LARGE SCALE ANISOTROPY OF THE COSMIC MICROWAVE BACKGROUND

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It is now generally accepted that the microwave background radiation, discovered in 1965 (Penzias and Wilson, 1965; Dicke *et al.*, 1965), is cosmological in origin. Measurements of the spectrum of the radiation, discussed earlier in this volume by Blair, are consistent with the idea that the radiation is in fact a relic of a hot, dense, initial state of the Universe – the Big Bang. If the radiation is cosmological, measurements of both its spectrum and its angular distribution are capable of providing important – and remarkably precise – cosmological data.

My task is to discuss possible anisotropies, or variations in the intensity, of the radiation on a large angular scale – say 10° or more. In fact, I have three tasks – first, to describe briefly the kinds of anisotropies we might expect; second, to give the present experimental results; and third, to describe some difficulties with these results.

First, let us consider the case of isotropic cosmological models with no rotation. In such models, the cosmic background radiation will be isotropic in co-moving coordinates. That is, if the Earth has no peculiar velocity of its own with respect to the co-moving coordinate frame of the expanding Universe, then the intensity of the radiation will be the same in all directions.

If, however, the Earth moves with respect to the comoving coordinate system because it revolves around the Sun, as Copernicus suggested, or because the whole solar system revolves around the center of the Galaxy, or because the Galaxy itself is in orbit about the center of the local supercluster – if, for any of these reasons, the Earth has a velocity relative to the comoving coordinate frame, the microwave background radiation will not be isotropic in intensity. It will be blue-shifted to larger intensities in the direction in which we move. The period of the spatial variation is 360° or 'dipole', and the amplitude of the variation is given simply by $\Delta I = (v/c)\, I$ for $v \ll c$ (Peebles and Wilkinson, 1968). Radio astronomers normally use antenna temperature as a measure of intensity; here $\Delta T/T = v/c$. If the measurements are made in the Rayleigh-Jeans region of the blackbody spectrum of the microwave background, T may be set equal to the thermodynamic temperature of the radiation, 2.7 K. This approximation works well for all measurements discussed here (see Boughn *et al.*, 1971).

I suspect Copernicus would have approved of the assumption that the Universe itself is isotropic. As he says early in *De Revolutionibus*, "The first point for us to notice is that the Universe is spherical." General relativity, however, permits a wider range of solutions, in particular some in which the Universe is *not* isotropic. The cosmic microwave background in such models will display an anisotropy with a characteristic spatial period of 180° ('quadrupole'). As Novikov (this volume) shows,

M. S. Longair (ed.), Confrontation of Cosmological Theories with Observational Data, 157–162.

a pure quadrupole anisotropy is present only for an Einstein-de Sitter model. A quadrupole anisotropy arises because anisotropic models have an axis along which the expansion proceeds at a maximum rate: in these directions, the background radiation temperature will have minima. A similar effect is present in cosmological models with rotation, as Hawking (1969) has shown.

Temperature variations on a smaller angular scale will be discussed in the following paper by Boynton. Here I might add only that there exists a gap in the measurements between angular scales of about 1° and 10°. Included in this gap is the interesting region of 1°–6° where Hauser and Peebles (1973) report evidence for the superclustering of galaxies.

1. Early Measurements

In the first few years after the discovery of the microwave background, isotropy measurements were made in a very simple way: by fixing a radiometer on the Earth and allowing the Earth's spin to carry the radiometer beam in a circle around the celestial sphere. This arrangement permitted us to measure the relative intensity of the radiation along a circle of constant declination. Unfortunately, this technique provides information only about the component (or projection) of the anisotropy in the plane perpendicular to the Earth's spin axis.

Results available by 1968 showed that the microwave background was isotropic in this plane to within a few parts per thousand: that is, $\Delta T \lesssim 5 \times 10^{-3}$ K. Such an upper limit on the 'dipole' anisotropy component implies that the Earth has no peculiar motion (in the plane perpendicular to the spin of the Earth) greater than 500 km s^{-1}. While this number is one of the most accurate results in experimental cosmology, it is not as accurate as we might wish. It is consistent with the known motion of the solar system about the galactic center, but does not permit us to refine our knowledge of the galactic rotation velocity. Nor of course does it permit us to perform the ultimate in Michaelson-Morley experiments, the measurement of the changing velocity of the Earth as it moves around the Sun.

These early results also fixed a comparable limit on the 'quadrupole' anisotropy in the plane perpendicular to the spin of the Earth – $\Delta T/T \lesssim 2$–3×10^{-3}. This upper limit is perhaps one order of magnitude better than measurements of the isotropy of the Universe based on observations of the isotropy of the Hubble parameter. As interpreted by Hawking, Novikov, Thorne, and Zel'dovich these measurements performed the useful service of reducing the 'embarras de richesses' of general relativity: that is, of reducing the number of allowed cosmological models for the Universe. Copernicus' intuition that the Universe was simple and symmetrical appears to be borne out. This matter will be discussed further in the contributions of Novikov and Hawking to this volume.

