LARGE-ANGULAR-SCALE ANISOTROPY IN THE COSMIC BACKGROUND RADIATION

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ABSTRACT

Measurements of the large-angular-scale anisotropy of the cosmic background radiation made from the northern hemisphere are in essential agreement with each other and indicate a first order spherical harmonic component with an amplitude of approximately 3 mK. New data from the southern hemisphere support these previous results. This first order anisotropy is interpreted as resulting from the motion of the solar system relative to the cosmic background radiation. There is no evidence of any higher order anisotropy to the level of 1 mK.

INTRODUCTION

The cosmic microwave background radiation not only provides the strongest evidence for a hot, compressed early universe - the Big Bang - but also one of the most direct means for studying the early universe. In particular, the large-angular-scale anisotropy of the cosmic background radiation is a sensitive probe of several phenomena of cosmological interest. These include the isotropy of the Hubble expansion, possible rotation of the Universe, and the existence of very long wavelength gravitational radiation. A large-scale anisotropy can also arise from the non-uniform distribution of matter at the time of decoupling.

Ever since the discovery of the cosmic background, experimenters have probed the isotropy of the radiation. The measurements on the large-angular-scale anisotropy have been directed toward the twin goals of finding an intrinsic anisotropy in the early universe and detecting the solar motion through the radiation. Early measurements of the anisotropy were hampered by atmospheric noise, Galactic radiation and limited sky coverage. In more recent experiments, low sidelobe horn antennas, careful radiometer design, higher observing frequencies and measurements from high altitude (balloon and aircraft) have minimized the systematic errors that plagued earlier measurements. Anisotropy in the cosmic background radiation has now been clearly observed by groups at Princeton and Berkeley. For both measurements, the

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anisotropy is well described by a first order spherical harmonic (dipole) distribution and is inconsistent with a quadrupole distribution. The new Berkeley measurements from the southern hemisphere are in good agreement with northern hemisphere results.

REVIEW OF BERKELEY AND PRINCETON EXPERIMENTS

The Berkeley and Princeton experiments each detected a first order anisotropy and set stringent upper limits on higher order components. The reported signals (3 mK) are extremely small when compared to the ambient temperature (300 K) and the equivalent noise temperature of the receivers. Maintaining the stability of a receiver to better than one part in 10^5 while pointing the apparatus from one part of the sky to the next would be exceedingly difficult; however, if the receiver is designed to have inputs from two identical antennas pointing at different parts of the sky simultaneously, the stability requirements are reduced typically to about a part in a thousand. The receiver must be well regulated thermally to provide the necessary stability. Because the inputs may not be precisely identical, the entire apparatus is also rotated, interchanging the positions of the two antennas roughly once per minute.

The results of earlier experiments have been limited by Galactic emissions -- primarily synchrotron radiation and thermal emission from HII regions at the low frequencies, and Galactic dust at very high frequencies. However, there is a natural window in the Galactic background in which to make anisotropy measurements (between 3 mm and 1.5 cm) where the Galactic contribution is lower than the reported cosmic background anisotropy.

Care must be taken to see that the two antennas are pointing through nearly identical pathlengths of atmosphere, so that the atmospheric microwave emission is balanced. This is very difficult to do at low altitudes (less than 12 km) because of the fluctuating atmospheric water vapor. At higher altitudes, the water vapor is reduced substantially and the remaining atmospheric emission is due primarily to oxygen which is much more uniformly distributed.

Finally, the experiments must guard against stray emissions from the earth, the apparatus itself, and other extraneous sources. The receivers must be designed and constructed carefully to ensure good performance and shielding against man-made interference. Rejecting the unwanted stray radiation also requires the use of ground shields and antennas with very low sidelobe response. All ferrite components are magnetically shielded.

Table 1 lists some of the relevant experiment parameters.

Table 1 Experiment Parameters

	Berkeley	Princeton
Vehicle	U-2	Balloon
Altitude	20 km	27 km
Duration	4 hrs/flight	2 @ 8 hrs
Frequency	33 GHz (9 mm)	19 GHz 24.8 + 31.4 GHz
Opening Angle	60°	90°
Rotation	64 seconds	∿1 minute
Origin of Flights	Ames, Cal lat 38°	Palestine, Texas lat 32°
Antenna	dual-mode corrugated horns	standard with ground shield + add flare on end.

