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Author

Muller, Richard A.

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Richard A. Muller

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COSMIC MICROWAVE BACKGROUND -- PRESENT STATUS AND FUTURE PROSPECTS

by

Richard A. Muller
Department of Physics, and
Lawrence Berkeley Laboratory
University of California
Berkeley, California

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the 13th Texas Conference on
Relativistic Astrophysics, Munich, Germany
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COSMIC MICROWAVE BACKGROUND -- PRESENT STATUS AND FUTURE PROSPECTS

*This is the signal primeval.
The murmuring microwave background,
Hidden in noise and galactic emission,
Indistinct in the starlight.**

*Bigbang! Bigbang! burning bright
In the darkness of the night!
What immortal hand or eye,
Could frame thy fearful symmetry?**

It has been 13 years since the discovery of the cosmic microwave radiation by Penzias and Wilson of Bell Laboratories,¹ but it is only recently that the explanation put forth by Dicke, Peebles, Roll and Wilkinson² has been nearly universally accepted by the astrophysics community. Only with the now clear observation of the peak of the Planckian spectrum and its Wien tail have the doubts of many skeptics been answered. The correct prediction of the entire spectrum after the observation of the intensity at only one frequency must certainly be considered one of the great triumphs of cosmological theory. One of the indications of the impact of their discovery has been the award of the Nobel Prize in physics to Penzias and Wilson this year. The cosmic microwave radiation is not only the strongest evidence we have for the hot, compressed early Universe, but it provides one of the most direct means for studying that Universe. After a brief review of the origin of the radiation according to the "standard model", I shall discuss the status of present measurements of the spectrum and the large-angular-scale isotropy, and finally indicate what the prospects are for improved measurements in the next decade.

ORIGIN OF THE RADIATION

The very existence now of a "standard model" for the origin of the Universe is a reflection of the present acceptance of the theory.³ In this model, half a million years after the big bang the Universe was uniformly

*Apologies to H.W. Longfellow and W. Blake

filled with a hot plasma of photons, electrons, protons and heavier atoms. The expansion of the Universe cooled the plasma to the point that the electrons and protons combined to form neutral hydrogen. The previously opaque Universe suddenly became transparent, since photons are much less strongly coupled to neutral hydrogen than to the plasma. From that period until now the cosmic blackbody photons have been traveling virtually unscattered,⁴ carrying information about the nature of the Universe at the time of the decoupling (see Figure 1). In the Lorentz frame moving with the plasma, the photons have a blackbody spectrum with a characteristic temperature of about 4500°K; however the Hubble expansion gives this frame a velocity with respect to ours large enough to redshift the radiation by a factor of 1500 to the observed temperature of 3°K. (The fact that a Doppler shift preserves the Planckian form of the spectrum was first derived by Peebles and Wilkinson.⁵) Study of the radiation is therefore a study of the shell of matter which last scattered the radiation.

The cosmic blackbody photons are coming from the most distant region of space ever observed, and were emitted earlier in time than any other cosmological signal. Although the "background" radiation was originally given that name because of its potential interference with satellite communications, the word has taken on a new and vivid meaning: the radiating shell of matter forms the spatial background in front of which all other astrophysical objects, such as the quasars, lie. Until methods are devised to detect the neutrinos or gravitons which decoupled earlier, we will have no direct means of viewing beyond this background.

SPECTRUM MEASUREMENTS

There have been more than twenty articles published on measurements of the spectrum of the radiation; for a review see ref(6). However only in the

last few years have accurate measurements truly verified the Wien tail of the Planck distribution. Particularly impressive are the recent results of D. Woody and P.L. Richards,⁷ shown in Figure 2. These results are plotted on linear/linear axes rather than the traditional log/log in order to emphasize the fact that most of the energy of the background radiation is in the range of frequencies measured in this experiment, a region which had few previous measurements because of intense atmospheric emission. Woody and Richards used a balloon-borne Fourier spectrometer, which is sensitive to the entire range of frequencies simultaneously. The spectrum is obtained by Fourier transform of the output signal, with correction for atmospheric emission and detector response. Their "raw" spectrum with instrumental correction but no atmospheric subtraction is shown in Figure 3. Note that even without atmospheric correction the Wien tail of the radiation is clearly seen in the raw data.

The striking confirmation of the Planckian shape is the most important result of the Woody/Richards experiment. However they point out that they do see a statistically significant deviation from the Planckian shape: their spectrum is high in the region of 3 to 7 cm^{-1} and low from 9 to 12 cm^{-1} . The probability of a fluctuation accounting for this effect is about 10^{-6} , corresponding to about 5 standard-deviations. (The spectrometer resolution is shown in Figure 2 and is about 1 cm^{-1} . Measurements of the spectrum separated by this interval are effectively statistically independent.) Great care was taken by the experimenters to determine if the deviation could be instrumental; this is particularly important to do since an overall reduction in normalization by 22% brings the data into good agreement with a 2.8°K blackbody curve. If the deviation from the blackbody curve is cosmological in origin, its interpretation is of great interest.