2. Recent Observations

What has been the progress in the past five years? Unfortunately not as great as might be hoped. We have improved measurements by at best a factor of 3. So this paper, unfortunately, is really a status report rather than a progress report.

There are, however, a few new results to mention. I shall present the results without giving any details of the experimental apparatus. In general, sources of error and problems in these measurements are *not* determined by the apparatus itself.

The most important new result is that of Paul Henry (1971), who employed a radiometer mounted on a rotating platform suspended beneath a balloon. Because he employed a rotating platform he was able to look for anisotropy over a wide area area of the sky (about one-half of the northern hemisphere), not just a circle of constant declination. In a single night, he was able to obtain enough data to establish a value for the component of the 'dipole' anisotropy parallel to the spin axis of the Earth. It is $\Delta T = (3.2 \pm 0.8) \times 10^{-3}$ K in the direction $\alpha = 10^{h}$–11^{h} and $\delta = -30°$. His results are consistent with the earlier results of Conklin (1969), but provide the important additional datum that the motion of the Earth with respect to the co-moving coordinate system (and parallel to the spin axis of the Earth) is small.

Meanwhile, Conklin refined and repeated his earlier measurement and reduced the statistical error. The results of his work are reported in the *IAU Symp.* **44** (1972). His device was located on the ground and scanned only a circle at $\delta = +32°$. Since the declination was fixed he has information only about component of anisotropy in the plane perpendicular to the spin axis of the Earth.

Both Henry and Conklin claim evidence for motion of the center of our Galaxy about the local supercluster, after subtraction of the 'dipole' anisotropy expected from solar motion about the center of the Galaxy. I shall return to this point later.

Several years ago Wilkinson, Beery and I also made a measurement with somewhat less accuracy than Conklin's, at $\delta = 0°$. The results are unpublished. They are notable only in that they agree with Conklin's results generally as far as the 'quadrupole' anisotropy is concerned, but do not agree well for the 'dipole', or 360°, anisotropy. Again, I shall return to this point at the end. Next I should mention very briefly a preliminary attempt to make somewhat similar measurements at 8 mm wavelength, carried out by Boughn, Fram and the present author. The attempt was not successful, in the sense that it did not reach limits comparable to the 3 cm measurements. The experiment was undertaken to check on the possibility of wavelength dependent anisotropy. It seems to me we should not lightly dismiss the possibility of wavelength dependent anisotropies merely because these do not occur naturally in the Big Bang picture.

I have summarized all the results to date in Table I. For all measurements but those of Conklin, the error quoted is a circular standard deviation of the mean (see Boughn *et al.*, 1971).

Finally, let me anticipate one exciting result which should soon appear – a measurement of the polarization of the microwave background radiation. Recall that Rees (1968) first pointed out that Thomson scattering of the microwave radiation in an anisotropic universe would produce a small polarization of the radiation with quadrupole character. Nanos and Wilkinson at Princeton University are searching for polarization with this signature.

TABLE I

Measurements of the anisotropy of the microwave background on large angular scales

Location (date)	Investigators	Decl. of Scan	λ cm	Amplitude, 10^{-3}K	R.A. of maximum
360° or 'Dipole' anisotropy					
Princeton (1967)	P&W[a]	$-8°$	3.2	2.2 ± 1.8	17^h
Yuma[b] (1968)	Dismukes, W & P	0° 42°	3.2 3.2	2.2 ± 2.1 1.5 ± 2.7	2^h [c] 8^h [c]
White Mt. (1972)	Conklin	32°	3.8	2.3 ± 0.9	11^h
Princeton (1971)	Boughn, Fram&P	0°	0.86	7.5 ± 11.6	6^h [c]
Texas (balloon, 1971)	Henry	–	2.9	3.2 ± 0.8	$10\text{–}11^h$, $\delta = -30°$
Los Alamos[b] (1968)	Beery, W&P	0°	3.2	0.7 ± 1.2	16^h [c]
180° or 'quadrupole' anisotropy					
Princeton (1967)	P&W	$-8°$	3.2	2.7 ± 1.9	7^h, 19^h
Yuma[b] (1968)	Dismukes, W&P	0° 42°	3.2 3.2	2.1 ± 2.0 4.0 ± 2.4	5^h, 17^h 8^h, 20^h
White Mt. (1972)	Conklin	32°	3.8	1.35 ± 0.8	6^h, 18^h
Princeton (1971)	Boughn, Fram&P	0°	0.86	5.5 ± 6.6	0^h, 12^h [c]
Los Alamos[b] (1968)	Beery, W&P	0°	3.2	1.9 ± 1.2	9^h, 21^h

[a] P = present author; W = Wilkinson.
[b] Unpublished.
[c] Not significant.

