5-1971

Isotropy of the Microwave Background at 8 mm

Stephen P. Boughn
Haverford College, sboughn@haverford.edu

D. M. Fram

Bruce Partridge
Haverford College, bpartrid@haverford.edu

5-1971

Isotropy of the Microwave Background at 8 mm

Stephen P. Boughn
Haverford College, sboughn@haverford.edu

D. M. Fram

R. B. Partridge
Haverford College

THE ASTROPHYSICAL JOURNAL, 165:439–444, 1971 May 1

ISOTROPY OF THE MICROWAVE BACKGROUND AT 8-MILLIMETER WAVELENGTH*

S. P. BOUGHN,† D. M. FRAM, AND R. B. PARTRIDGE‡
Joseph Henry Laboratories, Physics Department, Princeton University, Princeton, N.J. 08540
Received 1970 November 28

ABSTRACT

A preliminary measurement of the isotropy of the cosmic microwave background has been made at a relatively short wavelength, 8.6 mm. The measurement was made along the celestial equator. No statistically significant anisotropy was found.

I. INTRODUCTION

The cosmic microwave background, first observed by Penzias and Wilson (1965), was immediately interpreted as relict radiation from the primeval fireball, the hot initial phase of an expanding Universe (Dicke *et al.* 1965). In the fireball picture the radiation should have a blackbody spectrum. It should also appear isotropic when measured in the comoving coordinate frame, unless the expansion of the Universe is itself anisotropic (Thorne 1967). These two properties are considered to be the best tests of the fireball picture.

The degree to which the two tests have been met and passed by the original fireball model is disputed (see Partridge 1969). In particular, it is not yet certain whether the spectrum of the radiation at wavelengths below 3 mm is blackbody (see Muehlner and Weiss 1970, and references cited therein). The second test thus far appears to have been met more successfully: experiments by the Princeton group (e.g., Partridge and Wilkinson 1967) and more recently by Conklin (1969) at a wavelength of $\sim$3 cm have shown that the radiation is highly isotropic, at least on a large scale; any residual anisotropy can readily be accounted for by the peculiar velocity of the solar system with respect to the comoving coordinate frame (Peebles and Wilkinson 1968).

However, no accurate measurement of the isotropy of the radiation has yet been reported at a wavelength below 3 cm (which is still in the Rayleigh-Jeans region of the presumed blackbody spectrum). Epstein (1967) was able to draw some inferences about the small-scale isotropy of the radiation at 3 mm wavelength, but his limit on possible anisotropy was only $\Delta I/I \lesssim 1$ percent on a scale of 1°, and was even less sensitive for larger angular scales. We here report a measurement at 8.6 mm which is considerably more sensitive. This measurement should be regarded as a preliminary one; we decided to publish the results because of the interest expressed in them by theoreticians in the field and because our work does allow us to set some useful upper limits.

A measurement of the isotropy of the background radiation at a short wavelength is desirable for two reasons. First, nonthermal radiation from the plane of our Galaxy, which can introduce systematic errors into the data (as discussed by Conklin 1969), is less intense at shorter wavelengths and may safely be ignored at 8 mm. Second, it is important simply to check whether the isotropy of the radiation is independent of wave-

* This research was supported in part by the Office of Naval Research and the National Science Foundation.

† Present address: Department of Physics, Stanford University.

‡ Present address: Haverford College, Haverford, Pennsylvania 19041.

length. In the simple fireball picture, it is expected to be. However, there are other models which invoke discrete sources, such as galaxies or QSSs, to produce the observed radiation. In these models (e.g., Wolfe and Burbidge 1969), each region of the spectrum is dominated by sources at a particular redshift. Such a model would clearly allow a wavelength-dependent anisotropy in the background radiation. The flux at short wavelengths, in this picture, is predominantly produced by a relatively small number of nearby sources—that is, by those having the smallest redshifts. This suggests that the degree of anisotropy, if in fact it is dependent on wavelength, would be higher for shorter wavelengths.