ISOTROPY MEASUREMENTS

The large-angular-scale isotropy of the cosmic background radiation is the most sensitive probe we have of several phenomena of cosmological interest. These include the isotropy of the Hubble expansion, possible rotation of the Universe,⁸ and the existence of very-long wavelength gravitational radiation.⁹ Anisotropy can also arise from non-uniform distribution of matter at the time of the decoupling.

Anisotropy has now been clearly observed by at least two groups,^{10,11} however its smooth $\cos(\theta)$ behavior suggests that we should attribute it to a local rather than a cosmological effect: the motion of the earth relative to the radiation. After subtraction of the cosine term, there is no statistically significant anisotropy remaining. The most sensitive experiment so far is that done by our group at Berkeley^{11,12} using a 33 GHz twin-horn Dicke radiometer flown in a series of flights aboard the NASA-Ames Earth Survey Aircraft (U-2). In this experiment we were able to put an upper limit (90% confidence level) on the existence of a second-order (quadrupole) component to the background radiation of 1.1×10^{-3} °K or about 4 parts in 10,000 of a 2.8 °K signal.¹² This limit refers to 4 of the five possible quadrupole components; the fifth component is indistinguishable in the data from the dipole (cosine) component due to our lack of data in the southern hemisphere. The ambiguity will be resolved with a few flights in the southern hemisphere, scheduled to take place early in 1979. In addition to the quadrupole limit, we place an upper limit on the sky "roughness" (i.e. the statistical significance of the scatter of the data points around the cosine fit) of 0.60×10^{-3} °K at the 95% confidence level.¹²

Although my original interest in the experiment was due to the cosmological phenomena, perhaps the most interesting result turned out to be the local velocity of the earth. Like Michelson and Morley, we were surprised by the

result, but for the opposite reason: we obtained a velocity for the Milky Way (and the local group of galaxies) much higher than we had expected. The data for flights through early 1978 are shown in Figure 4, along with the cosine fit. The amplitude of the cosine is $3.61 \pm 0.54 \times 10^{-3} \text{ }^{\circ}\text{K}$, in a direction of R.A. = 11.23 ± 0.46 hours, dec = 19 ± 7.5 deg (ref 12). For a cosmic background temperature of T , this implies a velocity for the earth of $361 \times (3^{\circ}\text{K}/T) \text{ km/sec}$. When this is folded with the known velocity of the sun relative to the Milky Way galaxy (from galactic rotation) one finds a net velocity for the local group of galaxies (assuming $T = 2.8 \text{ }^{\circ}\text{K}$) of about $550 \pm 75 \text{ km/sec}$ in the direction R.A. = 10.5 hr, dec = -11 deg.

It is the large magnitude of this velocity that is particularly disturbing, especially since peculiar velocities for nearby galaxies are small. The relative velocity of the Milky Way and the Andromeda galaxy is only 80 km/sec, and Peebles has concluded¹³ that the peculiar (non-Hubble) velocity of the Virgo cluster is similarly small. But these large peculiar velocities seem to be cropping up recently in diverse areas of cosmology. V.C. Rubin reported at the last Texas symposium on a similarly high velocity for the Milky Way measured with respect to nearby ($3500 < cz < 6500 \text{ km/sec}$) galaxies¹⁴ (but in a different direction than ours, see refs. 11 and 12). And in this conference J. Peebles is reporting the recent results of his group at Princeton which sees similarly high velocity differences in pairs of (presumably) bound galaxies. It is difficult to reconcile the high kinetic energy of these galaxies with the belief that they are gravitationally bound unless one supposes that the mass of each galaxy is much greater than the visible mass. The missing mass must be comparable to that required to close the universe.

THE FUTURE

The deviations observed in the spectrum of the background radiation are tantalizing, and an order-of-magnitude improvement in sensitivity is going to be necessary in order to study them in detail. In addition one would like to study the deviations as a function of direction in the sky, a combined spectrum and isotropy experiment. The isotropy measurements have already yielded an unexpected discovery in the high peculiar velocity of the local group of galaxies, but as of yet no intrinsic anisotropy has been observed. Again one would like to see an order-of-magnitude improvement. Fortunately just such an improvement in both the spectrum and isotropy is on the near horizon: COBE.

COBE stands for Cosmic Background Explorer, a satellite which may be flown by NASA as early as 1983. The COBE scientific team includes many of the scientists in the U.S. who have made the best state-of-the-art measurements from roof-tops, balloons and airplanes. The planned configuration is shown in Figure 5, and includes the following experiments:

(1) Spectrum measurement from 3.3 to 0.33 mm, based on differential comparison with an adjustable temperature blackbody, with a sensitivity of $2 \times 10^{-14} \text{ w/cm}^2 \text{ sr cm}^{-1}$ for each 7 degree diameter field of view. This instrument should be capable of measuring the spectrum to 0.1% of the peak flux for each field of view on the sky.

(2) Anisotropy measurements at 4 frequencies: 23.5, 31.4, 53, and 90 GHz, again with a 7° field of view. The differential microwave radiometers should be able to detect deviations from isotropy to 10^{-4} of the background intensity, and should be limited only by the galactic synchrotron emission. Inclusion of four frequencies should allow subtraction of galactic emission.