The parameters of the best fit to a first order spherical harmonic distribution are:

	ΔT	α (hours)	δ	
Berkeley	3.5±0.5	11.2±0.5	16°±7°	(Smoot, Gorenstein & Muller)
Princeton	3.0±0.3	12.3±0.4	-1°±6°	(Cheng et al. 1979)

If these dipole distributions are due to the solar motion through the radiation, we can use the Doppler shift formula:

$$T(\theta,\phi) = T_o \gamma/(1-\beta\cos\theta)$$ where θ = angle between direction of motion and observation, β = velocity

$$\simeq T_o + T_o \beta\cos\theta$$ $\beta << 1$

The solar velocity is then found to be

$$V_\odot = \Delta T \times 100 \text{ km/sec} \times \frac{3°K}{T_{CBR}}$$

where the direction of the velocity aligns with the direction of maximum anisotropy.
Using canonical values,

$$V_\odot \simeq 300 \pm 40 \text{ km/sec.}$$

We can then calculate the velocity of the Galaxy and local group by subtracting the solar motion due to the rotation of the Galaxy (300 km/sec, ℓ=90°, b=0°). The local group has a large net velocity of 500 km/sec towards $\alpha = 10.5^h$ and $\delta = -19.5°$ (ℓ=264°, b=33°).

SOUTHERN HEMISPHERE MEASUREMENTS

With a positive result from anisotropy measurements in the northern hemisphere, our attention naturally turned toward possible southern sky coverage. First, the unsurveyed southern hemisphere could provide completely independent verification of the observed northern hemisphere anisotropy. Second, the southern sky coverage (or at least accurate data from a very different latitude) would be necessary to distinguish unambiguously between the polar dipole and a polar-axially-symmetric quadrupole component. The optimum location for separating the spherical harmonic polar components of first and second order is 30° south latitude. Unfortunately, the Galactic background, geography, and politics all conspire to make this a difficult latitude from which to make measurements.

On March 2-5, 1979, we were able to conduct a series of four flights from Lima, Peru. The U-2 flew to southern Peru, and most of the observations were conducted from 15° south latitude. The data from the March 5 flight were taken from 10° latitude in order to utilize the moon for an inflight calibration. Unfortunately, we were unable to finalize the arrangements on schedule, and the four flights occurred two weeks later than originally planned. This delay caused the first data points (taken just after dark) to be one hour later in siderial time than planned; the data-taking flight segments could not extend beyond the original cut-off, because the Galactic plane would have produced a significant background signal. In addition, there were other small time delays, and an error in which the pilot flew the flight plan from the previous day. These combined difficulties resulted in a sky coverage which was less than ideal, but which still provided much of the information we sought. The sky coverage actually achieved is shown in Figure 1.

The general operating conditions in Peru were more severe than California. In particular, atmospheric temperatures at altitude were significantly colder. The heaters in the thermal controller for the receiver and Dicke switch drew about one third more power, and the temperature sensors imbedded in the antennas near the exposed ends registered temperatures of less than -40°C, typically 10°C colder than on flights from Ames. This extreme cold and the high humidity in Lima combined to make the post-flight checkout a difficult task. As soon as each flight was over, we would begin the checkout by covering each antenna with a piece of Saran Wrap to keep out dust and any moisture which might condense. By the end of the checkout, the heaters would have warmed the equipment to a higher than ambient temperature, removing the possibility of condensation.