The disadvantages of working at 8 mm rather than, say, at 3 cm are observational: receivers at higher microwave frequencies are noisier, and microwave emission from the Earth's atmosphere is greater. The latter is the more serious difficulty. In the present experiment, atmospheric emission contributed $\sim 20^\circ$ K to the antenna temperature, whereas the antenna temperature of the background radiation was less than 3° K; and we were, of course, hoping to measure small variations in it. Some precautions taken to reduce the atmospheric contribution will be discussed below.

II. APPARATUS AND METHOD OF MEASUREMENT

The Dicke radiometer used to make these measurements was constructed by Wilkinson (1967). It operated at 35 GHz: the system noise temperature was $\sim 2500^\circ$ K, and the effective bandwidth was 10 MHz. It was placed on an aluminum platform and surrounded by fly-screen panels to reduce ground radiation. Two similar, conical, horn antennas, each with a half-power beamwidth of $\sim 4^\circ$, were attached to the two ports of a symmetrized ferrite switch. A large stationary reflector of aluminum (labeled A in Fig. 1) deflected one antenna beam to the zenith: this served as a reference. The other antenna beam struck a movable reflector (B in Fig. 1). In one position, reflector B deflected the beam to a point on the celestial equator 32° east of the meridian, and, in the other position, to a point on the celestial equator 32° west. The reflector position was

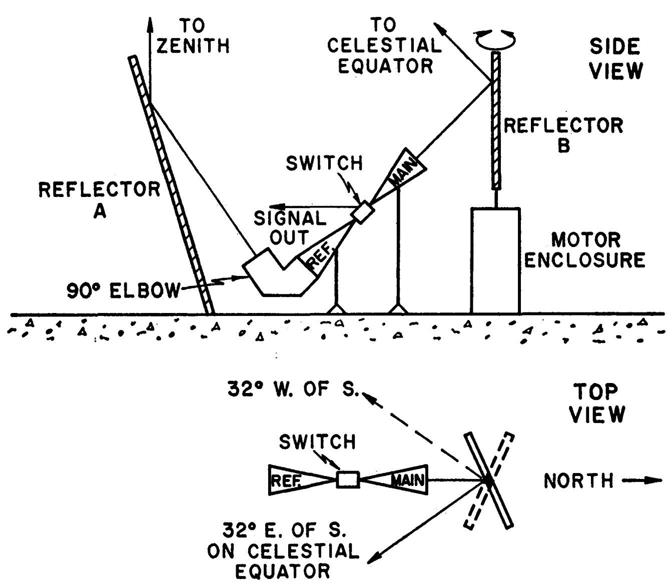

FIG. 1.—*Upper portion*, arrangement of the apparatus, with the fly-screen panels removed. *Lower portion*, view from above, showing how the main beam was alternately switched between two positions on the celestial equator.

switched every 20 minutes, and the average value of the radiometer output was determined visually from a chart record for each of these 20-minute blocks of data.

In terms of antenna temperature, we may write the output of the radiometer as

$$T = T_B + T_{\mathrm{ATM}} \sec z + T_S - T_{\mathrm{REF}} ,$$

where T_B is contributed by the background radiation; $T_{\mathrm{ATM}} \sec z$ is the atmospheric contribution at the zenith angle z of the beam; and T_S represents any instrumental contribution, due to a small asymmetry in the switch, etc. Also, T_{REF} is the antenna temperature of the reference antenna, consisting of two parts: the atmospheric contribution at the zenith ($z = 0°$) and the background radiation at the zenith. It may be taken as constant over the course of two adjacent 20-minute integrations, since the angular position of the reference beam changed by less than 10° in that time. Assuming also that T_S did not vary over a 40-minute interval, we may write for the difference in the output between east and west positions of the beam

$$\Delta T \equiv T(\mathrm{E}) - T(\mathrm{W}) = T_B(\mathrm{E}) - T_B(\mathrm{W}) + T_{\mathrm{ATM}} \sec z(\mathrm{E}) - T_{\mathrm{ATM}} \sec z(\mathrm{W}) .$$

The values of ΔT were our raw data.

