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INFRARED MEASUREMENTS FROM THE COSMIC BACKGROUND EXPLORER (COBE)

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Abstract—The Cosmic Background Explorer (COBE) satellite was developed by NASA's Goddard Space Flight Center to measure the diffuse IR and microwave radiation from the early universe, to the limits set by our astrophysical environment. It was launched 18 November 1989 and carried three instruments, a FIR Absolute Spectrophotometer (FIRAS) to compare the cosmic microwave background radiation with a precise blackbody, a Differential Microwave Radiometer (DMR) to map the cosmic radiation precisely, and a Diffuse Infrared Background Experiment (DIRBE) to search for the accumulated light of primeval galaxies. The cosmic microwave background radiation spectrum was measured 1000 times more precisely than was possible before the COBE launch. The microwave background was found to have an intrinsic anisotropy for the first time, at a level of a part in 10^5 with a smoothing of 10°. A comprehensive set of absolutely calibrated IR sky maps has been acquired to search for the cosmic IR background.

1. INTRODUCTION AND MISSION OBJECTIVES

The cosmic microwave background radiation is thought to be the radiative remnant of the primeval explosion of the universe about 15×10^9 years ago, and is our best tool for examining the structure of that great explosion. However, it is difficult to measure because it is faint by terrestrial standards and is absorbed by our atmosphere. It has now been measured by many instruments at wavelengths from 70 cm to 0.5 mm and its blackbody nature is a stringent test of the Big Bang theory.

As the universe expanded it cooled, and when it reached a temperature of about 3000 K the primeval plasma became neutral atomic hydrogen and helium. At that time, about 300,000 years after the Big Bang, light was free to move through the universe without scattering from free electrons, so we observe the cosmic radiation distribution as it was at that time. If the primeval universe was slightly inhomogeneous, we should be able to measure that the cosmic background radiation is slightly anisotropic.

At the same time, ordinary matter was freed from the radiation drag that prevented gravity from pulling it together into objects. An object 300,000 light years across at that time was equal in dimension to the distance that light had traveled in the age of the universe then. The universe has expanded by a factor of 1000 since then, so it is no surprise that the largest structures now known are approx. 300,000,000 light years across, and are great superclusters of galaxies and huge voids between them. It is thought that these objects could not have formed unless there were primeval inhomogeneities of comparable dimensions.

Galaxies and stars presumably formed later, but the details are entirely unknown. It is known that they continue to evolve, and that their luminosities and colors and numbers are quite different than they were when the universe was only half the size it is now. The light from these first objects may have been very intense, in which case the present universe should be filled with a diffuse IR background radiation field.

The main objectives of the COBE are to measure the cosmic microwave background spectrum and anisotropy, and to measure the general diffuse infrared background from early generations of objects. Secondary objectives include determination of the radiation from our local environment, such as interstellar and interplanetary dust, interstellar electrons, and starlight. The COBE instruments are sufficiently sensitive and accurate that these local sources limit the accuracy of the cosmological background measurements.

II. MISSION CONCEPT—ORBIT, ATTITUDE, SPACECRAFT

There are three instruments on the COBE: a Far-Infrared Absolute Spectrophotometer (FIRAS) to cover the range from 100 μm to 1 cm wavelength with a 7° resolution, a Diffuse Infrared Background Experiment (DIRBE) to cover the range from 1 to 240 μm with a 0.7° resolution in 10 broad bands, and a Differential Microwave Radiometer (DMR) to map the sky at 31.5, 53, and 90 GHz with a 7° resolution. Overviews of the COBE and early results have been given previously,(1–15) and engineering descriptions have also been published.(16–27)

The two IR instruments were cooled by liquid helium to about 1.5 K for 10 months, and after the helium was exhausted they rose to about 60 K. The 1.2–4.9 μm detectors of the DIRBE continue to operate at this temperature. The microwave radiometers are in radiative equilibrium with their environment, with the 31.5 GHz receivers heated to 300 K and the others at 140 K. All are protected by a conical shield which is nearly coplanar with the highest points of their apertures, and the Sun and Earth do not illuminate them. This is possible in the 900 km altitude circular orbit, which is inclined 99° to the equator and oriented approximately perpendicular to the Sun line. The spacecraft is oriented away from the Earth and nearly perpendicular to the Sun. It spins about its symmetry axis at 0.8 rpm to scan the DMR and DIRBE beams from 64 to 124° from the Sun.

III. INSTRUMENTS AND RESULTS

1. DMR description

The DMR contains 6 microwave radiometers, each with a ferrite Dicke switch, Schottky diode mixers, and HEMT IF amplifiers. The instrument and data analysis have been described previously.(28–35) The two antennas for each receiver are corrugated circular horns and define beams 7° in diameter and 60° apart. The receiver output is the difference of brightness of the sky seen by the two antennas. As the spacecraft spins and orbits, all possible pairs of points 60° apart are compared. The sky map is built up by a least squares solution that best represents all these measured differences. After one year of observation, the typical map sensitivities per 7° pixel are about 0.15 mK rms at 53 and 90 GHz, and 0.3 mK at 31.5 GHz.

