OBSERVATION AND INTERPRETATION OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM

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ABSTRACT

Recent precise observations of the microwave and submillimeter cosmic background radiation are summarized, including rocket experiments, the FIRAS (Far InfraRed Absolute Spectrophotometer) on the COBE, CN results, and microwave measurements. Theoretical implications are summarized.

1. INTRODUCTION

According to the Big Bang theory, the cosmic microwave background radiation (CMBR) is the radiant fossil of the primeval cataclysm that started the expanding universe. It is a sink for energy conversion from other forms, and therefore may deviate from the nearly perfect blackbody predicted by a simple Big Bang. Objects ranging from galactic and interplanetary dust to normal and infrared galaxies and galaxy clusters all add energy to the CMBR.

For redshifts $z>10^{6.4}$, the free-free and double-quantum processes keep the radiation field in local thermal equilibrium with all other fields, because photons are freely created and destroyed at thermal energies. Following that epoch, photons are not so easily created and destroyed, except at long wavelengths, and a Bose-Einstein distribution with a dimensionless chemical potential μ may arise. For $z<10^{4.5}$, even this pseudoequilibrium does not apply, and a Compton scattered spectrum may develop, characterized by the parameter y (Zel'dovitch and Sunyaev, 1969). For $z<1100$, the standard Big Bang picture holds that the matter became neutral and decoupled from the CMBR, so additional effects of matter on radiation require reionization, condensed objects, or particle decay. The formation of galaxies may well be accompanied by the creation of a hot intergalactic medium, which could produce anisotropies and spectral distortions in the CMBR as well as a signature in the infrared. Furthermore, it is expected that precursors to the large scale structures should have left anisotropies and possibly spectral distortions in the CMBR and X-ray background.

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2. PRECISE RESULTS

Hundreds of experiments have been performed to measure the spectrum and anisotropy of this radiation field. The spectrum experiments are of three types: ground-based and balloon-borne microwave radiometers, telescopic measurements of interstellar CN molecular thermometers, and balloon, rocket, and satellite photometers and spectrophotometers. Most agree about the absolute temperature of the radiation, regardless of wavelength, confirming the blackbody nature of the radiation.

The first type has been well summarized by Kogut *et al.* (1991). In this approach a microwave radiometer is used to measure the temperature difference between a fixed reference load and the sky. Contributions to the input signal arise from the cosmic background, from Galactic synchrotron and bremsstrahlung and dust, from atmospheric emission and absorption, and from instrument sidelobes seeing the ground. Galactic contributions are recognized by comparing sky maps at multiple wavelengths to fit parametric models, but the Galactic sources are not all simple. Atmospheric emissions are determined by zenith angle scans, and sidelobes are mapped with modulated sources carried near the instrument. Absolute calibration involves viewing a liquid helium cooled calibrator, which can be coupled optically (for short wavelengths or large calibrators) or through waveguide. In either case a thermal gradient between receiver and calibrator requires careful attention. A cold differential front end to the receiver solves this problem, but unless the receiver is in a space environment there must still be a thermal gradient between receiver and atmosphere.

Results from ground based and other measurements have been summarized in the reviews by Smoot *et al.* (1988) and by Kogut *et al.* (1991), based on the many references cited below. There is no evidence for a long wavelength distortion of the cosmic background radiation spectrum, and the weighted average of all CMBR temperature measurements is 2.74 $\pm$ 0.01 K, with $\chi^2 = 37$ for 40 DOF.

The second technique is to measure the absorption lines of interstellar molecules. The only precise interstellar thermometer measured to date is the CN molecule, but others (CH, CH^+, H_2CO) are also influenced by the CMBR. In each case, the rotational temperature of the molecule at the frequency of a microwave transition is determined by observations of the strengths of other transitions connected to the two states. For CN, the other transitions are optical, observed as interstellar absorption lines against distant stars. For H_2CO, they are at other microwave frequencies and are determined with radio telescopes, either in emission or in absorption against more distant continuum radio sources. Local corrections include excitation of the molecules by the warm electrons around them, by the warm dust which adds to the local microwave background radiation, and by pumping through