If the zenith angles of the east and west beams had been exactly equal, the atmospheric emission in the two beams would have canceled. Unfortunately, the zenith angles of the two beams depended on the alignment of the apparatus, especially of reflector B, and this changed slightly from run to run. For each run i, we thus had a net atmospheric contribution $Q_i = T_{\mathrm{ATM}} \sec z_i(\mathrm{E}) - T_{\mathrm{ATM}} \sec z_i(\mathrm{W})$. Values for Q_i varied between 0.1° and 0.4° K despite our efforts to keep the alignment of the apparatus fixed. The latter figure corresponds to a misalignment of about 1° of arc.

The atmospheric contribution was expected to be constant during a run *as long as* the atmospheric temperature T_{ATM} did not vary with time. Let us consider what would happen if T_{ATM} varied diurnally, say by a factor ϵ. Then there would be a spurious 24-hour periodicity of amplitude ϵQ_i introduced into the data for that run. This is a major source of systematic error in all measurements of this type. We took two precautions to reduce it. First, measurements were not made on days when it was clear that T_{ATM} was likely to change markedly (i.e., when fronts passed by). Second, we ran for a sufficiently long time to ensure that solar-time effects of this sort were partially averaged out in sidereal time (see Partridge and Wilkinson 1967). A further discussion of this source of error appears below.

With the arrangement shown in Figure 1, the entire celestial equator can be scanned every 24 hours as the Earth rotates (cf. Partridge and Wilkinson 1967; Conklin 1969). Motion of the solar system with respect to the comoving coordinate frame produces a Doppler shift, which will introduce an anisotropy with a 24-hour sidereal period. Anisotropic expansion of the Universe would introduce a 12-hour sidereal period.

Such anisotropies would appear in the data as time variations in ΔT. For the arrangement we employed, a simple trigonometric calculation shows that a real anisotropy in the microwave background with a 24-hour sidereal period A_{24} and a maximum at right ascension α_{24} would produce an observed 24-hour periodicity $\Delta T(t)_{24}$ given by

$$\Delta T(t)_{24} = 1.06 \, A_{24} \cos\left[\left(\tfrac{2}{24}\pi\right)(t - \alpha_{24} + 6)\right] + Q . \quad (1)$$

Likewise, a real anisotropy with a 12-hour sidereal period and with a maximum at α_{12} would produce an observed 12-hour periodicity

$$\Delta T(t)_{12} = 1.80 \, A_{12} \cos\left[\left(\tfrac{2}{12}\pi\right)(t - \alpha_{12} + 3)\right] + Q . \quad (2)$$

In each case, the additional $\frac{1}{2}\pi$ enters the argument of the cosine because taking $T(\mathrm{E}) - T(\mathrm{W})$ effectively differentiates the incoming signal. Note that the magnitude of a 12-hour anisotropy signal is enhanced by nearly a factor of 2 with the experimental arrangement we employed.

More than thirty runs, lasting a day or longer, were made during the period 1969 March to 1969 September. At the beginning and the end of each run the instrument was calibrated by terminating the main antenna with an ambient temperature load of Eccosorb (Stokes, Partridge, and Wilkinson 1967).

III. DATA ANALYSIS AND RESULTS

During March and April and again during September, the Sun was close to the celestial equator, and thus radiated into our main antenna about 2 hours before noon (32° east of the meridian) and again 2 hours after noon. To eliminate this large spurious signal, we discarded *all* data taken between 8:30 A.M. and 3:30 P.M., solar time, during these periods. Then, separately for each run, the mean value Q_i of the temperature differences ΔT was found and subtracted from each ΔT.

Next, the values of $(\Delta T - Q_i)$ were placed in 1-hour time bins in both solar and sidereal time. The poor angular resolution of the instrument precluded analysis on any finer scale. For each bin, a mean and a standard deviation of the mean were estimated. For the sidereal-time bins, the standard deviation of the mean was approximately 0.025–0.030° K. For the solar-time bins, it varied between 0.017° and 0.059° K, being largest, of course, around solar noon where we had fewer data.

Then, 12-hour and 24-hour sine and cosine waves were fitted to both the solar-time data and the sidereal-time data. From the fitting program we can deduce both phase and amplitude for a cosine-wave fit to the data, and also the associated errors.