2. DMR results

The main result is the first detection of primeval anisotropy in the cosmic background radiation. The fluctuations are approx. 15° in size and have an amplitude of 30 μK, about a part in 10^5 of the total brightness. These fluctuations have no preferred physical scale, consistent with predictions of the inflationary theory of the early universe, but other theories also predict similar results. In order to explain the existence of present day large scale structures such as clusters and superclusters of galaxies, and the great voids between them, it seems necessary to postulate the existence of a dark matter component that gives 10–100 times as much gravitational force as the ordinary baryonic matter of which the known objects are made. This dark matter is supposed to be able to move and cluster even before the radiation and ordinary matter decoupled 300,000 years after the explosion.

The maps show two main effects at first, the dipole anisotropy due to the Doppler shift from the motion of the Earth, and the emission of the Milky Way galaxy. Both of these must be removed to determine the cosmic signals. The dipole is a part in 1000, and data from the six DMR channels are consistent(53) with a Doppler-shifted Planck function of dipole amplitude $\Delta T = 3.365 \pm 0.027$ mK toward direction $(l^{\mathrm{II}}, b^{\mathrm{II}}) = (264.4° \pm 0.3°, 48.4° \pm 0.5°)$. The galactic emission is removed by making linear combinations of the maps at different frequencies, taking advantage of the fact that the spectrum of the Galaxy is very different from that of the cosmic background.

3. *FIRAS instrument and results*

The FIRAS instrument covers the wavelength range from 0.1 to 10 mm in two bands, separated at 0.5 mm. Its objective is to compare the cosmic microwave background to an accurate blackbody, and to observe the dust and line emission from our Galaxy. Its spectral resolution is approx. $0.8\,\mathrm{cm}^{-1}$ in short strokes, and the low frequency channel long strokes give $0.2\,\mathrm{cm}^{-1}$. Its beamwidth is 7°. It is cooled to 1.5 K to reduce its thermal emission and enable the use of sensitive bolometric detectors. It is a polarizing Michelson interferometer, operated differentially with an internal reference blackbody. It is calibrated by an external blackbody having an estimated emissivity of better than 0.9999. It is symmetrical, so there are altogether four detectors, each with a sensitivity of the order of $3 \times 10^{-15}\,\mathrm{W/Hz}^{1/2}$.

The calibration is derived from measurements of the calibrator made with the other emitting sources at a variety of temperatures. Fixsen *et al.*(36) showed that the color temperature scale, based on the wavelength dependence of the Planck function, agrees with the direct measurement of the temperature within 8 mK. Mather *et al.*(37) used the new calibration and the most stable period of operation to measure the extragalactic background radiation, using a model of the Galaxy to subtract its effects. The resulting temperature for the cosmic background is 2.726 ± 0.010 K, over the frequency range from 2 to $20\,\mathrm{cm}^{-1}$. Over this range the maximum deviation from the blackbody form is less than 0.03%, with a weighted rms value of only 0.01%. Fits to the dimensionless cosmic distortion parameters give 95% confidence limits of $|\mu/kT| < 3.3 \times 10^{-4}$ and $|y| < 2.5 \times 10^{-5}$ respectively.

The implications of these limits are summarized by Wright *et al.*(38) Less than 0.03% of the energy in the CMB was added to it after the first year of the expansion. Less than 10^{-4} of the diffuse X-ray background can be produced by a smooth hot intergalactic medium. Less than 1% of the mass of hydrogen could be burned by Population III stars after a redshift of 80, and less than 1% of the hydrogen could be burned by an evolving population of galaxies like those seen by the IRAS. These limits are based on $\Omega_{\mathrm{baryon}} = 0.0125h^{2}$. The Steady State theory is conclusively ruled out, as are theories of a Cold Big Bang with needle-shaped dust to thermalize stellar radiation.

The dipole anisotropy of the CMB, presumed due to our peculiar motion relative to the Hubble flow, can be seen clearly in the FIRAS data as well as the DMR data. Fixsen *et al.*(39) give the most recent dipole results. The FIRAS data show for the first time that the spectrum of the dipole is that expected from the Doppler shift acting on a blackbody spectrum. The dipole amplitude measured by FIRAS is 3.343 ± 0.016 mK in the direction $(\alpha, \delta) = (168.9° \pm 0.5°, -7.5° \pm 0.5°)$, $(l, b) = (265.6°, 48.3°)$. The color temperature of the dipole is 2.714 ± 0.014 K, and the maximum deviation of the dipole spectrum from the expected form is only 0.005% of the peak intensity of the CMB.