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higher levels of the molecules by UV and shorter wavelength IR. Corrections must also be made for optically thick lines. Recent data have been reported by Meyer and Jura (1985) who found 2.70 $\pm$ 0.04 K, Crane *et al.* (1989) who got 2.796 (+0.014, -0.039) K, and Kaiser and Wright (1990) who obtained 2.75 $\pm$ 0.04 K. Kaiser's thesis (1990) reported 2.73 $\pm$ 0.05 K. Meyer, Roth, and Hawkins (1989) obtained 2.76 $\pm$ 0.07 K at 2.64 mm, and 2.83 $\pm$ 0.09 K at 1.32 mm. Palazzi *et al.* (1990) found 2.834 $\pm$ 0.085 K at 2.64 mm and 2.831 $\pm$ 0.056 at 1.32 mm. Black and van Dishoeck (1991) have used the measured CMBR temperature to review the calculated interstellar excitations of CN.

The third method is the broadband infrared photometer or spectrophotometer. After a long series of lower altitude attempts, two spaceborne instruments were launched in a two month period by two groups. Gush *et al.* (1990) describe a brief sounding rocket flight, while Mather *et al.* (1990) described the first results from the Far Infrared Absolute Spectrophotometer (FIRAS) on the Cosmic Background Explorer (COBE). The COBE has been described by Mather (1982). Both are far infrared polarizing Michelson interferometric spectrometers of similar design; fortunately they also give similar results. Each is cooled by liquid helium to about 1.5 K, has a Winston quasioptical parabolic concentrator antenna, and operates in a differential mode, continuously comparing the sky with a matched internal blackbody. They differ primarily in scale (the FIRAS has much larger throughput than the Gush *et al.* instrument), in observing time (10 months versus 5 minutes), and in calibration strategy. To make up for the short observing time and the smaller throughput, the rocket payload has far superior detectors cooled by liquid ^{3}He. The Gush *et al.* instrument uses an accurately balanced ($\sim 1\%$) differential instrument with a preflight calibration by a full beam blackbody, since the short flight and small space do not allow for an external inflight calibrator. The FIRAS calibrator is a full beam temperature controlled blackbody that was inserted repeatedly into the aperture to make a direct comparison against the sky.

Results from these experiments are in excellent agreement. Gush *et al.* reported a temperature of 2.736 $\pm$ 0.017 K, where the uncertainty is the result of a conservative estimate of systematic errors. Their data show an rms deviation of 1 % of the peak, and no deviation from the best fit blackbody greater than 3 % , except for two points with known interference from rocket vibrations. Mather *et al.* (1990) reported a temperature of 2.735 ± 0.06 K from 1 to 20 cm^{-1}, where the larger error bar is due to concern about thermometer calibration. Their data showed no deviations from the best fit blackbody larger than 1% of the peak spectral intensity. Cheng *et al.* showed that the dipole anisotropy has the expected Doppler shifted blackbody form with an amplitude of 3.3 $\pm$ 0.3 mK. Improved calibration applied to data from Baade's hole at (l=142, b=55) by Shafer (1991) enabled a stronger limit of only

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0.25% from 3 to 20 cm^{-1}, and allowed improved limits on $|y|<0.0004$ and $|\mu|<0.005$. Dust emission in this region was small and clearly detectable, especially around 40 cm^{-1}, but had little effect on the fitted distortions because the shape of its spectrum is very different.

3. SIGNIFICANCE FOR THEORY

The Big Bang picture is strongly confirmed, as it predicts a nearly perfect blackbody spectrum without *ad hoc* tinkering with the theory. There is no confirmation of the large spectrum distortion reported by Matsumoto *et al.* (1988). There is no indication of spectrum distortions due to the recombination of hydrogen. A hot smooth intergalactic medium capable of emitting more than 1% of the diffuse X ray background flux is ruled out. Similarly, an epoch of pregalactic explosions capable of explaining the large scale distribution of galaxies is also ruled out. On the other hand, the Doppler instability concept of Hogan (1991) is not ruled out.

4. FUTURE MEASUREMENTS

Spectrum measurements at long wavelengths are limited by Galactic emission and man-made interference, and can be significantly improved but only with great care. They are important for measuring the chemical potential (μ) distortions. At intermediate wavelengths of a few cm, microwave radiometers on balloons can do much better than the spaceborne infrared instruments. Improvements to the CN measurements are difficult but useful in making remote observations, and in confirming the calibration of the infrared measurements. The FIRAS data will be improved by continuing attention to calibration, modeling the Galactic dust, and averaging more data.

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