Finally, equations (1) and (2) were applied to convert the results to values for A_{12}, α_{12}, A_{24}, and α_{24}.

For the *sidereal-time* results only, two additional corrections are necessary to give true values for the anisotropy of the cosmic microwave background. First, we estimate that the absorption of the Earth's atmosphere at $z \sim 45°$ was $\sim$10 percent, and have corrected the data accordingly. A second correction involves a more subtle point. Thus far, we have been discussing the amplitude of possible anisotropies in terms of antenna temperature. But at 8 mm wavelength we are no longer in the Rayleigh-Jeans region of the assumed blackbody spectrum, so that the antenna temperature and the true thermodynamic temperature are no longer equal. The relationship between the two is given by Roll and Wilkinson (1967) as

$$T = T_\theta \frac{h\nu/kT_\theta}{\exp(h\nu/kT_\theta) - 1} \approx T_\theta\left[1 - \frac{1}{2}\frac{h\nu}{kT_\theta} + \frac{1}{12}\left(\frac{h\nu}{kT_\theta}\right)^2\right],$$

where T_θ is the true thermodynamic temperature of the microwave background, taken as 2.7° K (Stokes *et al.* 1967). At our operating frequency, $(h\nu/kT_\theta) = 0.62$, so the difference between T and T_θ is not negligible. However, it is important to recall that our data consist of *small temperature differences*. Consider now the case in which measurements are made at two different regions of the celestial equator where the difference in the true thermodynamic temperature of the cosmic microwave background is a small δT_θ. Then the measured difference in the antenna temperature is

$$\delta T = (T_\theta + \delta T_\theta)\left[1 - \frac{1}{2}\frac{h\nu}{k(T_\theta + \delta T_\theta)} + \frac{1}{12}\frac{h^2\nu^2}{k^2(T + \delta T_\theta)^2}\right] - T_\theta\left(1 - \frac{1}{2}\frac{h\nu}{kT_\theta} + \frac{1}{12}\frac{h^2\nu^2}{k^2T_\theta^2}\right).$$

Expanding the denominators of the terms in brackets and simplifying, we find that to first order in $(h\nu/kT_\theta)$, $\delta T = \delta T_\theta$. Keeping terms of order (δT_θ) only, we find

$$\delta T \approx \delta T_\theta \left[1 - \frac{1}{12}\left(\frac{h\nu}{kT_\theta}\right)^2\right] = 0.968\, \delta T_\theta \,.$$

This small correction was also applied to the sidereal-time results.

The final results of this experiment appear in Table 1, where they are compared with the temperature of the background radiation determined by Stokes *et al.* (1967). The errors are formal statistical errors and do *not* reflect possible systematic errors, which are discussed in the following paragraphs. The errors in A_{12} and A_{24} are "circular standard deviations" of the means: that is, in a polar plot of A_{12} (radial variable) and α_{12} (angular variable), the probability is formally 68 percent that the true amplitude and position of a 12^h anisotropy will fall within a circle of radius equal to the size of the quoted error, drawn about the given point.

As we pointed out earlier, a diurnal variation in $T_{\rm ATM}$ may introduce into the data a spurious 24-hour solar-time periodicity. Direct heating of the apparatus by the Sun would produce the same effect. The amplitude of the 24-hour cosine wave in solar time shows that our effort to reduce this source of error was not entirely successful. However, one must recall that we ran for an appreciable fraction of a year, so that solar-time effects tended to average out in sidereal time. Thus our smaller value for the 24-hour amplitude, A_{24}, in sidereal time seems reasonable. Nevertheless, because the possibility for systematic error was present, we are inclined to treat our value for A_{24} cautiously. Clearly, since a null result for A_{24} is consistent with the data, α_{24} has no statistical significance.

The situation with the 12-hour results is somewhat different. There is no large significant 12-hour periodicity in solar time, so our results for A_{12} should be free of the kind of systematic error discussed above. We feel that in this case, statistical error is dominant. Again we note that our results are consistent with a null value for the 12-hour anisotropy.