FIRAS results also include the first nearly all-sky, unbiased, FIR survey of the galactic emission at wavelengths greater than 120 μm.(40) They present a map of the dust emission across the sky from the COBE FIRAS experiment. The total FIR luminosity of the Galaxy is inferred to be $(1.8 \pm 0.6) \times 10^{10}\,L_{\odot}$. Spectral lines from interstellar [C I], [C II], [N II], and CO are detected in the mean galactic spectrum, $g(\nu)$. The lines of [C II] at 158 μm and [N II] at 205.3 μm were sufficiently strong to be mapped. This is the first observation of the 205.3 μm line. We interpret the [C II] line as coming from photodissociation regions and the [N II] lines as partially arising from a diffuse warm ionized medium and partially arising from dense H II regions.

4. DIRBE description

The DIRBE obtains maps of the sky in 10 photometric bands: ($J\,[1.2\,\mu\text{m}]$, $K\,[2.3\,\mu\text{m}]$, $L\,[3.4\,\mu\text{m}]$, and $M\,[4.9\,\mu\text{m}]$; the four IRAS bands at 12, 25, 60, and $100\,\mu$m; and 140 and $240\,\mu$m bands). Linear polarization is also determined in the J, K, and L bands, and measurements are made at a range of angles from the Sun from 64 to 124°. After 10 months of cryogenic operation the rms map sensitivity per field of view is $\lambda I(\lambda) = (1.0,\ 0.9,\ 0.6,\ 0.5,\ 0.3,\ 0.4,\ 0.4,\ 0.1,\ 11.0,\ 4.0) \times 10^{-9}\,\text{W m}^{-2}\,\text{sr}^{-1}$, respectively for the 10 wavelength bands listed above. These are sufficient to measure local diffuse radiation as well as predicted extragalactic radiation sources.(41)

The DIRBE is absolutely calibrated using a cold interior as a dark reference and known point sources to measure the gain. It is an off-axis Gregorian telescope with a 19 cm primary, and has extremely good off-axis rejection of stray light.(42–44) To achieve this it uses a super-polished primary, a reflective forebaffle, extensive and carefully designed baffle tubes, and Lyot and secondary field stops. It has no structural elements in the optical beam. It is also operated at a protected location within the cryostat, where it is not illuminated by Sun or Earth. The incoming signals are modulated at 32 Hz by a tuning fork chopper. Instrumental offsets are determined with a cold shutter, and instrument gain stability is verified frequently with a commandable reference source. All bands view the same field of view instantaneously, which is a square 0.7° on a side, oriented 30° from the spacecraft spin axis. The instrument beam profile was determined on the ground and in orbit, to allow conversion from point source calibrations to diffuse surface brightness measurements.

The detector stability is very good, with little response change from nuclear radiation ($< 1\%$) in all detectors except the Ge:Ga photoconductors used at 60 and $100\,\mu$m. Thermal and radiative annealing procedures applied to these detectors following passages through the South Atlantic Anomaly allow response correction to a few percent at these wavelengths. It is expected that fully reduced DIRBE sky maps will have photometric consistency over the sky better than 2% at each wavelength, nearest neighbor band-to-band (color) brightness accuracy of 3% or better, and absolute intensity scale accuracy better than 20%. Due to strongly non-linear response of the Ge:Ga detectors, the 60 and $100\,\mu$m data may not meet these goals.

5. DIRBE results

Initial results have been described previously.(45–51) The maps show stellar emission at $1.2\,\mu$m from the galactic plane, the galactic nuclear bulge, and isolated stars. Zodiacal light from interplanetary dust is also very bright, and is seen in the short wavelength bands (1.2–$3.5\,\mu$m) as scattered sunlight, and at longer wavelengths as re-radiated IR emission. The scattered light is clearly polarized in the expected direction.

The wavelength-dependent dust extinction toward the galactic center is clearly seen, and correlates very well with the FIR emission in the same directions. At wavelengths of $60\,\mu$m and longer, emission from the interstellar medium dominates the galactic brightness, and the interplanetary dust emission becomes progressively less apparent. The patchy IR cirrus noted in IRAS data(52) is evident at all wavelengths longer than $25\,\mu$m. False color all sky images prepared from DIRBE data have recently been presented by Hauser.(46)

Initial galactic studies based on DIRBE data have recently been reported. These include investigation of the warp of the plane in the stellar and interstellar dust components,(48) examination of the color and extinction of integrated galactic starlight,(49) study of asymmetries in the starlight from the bulge, supporting the suggestion of a stellar bar,(50) and study of physical conditions in the interstellar medium in the galactic plane.(51) The first results of polarization measurements with the DIRBE have also been presented.(47)

The best directions and wavelengths for searching for an extragalactic background are those at which the foreground is least bright. These are at high ecliptic and galactic latitude, at wavelengths near 3.5 μm and longer than 200 μm. Preliminary results toward the south ecliptic pole were given by Hauser *et al.*(45)

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