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PENZIAS & WILSON'S DISCOVERY OF THE COSMIC MICROWAVE BACKGROUND

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The discovery of the thermal cosmic background radiation (CBR) was an important step in establishing our present understanding of the physical nature of the universe. The thermal spectrum could not have been established in the universe as it is now because space is transparent: distant radio galaxies are observed at CBR wavelengths. Thus the CBR is compelling evidence that our universe expanded from a hotter, denser state in which space was opaque enough to have relaxed the radiation to statistical equilibrium. The present CBR temperature, with conventional physics, fixes the thermal history of the universe, allowing computation of relicts from departures from thermal equilibrium at high redshift, notably helium and deuterium. The thermal history also tells us the dynamical effect of the radiation on the gravitational growth of clustering of matter, and the growth of clustering in turn imprints a signature on the distribution of the CBR. These are key elements in the study of the evolution of our expanding universe.

The discovery paper[1] treats the interpretation of the CBR with all due caution. Penzias & Wilson (1965) present a careful case for the detection of radiation that is close to "isotropic, unpolarized, and free from seasonal variations." The only comment on the possible significance for cosmology is their reference to a companion paper (Dicke et al. 1965), which points out that if this were radiation thermalized in the early universe the signature would be a blackbody spectrum.[2] Within a year three measurements tested the spectrum. The instrument Roll & Wilkinson (1966) were building to search for the CBR yielded the isotropic energy flux density at 3 cm wavelength. It was news of this project that triggered the discovery. Howell & Shakeshaft (1966) measured the flux density at 20.7 cm wavelength. With the measurement by Penzias & Wilson at 7 cm wavelength this was a significant exploration of the spectrum. Another point on the spectrum came from optical astronomy. N. J. Woolf and G. B. Field independently saw a resolution to a long-standing puzzle: the population of the first rotationally excited level of interstellar cyanogen is hard to explain by collisional excitation in the interstellar medium, but would be a natural consequence of a sea of blackbody radiation at the temperature Penzias & Wilson found. This led to two new sets of measurements of the ratio of populations in the CN ground and excited levels (Field & Hitchcock 1966; Thaddeus & Clauser 1966). All these results fit a blackbody spectrum. This encouraged a rapid general acceptance of the CBR interpretation.[3] The four points could be equally well fitted by a power law, however, and almost as well by a dilute blackbody spectrum. A full and convincing case requires measurements at shorter wavelengths, past the Wien peak of a blackbody spectrum. By the mid-1970s measurements above the atmosphere ruled out a dilute blackbody spectrum (Williamson et al. 1973; Muehlner & Weiss 1973; Robson et al. 1974). By the early 1980s the measurements showed the spectrum is close to blackbody over the peak, but with indications of departures from a pure thermal spectrum (Woody et al. 1975; Woody & Richards 1979; Gush 1981). The definitive measurements 25 years after the discovery of the CBR showed the spectrum is very close to thermal (Mather et al. 1990; Gush, Halpern, & Wishnow 1990).

The discovery of the CBR, the demonstration of its thermal spectrum, and the detection of angular fluctuations at about the level expected from the gravitational growth of the present large-scale departures from a homogeneous mass distribution (Smoot et al. 1992) are important advances in cosmology. During four decades of involvement with this subject, I have grown used to hearing that such advances have at last made cosmology an active physical science. I tend to react badly because I think cosmology has been an active physical science since 1930, when people had assembled a set of measurements, a viable theoretical interpretation, and a collection of open issues that drove further research. This equally well describes cosmology today; the big differences are the vast increase in the network of data and theoretical issues, and the present frenetic level of activity.

The measure of the situation in Figure 1 is the distribution of publication dates of citations in two of my attempts to survey the state of research in cosmology (Peebles 1980, 1993). Both histograms peak a year or two before publication, a reflection of the tendency to emphasize the latest results. That aside, one sees reasonable stability of these two measures of my state of mind. Another author would distribute the emphasis differently, of course, but I suspect would end up with similar trends. One sees the peak of activity in the 1930s that followed the recognition of the possible relation between Hubble's law of the general recession of the nebulae and the Friedmann-Lemaître solution to Einstein's field equation. The lull during World War II is followed by another peak in the 1940s. This was driven in part by the steady state cosmology and in part by the work by Gamow's group on element production in the early universe that led to the first prediction of the CBR temperature (Alpher & Herman 1948). The picture of element buildup by neutron capture (Alpher, Bethe, & Gamow 1948) has been transferred from the expanding universe to exploding stars. Gamow's (1948) picture for the origin of helium remains the basis for the standard model.

Figure 1 illustrates the rapid increase of activity in the 1960s. The discovery of the CBR was a large factor, and the CBR figures prominently in the present lively state of cosmology. But it will be noticed that the rise in the 1960s precedes the discovery of the CBR. People were starting to recognize the interesting physics of an expanding universe, an activity that was encouraged by experimental and observational progress.

[1] The history of the discovery of the CBR is a fascinating example of the often chaotic ways science advances: this discovery was serendipitous despite a considerable number of observational and theoretical hints to the existence of the CBR. The story from the point of view of Bob Dicke's group at Princeton University is reviewed in Wilkinson & Peebles (1999).

[2] Tolman (1934) showed that homogeneous isotropic expansion preserves the thermal spectrum of free radiation. At present temperature $T \sim 3$ K the interaction of the radiation with matter has little effect on the spectrum because the heat capacity of the radiation is so much larger.