We believe that the apparatus got very cold during the flight down from California, and condensed water when it landed in Panama and/or Lima. The condensation probably caused the atmospheric monitor (54 GHz radiometer) to fail before the first flight. We discovered the failure in the checkout before the flight, but had insufficient time to repair the 54 GHz radiometer (the equipment had arrived only four hours before the scheduled flight). We found water in the Dicke switch waveguide when we disassembled and repaired it. Our previous and, as it

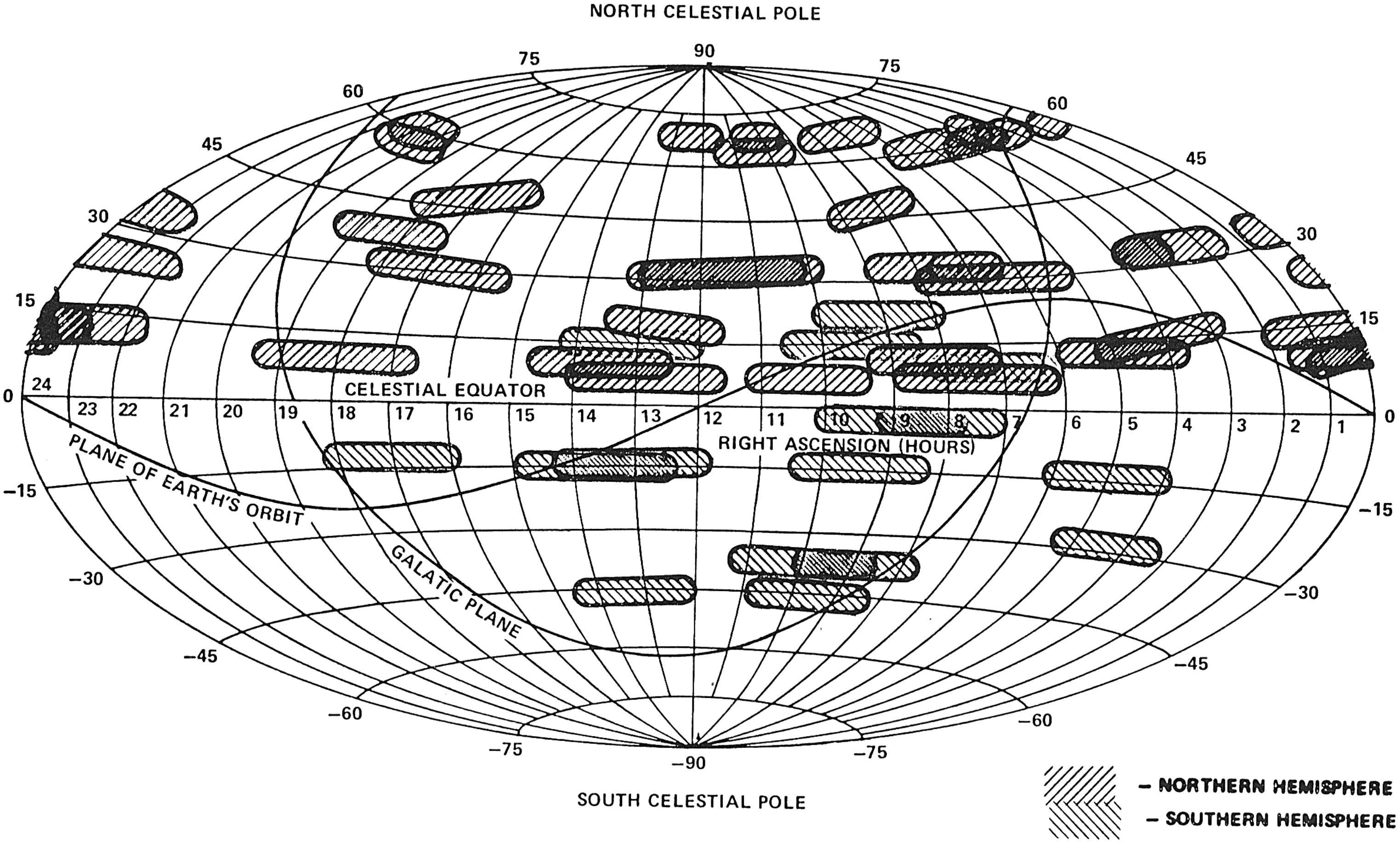

Figure 1. Plot of Sky Coverage in Celestial Coordinates. Sky coverage for the northern flights from NASA Ames in California and southern flights from Lima, Peru is indicated by the shaded regions. The width of each region is set by the 7° antenna beam widths, and the length is set by the rotation of the earth and the motion of the U2 back and forth along its flight path. The galactic and ecliptic planes are shown for reference.

turns out, succeeding experience verified that the U-2 flies sufficiently level to make the atmospheric corrections negligible, and the data from the first flight appear to be satisfactory.

