Cosmic Background Explorer: COBE

NASA's Cosmic Background Explorer (COBE) satellite (figure 1) was developed to measure the diffuse infrared and microwave radiation from the early universe to high precision. COBE was designed as NASA's first cosmology satellite at a time when our understanding was much less developed. The science team decided to focus on making precise observations of the cosmic background microwave and infrared radiations to a level limited by astrophysical foregrounds. The COSMIC MICROWAVE BACKGROUND (CMB) is the relic radiation from the hot dense phase of the big bang (see BIG BANG THEORY), while the cosmic infrared background (CIB) is believed to be the combined light of first- and later-generation stars burning the primordial light elements into heavier elements. The general approach was to cover the spectrum into which starlight could be converted and be redshifted to by the expansion of the universe. Great effort went into making the detectors stable and the spacecraft motions and orbit so that the full sky could be mapped accurately and reliably. All detectors were cooled either passively or actively with superfluid liquid helium to improve their sensitivities.

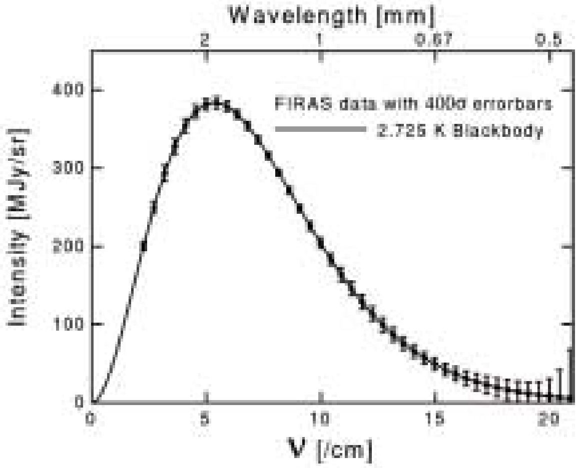
Figure 1. Artist's rendering of COBE satellite with callout of instruments and components.

During the epoch when COBE was being designed and constructed members of the science team and other scientists were conducting observations from the ground, aircraft and balloons to determine whether there were variations in the CMB intensity as a function of angular position on the sky. The limits on anisotropy were becoming sufficiently low that simple models of the formation of galaxies from simple ordinary matter were in difficulties. There were articles stating that the big bang model was in jeopardy because it could not explain the formation of galaxies, while others were calling for a new non-standard matter (dark matter in forms such as weakly interacting massive particles; see DARK MATTER IN GALAXIES and WIMPS AND MACHOS) and for mechanisms other than gravitational attraction being instrumental in galaxy and cluster formation. What if COBE had not detected anisotropy?

COBE was launched on 18 November 1989 on a Delta rocket and carried three instruments, a Far Infrared Absolute Spectrophotometer (FIRAS) to compare the spectrum of the CMB radiation with a precise blackbody, a Differential Microwave Radiometer (DMR) to map the cosmic radiation sensitively, and a Diffuse Infrared Background Experiment (DIRBE) to search for the CIB radiation. Each COBE instrument yielded a major cosmological discovery.

FIRAS

The CMB spectrum (intensity versus frequency) (figure 2) is that of a nearly perfect blackbody with a temperature of 2.725 ± 0.002 K. The FIRAS team designed and tested a special reference blackbody target to compare with the input CMB signal. By definition a blackbody is one that absorbs all the light that comes to it. This FIRAS target was made of highly absorbing material and a geometry so that incident light from the direction of the



FIRAS spectrum (frequency vs. intensity) with errors expanded 400 times

Figure 2. This FIRAS observation matches the predictions of the hot big bang theory extraordinarily well and indicates that nearly all of the radiant energy of the universe was well established within the first year after initiation of the big bang. It rules out many alternative cosmological models because of the preciseness of the observed thermal spectrum.

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instrument must undergo seven bounces, each much more likely to absorb than reflect onward or back out. As a result the reference target absorbs more than 99.99% of the incident light. The target was also designed to have good thermal conductivity and metrology traceable back to the National Bureau of Standards so that its temperature would be uniform and known. Cross-checks come from the shape of the emission as a function of wavelength. The FIRAS covers the wavelength range from 0.1 to 10 mm in two spectral channels separated at 0.5 mm and has approximately 5% spectral resolution. A flared horn antenna aligned with the COBE spin axis gives the FIRAS a 7° field of view. The instrument was cooled to 1.5 K to reduce its thermal emission and to enable the use of sensitive bolometric detectors. The FIRAS ceased to operate when the supply of liquid helium was depleted on 21 September 1990, by which time it had surveyed the sky 1.6 times.