(3) Diffuse Infrared Background photometer: to measure the infrared region 8 to 300 microns in 6 octave bands; sensitivity of $10^{-13} \text{ w/cm}^2 \text{ sr}$ for each 1° field of view.

As a physicist who is not actively working on COBE I feel free to express my delight at the beautiful design of the experiments, and to express unbiased optimism for the expected data. Without a satellite an order-of-magnitude improvement over the existing data would be nearly impossible; with COBE we can expect to have it in the next few years. The advantages of COBE come not only from the sensitivity, but also from the complete sky coverage afforded by its polar orbit. The COBE sensitivity is such that the uncertainty in the galactic synchrotr . emission may set the limit to the accuracy of its measurements. If this is the case, then COBE may also provide the ultimate limit to the knowledge that we can derive from measurements of the cosmic background.

REFERENCES

1. A. Penzias and R. Wilson, *Astrophys.J.* 142, 419 (1965).
2. R.H. Dicke, P.J.E. Peebles, P.G. Roll, D.T. Wilkinson, *Astrophys.J.* 142, 414 (1965).
3. E.R. Harrison, *Ann. Rev. Astron. Astrophysics* 11, 155 (1973); also P.J.E. Peebles, *Physical Cosmology*, Princeton Univ. Press (1971).
4. It is possible that the radiation was last scattered at a z of about 6 when the formation of stars could have reionized intergalactic matter. Such a rescattering affects our interpretation of the background measurements but does not alter their importance; $z = 6$ is still quite remote.
5. P.J.E. Peebles and D.T. Wilkinson, *Phys. Rev.* 174, 2168 (1968).
6. L. Danese and G. De Zotti, *Rivista del Nuovo Cimento* 7, 277 (1977).
7. D. Woody and P.L. Richards, *Phys. Rev. Lett.*, to be published.
8. S.W. Hawking, *Mon. Not. Roy. Astron. Soc.* 135, 413 (1967); also C.B. Collins and S.W. Hawking, *Mon. Not. Roy. Astron. Soc.* 162, 207-320 (1973).
9. W.L. Burke, *Astrophys.J.* 196, 329-334 (1975).
10. B.E. Corey and D.T. Wilkinson, *Bull. Astron. Astrophysics Soc.* 8, 351 (1976).
11. G.F. Smoot, M.V. Gorenstein, R.A. Muller, *Phys. Rev. Lett.* 39, 898 (1977); M.V. Gorenstein, R.A. Muller, G.F. Smoot, J.A. Tyson, *Rev. Sci. Inst.* 49, 440 (1978); R.A. Muller, *Sci. American* 238, 64-74 (May 1978).
12. M.V. Gorenstein, Ph.D. Thesis, University of California, Berkeley, November 1978 (unpublished).
13. P.J.E. Peebles, *Comments Astrophys* 7, 197-205 (1973).
14. V.C. Rubin, N. Thonnard, W.K. Ford Jr., M.S. Roberts, *Astro. J.* 81, 687 (1976).

FIGURE CAPTIONS

1. Origin of the cosmic background radiation. About 0.5 million years after the big bang, the free electrons and protons in the plasma combine to form neutral hydrogen, and the mean-free-path of the black-body photons becomes comparable to the size of the Universe. Those photons which will reach the earth in A.D. 1978 are drawn with the heavier lines; the future position of the earth is indicated with the letter E. In a comoving frame the photons have a temperature of about 4500 °K; in the earth frame their temperature is Doppler shifted to about 3 °K.
2. Measured spectrum of the cosmic background radiation, from the experiment of Woody and Richards (ref. 7). The shaded region corresponds to the $\pm 1\sigma$ limits. The gaps in the data are at frequencies at which strong atmospheric emission lines cause the errors to become very large.
3. The "raw data" from the Woody/Richards experiment is shown in (a), adapted from ref. 7. Plotted is the Fourier transform of the instrument output, corrected for instrument response. Note that the Wien tail of the spectrum can be seen without correction for atmospheric emission. The calculated atmospheric emission is shown in (b), and then net cosmic background is shown in (c) and (d) at two different spectral resolutions.
4. Anisotropy data from the 33 GHz U-2 experiment, adapted from ref. 12. The measured anisotropy ΔT in millidegrees Kelvin is plotted vs. the angle between the instrument axis and the observed direction of maximum temperature $\hat{n} = (11.23 \text{ hours R.A., } 19^\circ \text{ dec.})$. The data shown is for the seven flights between April 1977 and May 1978. Each point is

an average of approximately five 20-minute "legs" of straight and level flight.

5. The planned COBE satellite; an artist's conception. The apertures at the center are for the 3.3 to 0.33 mm spectrum radiometer and for the diffuse infrared photometer; the four pairs of microwave horns are for the isotropy radiometers. The radiometers are shielded from the sun and earth by the large conical shade.

XBL 792 - 428

Figure 1

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Figure 2

XBL 792-8395

Figure 3

XBL 792 - 427

Figure 4

COSMOS BACKGROUND EXPLORER

Figure 5

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