RESULTS

Measurements from the southern hemisphere flight paths are shown in Figure 2 along with the predicted response based on our northern hemisphere data. The results are very encouraging, since they show an anisotropy of roughly the same magnitude and direction as the northern data. Fitting these southern data to a first order spherical harmonic anisotropy produces:

	ΔT (m°K)	α(hours)	δ
Uncorrected	2.4±0.7	12.5±1	2°±13°
Corrected for Galactic Bkg	2.9±0.7	12.3±1	1°±13°

These results are in remarkable agreement with those of Princeton and in reasonable agreement with our own northern hemisphere data.

To obtain the best value for the first-order anisotropy and limits on higher order spherical harmonics, we combined the northern and southern hemisphere measurements. For the dipole solution, we find:

$$\Delta T = 3.1\pm0.4 \text{ m°K},\ \alpha = 11.4\pm0.4 \text{ hours, and } \delta = 10° \pm 6°$$

The combined dipole and quadrupole best-fit parameters are:

$$\Delta T = 2.9\pm0.4 \text{ m°K},\ \alpha = 11.1\pm0.5 \text{ and } \delta = -4°\pm10°$$

so that 95% of the anisotropy remains in the three first-order components. The net quadrupole amplitude is approximately 0.5±0.5 mK, consistent with no net quadrupole term in a combined first and second order fit to the level of 1 mK.

CONCLUSION

The data from the southern hemisphere support and complement the northern sky measurements. The combined data indicate a global first order anisotropy at about the 3 mK level and limit any second or higher order anisotropy to significantly lower levels. This conclusion, in turn, supports the interpretation that the observed anisotropy arises via a Doppler shift caused by the solar motion relative to the background radiation. A 3 mK anisotropy translates into a solar motion of approximately 300 km/sec; when the rotation of the galaxy is taken into account, we find a net velocity of approximately 500 km/sec for the local group. This relatively high velocity disagress with the velocities inferred from the anisotropy in the Hubble diagram. Thus, the southern measurements have highlighted the apparent inconsistency