3. A Few Words of Caution

Now, for a moment, let us examine these results critically. What problems have prevented experimentalists from improving these values much over the past five years? The first difficulty facing observers is absorption and re-emission of microwave radiation by the Earth's atmosphere. The worst culprit is water vapor. When it is clumped, as it often is, it introduces statistical noise in the data. An even more dangerous situation may arise if the water vapor is anisotropically distributed on a large scale – as it might be in the presence of prevailing winds. Anisotropic water vapor will produce anisotropy in the measured antenna temperature, and therefore a spurious anisotropy signal. For these reasons, most observers have attempted to work at wavelengths longer than 3 cm, where water vapor emission is not so troublesome. Unfortunately, this forces us onto the other horn of our dilemma, nonthermal radio emission from our own Galaxy, which becomes non-negligible at wavelengths $\gtrsim 1$ cm. Consequently a new source of systematic error arises, since the Galaxy is obviously *not* isotropically distributed about us.

If we had accurate maps of galactic emission at short wavelengths we could easily correct our observations. Unfortunately we do not. We must therefore extrapolate longer wavelength maps down to 10 GHz using some assumed value for the spectral index, α. Here problems can arise. The very important work of Webster (1974) has shown that α varies from place to place in the Galaxy. In particular his work shows that α varies strongly in the region 16^h right ascension, $+40°$ declination, a region covered by Conklin's scans. In fact, Webster has shown that a simple extrapolation of his observations down to 4 cm appears to explain almost entirely the observed dipole anisotropy reported by Conklin (1969). In other words, the intrinsic, cosmological, anisotropy may be close to zero. Here I note that our measurements (Beery *et al.*, 1968), which were made at $\delta = 0°$, rather than $+32°$, do in fact show a smaller anisotropy signal.

Some support for the idea that galactic emission influences these measurements is provided by the observations of 'quadrupole' anisotropy. Consider first scans made along the celestial equator: these scans will cut the galactic plane at two points exactly 12 hr apart, since both are great circles. One might expect a galactic component with maxima at approximately 7^h and approximately 19^h right ascension, which is indeed where the measurements cluster. That the 'quadrupole' component is somewhat smaller for Conklin's observations is to be expected, since his scan at $\delta = 32°$ is not a great circle, and therefore does not cut the galactic plane at two points 12 hr apart.

It seems to me we must face the possibility that we have in the past overestimated the magnitude of the cosmological anisotropy in the microwave background. If so, the agreement between the observed velocity of the solar system and that predicted by the models of Sciama (1967), Stewart and Sciama (1967), and de Vaucouleurs and Peters (1968) is weakened. Here is a possible confrontation between theory and observation. To end on a more speculative note, *if* the motion of the solar system with respect to the background radiation has no large component due to motion of the Galaxy as a whole, then the point made yesterday in Tammann's report is strengthened: the local density inhomogeneity represented by the local supercluster has little gravitational effect on the Galaxy, implying a low value for Ω, the ratio of the mean mass density in the Universe to the critical density.

I suspect this connection between the motion of the Earth and one of the deepest questions of cosmology would have pleased the man we honor this year, Nicholas Copernicus.

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DISCUSSION

Novikov: My comment concerns the theoretical implications of the observational upper limits to the anisotropy of background relic radiation on large scales. Let us assume that in the past the matter distribution was homogeneous, but that perhaps the Universe expanded anisotropically. We denote the moment when the expansion becomes isotropic by t_F.

The theory gives the following predictions:

If $\varrho \approx \varrho_{\text{crit}}$ the angular distribution of ΔT is quadrupole and the amplitude of $\Delta T/T$ can be calculated as a function of t_F. If $t_F \approx 10^{-43}$ s and z_e (redshift of the moment when the Universe becomes transparent) is 10^3, $(\Delta T/T)_{\text{max}} = 5 \times 10^{-3}$. So in this case the observations show that the expansion should have been isotropic from the very beginning.

In the case $\varrho < \varrho_{\text{crit}}$ one cannot say the same. The value of $\Delta T/T$ differs from zero only in one small spot. Since $\Delta T/T$ has not been measured over the whole sky, this spot might have been missed, and it is an interesting problem for observers to find this small spot on the sky if it exists.

McCrea: Have any measurements been made in the southern hemisphere?

Partridge: No – and it is a pity, since measurements of the type reported here are easy to make.

Blair: In view of the experimental difficulties associated with improving these measurements, do you have any comments about how best to proceed?

Partridge: The most important things to avoid are those sources of systematic error which are hard to calculate. I refer specifically to the non-thermal microwave emission from the Galaxy. So I would be inclined to work at a wavelength less than 1 cm. To avoid problems arising from emission in the Earth's atmosphere, one would probably have to work above the atmosphere – using balloons or satellites. Such measurements are orders of magnitude more difficult and more expensive than ground-based measurements.

Urbanik: Could you give us some information about the location of the axis of anisotropy at 8 mm?

Partridge: The error in the measured temperature anisotropy at 8 mm is too large to define precisely the coordinates of the anisotropy maximum.