IV. CONCLUSIONS

First, we stress that we have measured only that component of any anisotropy in the background radiation which lies in the plane of the celestial equator.

Next, we should mention that our method of measurement did not allow us to search

TABLE 1

RESULTS OF THE ISOTROPY MEASUREMENT AT λ = 8 MILLIMETERS

Period	Amplitude* (Millidegrees K)	Fraction of 2.7° K	Right Ascension of Maximum
	Sidereal-Time Results		
12 hr	A_{12}=5.5± 6.6	0.20±0.24%	$\alpha_{12}=12^h$
24 hr	A_{24}=7.5±11.6	0.28±0.43%	$\alpha_{24}=6^h$
	Solar-Time Results		
12 hr	7.6± 6.3	...	...
24 hr	26.1±10.8	...	...

NOTE.—As explained in the text, A_{12} and A_{24} are the amplitudes of 12-hour and 24-hour cosine waves, and the associated errors are "circular standard deviations" of the means. Values for α_{12} and α_{24} are given even though they have little statistical significance in view of the size of the errors in A_{12} and A_{24}.

* Corrected for atmospheric absorption and converted to thermodynamic temperature.

for random anisotropy or inhomogeneities of the background radiation on scales smaller than about 6^h in right ascension. We could, without confusion, have detected a *single* small region of increased temperature: it would have appeared in our raw data as an increase in ΔT when the region passed through the east position of the beam, followed about 4 hours later by a similar decrease in ΔT as the region passed through the west position. An examination of our data allows us to fix a limit of 0.050° K on the magnitude of any such a local "hot spot," at $\lambda = 8$ mm.

Our results for A_{24} are considerably less accurate than those of Conklin (1969), and thus provide no new information on the motion of the solar system with respect to the comoving coordinate frame. However, to within the cited error, our results are in accord with Conklin's, and also with previous Princeton results obtained at 3-cm wavelength.

The upper limit on A_{12} implies that the fractional anisotropy in the microwave background radiation produced by anisotropic expansion is less than $\sim$0.4 percent. This limit represents our value of A_{12} plus one "circular standard deviation" of the mean. Since measurements at $\sim$4 cm (Conklin 1969) set even lower limits, we may say that over a wavelength range of nearly five, the anisotropy of the radiation is less than 0.4 percent. This result is necessary for the fireball picture, but is not, of course, sufficient to ensure that it is the correct model for the cosmic microwave radiation.

Discussions with David T. Wilkinson and Paul S. Henry in the course of this experiment and afterwards have been extremely useful. We would also like to thank Dr. W. P. Ernst, of the Plasma Physics Laboratory, Princeton, for lending us an intermediate-frequency amplifier.

REFERENCES

Conklin, E. K. 1969, *Nature*, **222**, 971.
Dicke, R. H., Peebles, P. J. E., Roll, P. G., and Wilkinson, D. T. 1965, *Ap. J.*, **142**, 414.
Epstein, E. E. 1967, *Ap. J.* (*Letters*), **148**, L157.
Muehlner, D., and Weiss, R. 1970, *Phys. Rev. Letters*, **24**, 742.
Partridge, R. B. 1969, *Am. Scientist*, **57**, 37.
Partridge, R. B., and Wilkinson, D. T. 1967, *Phys. Rev. Letters*, **18**, 557.
Peebles, P. J. E., and Wilkinson, D. T. 1968, *Phys. Rev.*, **174**, 2168.
Penzias, A. A., and Wilson, R. W. 1965, *Ap. J.*, **142**, 419.
Roll, P. G., and Wilkinson, D. T. 1967, *Ann. Phys.*, **44**, 289.
Stokes, R. A., Partridge, R. B., and Wilkinson, D. T. 1967, *Phys. Rev. Letters*, **19**, 1199.
Thorne, K. S. 1967, *Ap. J.*, **148**, 51.
Wilkinson, D. T. 1967, *Phys. Rev. Letters*, **19**, 1195.
Wolfe, A. M., and Burbidge, G. R. 1969, *Ap. J.*, **156**, 345.