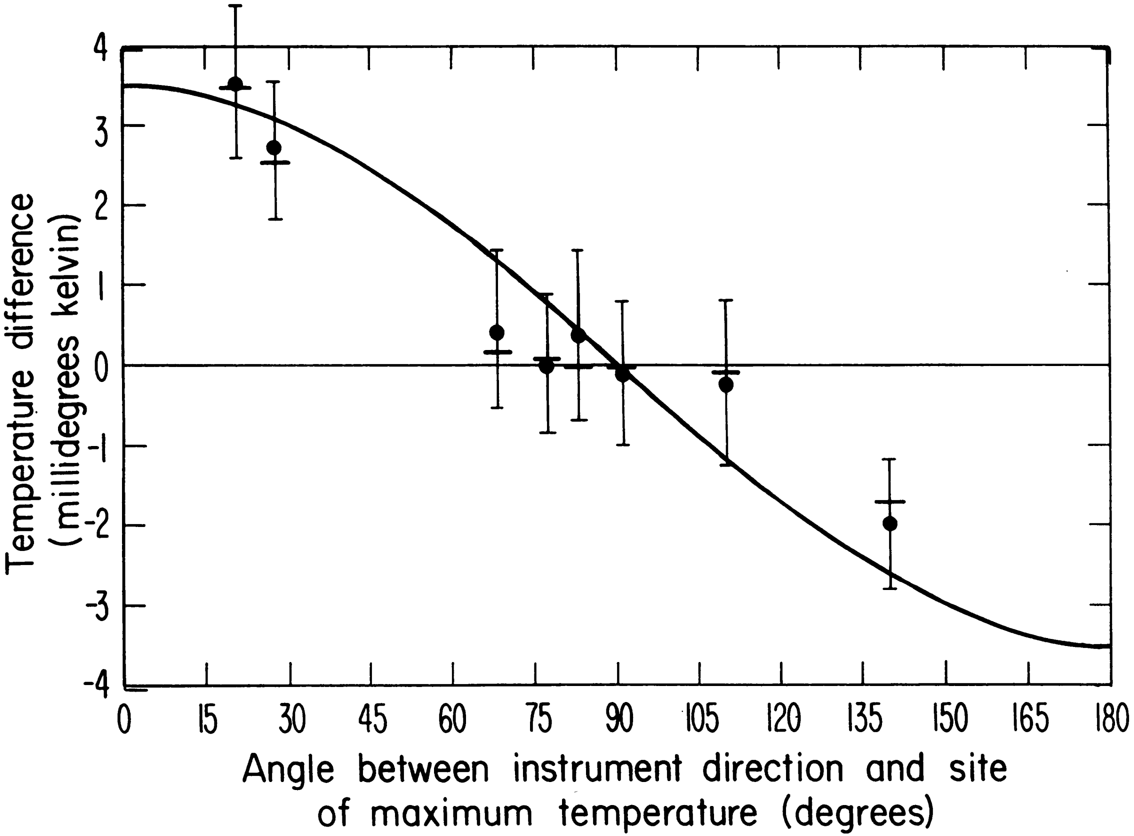

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Figure 2. Comparison of southern hemisphere data with predictions from northern measurements. The temperature difference, $\Delta T = T(\hat{\theta}_1) - T(\hat{\theta}_2)$, observed is plotted versus the angle between the instrument direction, $\hat{d} = \hat{\theta}_1 - \hat{\theta}_2$, and the direction of maximum temperature, $\hat{n} = \alpha = 11.2$ hours and $\delta = 16°$. The heavy horizontal bars represent the uncorrected data, while the dots show the data corrected for estimated galactic background.

between the background radiation measurements and the galaxy-magnitude-redshift studies.

The lack of observed higher-order anisotropy (no component with greater than 1 m°K amplitude) emphasizes the intrinsic large-scale isotropy of the universe and supports the Cosmological Principle. Apparently, the discovery of any intrinsic large-angular-scale anisotropies must await the next generation of experiments, or perhaps the full-sky coverage that will be achieved by the Cosmic Background Explorer (COBE) Satellite.

The COBE satellite will carry anisotropy-measuring radiometers operating at four frequencies, in order to distinguish between Galactic radiation and the intrinsic anisotropy in the cosmic background based on frequency dependence. The space craft will rotate at about 1 RPM to interchange the antennas, and will be in a polar orbit perpendicular to the sun-earth line. This orbit allows the radiometers to look away from the earth at all times, and to be shaded from the sun by a large conical shield. The radiometers will cover the entire sky in six months. The anisotropy measuring experiment should achieve a sensitivity of 0.1 mK on all angular scales larger than about 10°, and thus be able to detect higher order components which are approximately 1/30th the amplitude of the observed first-order anisotropy.

REFERENCES

Cheng, E.S., Saulson, P.R., Wilkinson, D.T., and Corey, B.E.: 1979, Astrophys.J.Letters, very soon.
Gorenstein, M.V., Muller, R.A., Smoot G.F., and Tyson, J.A.: 1978, Rev. of Sc. Ins. 49, 4, p. 440.
Gorenstein, M.V. and Smoot, G.F.: 1980, to be submitted to Astrophys.J.
Smoot, G.F., Gorenstein, M.V., and Muller, R.A.: 1977, P.R.L. 39, 898.
Smoot, G.F. and Lubin, P.M.: 1979, Astrophys.J.Lett. - soon.

DISCUSSION

Tyson: What is the magnitude of the left-right based anisotropy, and was it the same in the south?

Smoot: For the northern hemisphere data the equipment centered anisotropy revealed by reversing the aircraft flight path was about 2 mK. For the southern flights the aircraft centered offset appears to be about twice this value. The effect appears to be stable and cancels because we take our data in pairs of opposing direction flight paths. We do not yet understand why the offset is greater for the southern flights.