[3] A willingness to believe such an elegant gift from nature surely also played a significant role in the early acceptance of the CBR interpretation. A review of the evidence five years after the discovery, under the header "Is This the Primeval Fireball?" was more positive than not (Peebles 1971, p. 154).

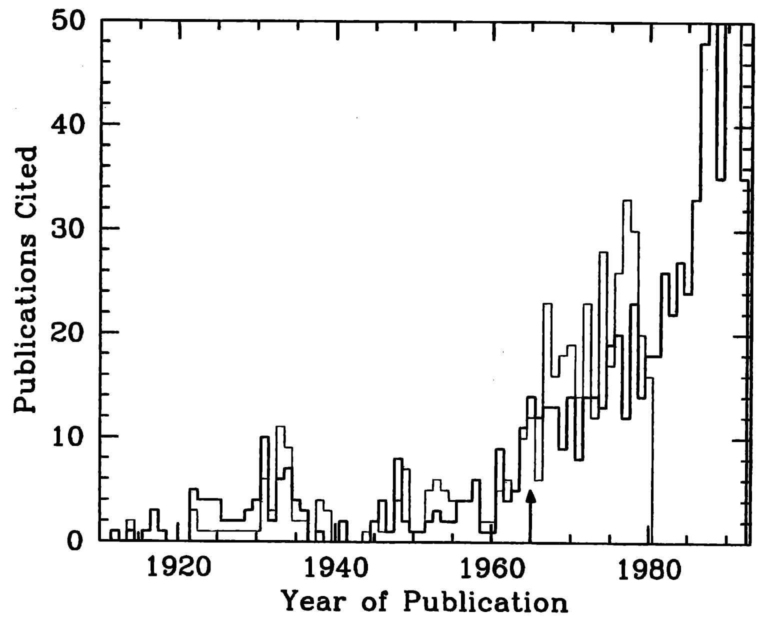

FIG. 1.—Distributions of year of publication of citations in two surveys of the state of cosmology (Peebles 1980, 1993). The arrow marks the date of discovery of the CBR.

Thus people were considering the origin of the isotropic X-ray–γ-ray background, and the nature of radio galaxies and quasars and their energy sources. If Penzias & Wilson had not discovered the CBR, Roll & Wilkinson were ready to find it a few months later. Absent those two groups, the discovery likely would not have been very much later; radio astronomers had the technology.

The present rate of publication in cosmology is well off the scale of the figure. CBR measurements now focus on the angular fluctuations in its temperature and polarization, a probe of how structure formed. If all goes well (and assuming nature has cooperated by not putting too much foreground emission in sources with spectra close to that of the CBR), a large step will be precision satellite measurements.[4] This, coupled with work in progress on completion of the classical cosmological tests, surveys of the present mass distribution from gravitational lensing and galaxy distributions and motions, and observations of the evolution of the intergalactic medium and galaxies and their space distribution back in time (to redshifts that already reach $z \sim 5$), will give us a rich and tightly cross-checked picture of how our universe evolved. But I am betting cosmology will remain an active physical science.

[4] The MAP project (http://map.gsfc.nasa.gov) is scheduled for launch late in the year 2000; for the PLANCK project (http://astro.estec.esa.nl/SA-general/Projects/Planck/), the expected launch date is 2007.

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REFERENCES

Alpher, R. A., Bethe, H., & Gamow, G. 1948, Phys. Rev., 73, 803
Alpher, R. A., & Herman, R. 1948, Nature, 162, 774
Dicke, R. H., Peebles, P. J. E., Roll, P. G., & Wilkinson, D. T. 1965, ApJ, 142, 414
Field, G. B., & Hitchcock, J. L. 1966, Phys. Rev. Lett., 16, 817
Gamow, G. 1948, Phys. Rev., 74, 505
Gush, H. P. 1981, Phys. Rev. Lett., 47, 745
Gush, H. P., Halpern, M., & Wishnow, E. H. 1990, Phys. Rev. Lett., 65, 537
Howell, T. F., & Shakeshaft, J. R. 1966, Nature, 210, 1318
Mather, J. C., et al. 1990, ApJ, 354, L37
Muehlner, D. J., & Weiss, R. 1973, Phys. Rev. Lett., 30, 757
Peebles, P. J. E. 1971, Physical Cosmology (Princeton: Princeton Univ. Press)
———. 1980, The Large-Scale Structure of the Universe (Princeton: Princeton Univ. Press)
———. 1993, Principles of Physical Cosmology (Princeton: Princeton Univ. Press)
Penzias, A. A., & Wilson, R. W. 1965, ApJ, 142, 419
Robson, E. I., Vickers, D. G., Huizinga, J. S., Beckman, J. E., & Clegg, P. E. 1974, Nature, 251, 591
Roll, P. G., & Wilkinson, D. T. 1966, Phys. Rev. Lett., 16, 405
Smoot, G. F., et al. 1992, ApJ, 396, L1
Thaddeus, P., & Clauser, J. F. 1966, Phys. Rev. Lett., 16, 819
Tolman, R. C. 1934, Relativity, Thermodynamics, and Cosmology (Oxford: Clarendon)
Wilkinson, D. T., & Peebles, P. J. E. 1999, Phys. Scripta, in press
Williamson, K. D., Blair, A. G., Catlin, L. L., Hiebert, R. D., Loyd, E. G., & Romero, H. V. 1993, Nature Phys. Sci., 241, 79
Woody, D. P., Mather, J. C., Nishioka, N. S. & Richards, P. L. 1975, Phys. Rev. Lett., 34, 1036
Woody, D. P., & Richards, P. L. 1979, Phys. Rev. Lett., 42, 1979