap. J., 234, pL83. Weiss, R.: 1980, Ann. Rev. Astron. Astrophys., 18, p.489.

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3. Fabbri, R., Guidi, I., Melchiorri, F., and Natale, V.: 1980, Phys. Rev. Letters, 44, p1563; erratum: 1980, Phys. Rev. Letters, 45, p401. Boughn, S.P., Cheng, E.S., and Wilkinson, D.T.: 1981, Ap. J., 243, pL113.
4. Peebles, P.J.E.: 1981, Ap. J., 243, pL119. Wilson, M.L., and Silk, J.: 1981, Ap. J., 243, p14.
5. Fixsen, D.J.: 1982, "A Balloon Borne Maser Measurement of the Anisotropy of the Cosmic Background Radiation", Ph.D. Thesis, Princeton University. Fixsen, D.J., Cheng, E.S., and Wilkinson, D.T.: 1982, in preparation.
6. Lubin, P.M.: 1982, Varenna Conf. Course LXXXVI, preprint. Lubin, P.M., Epstein, G., and Smoot, G.F.: 1982, in preparation.
7. Wilkinson, D.T.: 1982, Phil. Trans. Roy. Soc., Oct. 15, 1982.
8. Haslam, C.G.T., Salter, C.J., Stoffel, H., and Wilson, W.E.: 1982, Astron. and Astrophys. Suppl., 47, p1.
9. Reynolds, R.J.: 1980, Ap. J., 236, p153. Sivan, J.P.: 1974, Astron. and Astrophys. Suppl., 16, p163.
10. Hart, L., and Davies, R.D.: 1982, Nature, 297, p191.
11. See Boughn, et al., ref. 3, for a definition of the Q's.
12. Mather, J.: 1980, Physica Scripta, 21, p671.

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DISCUSSION

F. Melchiorri: Is our "hot spot" at a level of 0.1 mK, extending about 20 by 20 degrees, detectable in your data?

Wilkinson: Yes. An object of this size would be detectable at the 0.1 mK level in the maser data. A fit could easily be made, if you give us the coordinates of your cloud.

Davies: The impressive new results on the dipole anisotropy by the Berkeley and Princeton groups show a formal difference in amplitude of about 15 percent. This difference translates into a difference in the derived solar motion and is important in comparisons with other determinations of the solar motion. I note that the two estimates of the solar motion differ by ~ 4 times the sum of the quoted errors. Would the two authors care to comment on this discrepancy?

Wilkinson: The errors given in the tables include only statistical errors; they will probably double when systematic errors are included. All three pairs of three measurements by the Berkeley-Princeton groups have shown discrepancies not quite covered by the error bars. We believe that calibration errors have been underestimated. Calibration in flight is difficult, and only recently have the techniques improved. Both groups are aware of this problem and are working on it. For now, I suggest that the results be averaged and that errors include both results, as has been done in this paper.

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