DMR

The CMB was found to have intrinsic anisotropy (variation with angle on the sky) for the first time (figures 3–6). These variations were observed on angular scales of 7° to the full sky and are at a level of 1 part in 100.000. These tiny variations in the intensity of the CMB over the sky trace the very-large-scale distribution of matter and energy when the universe was still very young — order of 100.000 years — but the variations are very likely to be nearly unchanged from earliest seconds of the universe's existence. The DMR maps show us the very early embryonic universe. Later the early structures seen by DMR developed into galaxies, galaxy clusters and the large-scale structure that we see in the universe today.

The DMR instrument consists of six differential microwave radiometers, two nearly independent channels that operate at each of three frequencies: 31.5, 53 and 90 GHz. These frequencies were chosen to minimize the contamination from Galactic emission. Each differential radiometer measures the difference in power received from two directions in the sky separated by 60°, using a pair of horn antennas. Each antenna has a 7° (FWHM) beam. The COBE satellite rotates at approximately 0.8 rev min $^{-1}$ and precesses in near-polar orbit, following the day–night terminator. As a result the DMR makes highly redundant observations of the entire sky in a 6-month period. Over the 4 years of observations the DMR mapped the full sky eight times in different configurations and alignments. Great care was taken in the experiment design, operations, data processing and analysis to avoid contamination and undesirable systematic effects and to reveal any residuals.

DIRBE

Infrared absolute sky brightness maps in the wavelength range 1.25–240 μm were obtained to carry out a search for the CIB (figures 8 and 9). The CIB was originally detected in the two longest DIRBE wavelength bands, 140 and 240 μm, and in the short-wavelength end of the FIRAS spectrum. Subsequent analyses have detections of the CIB in the near-infrared DIRBE sky maps. As a result of the cosmic redshift and reprocessing by dust of short-wavelength radiation, the wide spectral range from 1 to 1000 μm contains much of the energy released since the formation of luminous objects. The CIB represents a 'core sample' of the universe; it contains the cumulative emissions of stars and galaxies dating back to the epoch when these objects first began to form. The

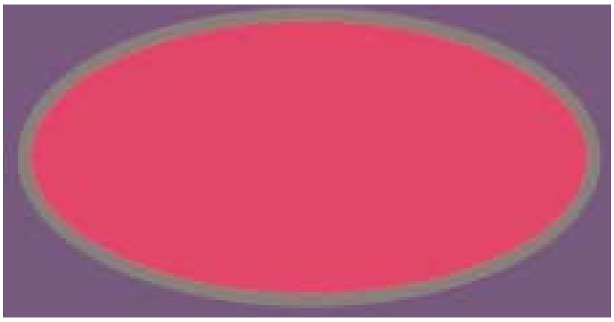

Figure 3. The DMR observations of the microwave sky showing it to be quite uniform.

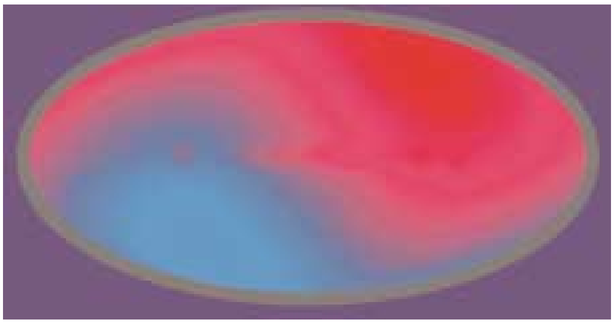

Figure 4. DMR map with 2.728 K monopole removed and scale expanded to show the dipole anisotropy which varies smoothly from about plus one part in a thousand to minus one part in a thousand. The map covers the full sky and in Galactic coordinates with the center of the Galaxy in the center and the plane of the Galaxy running horizontally.

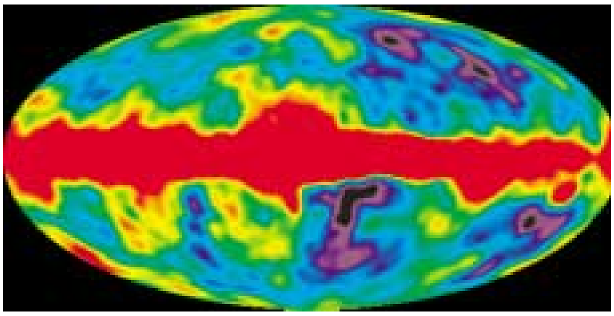

Figure 5. DMR anisotropy map.

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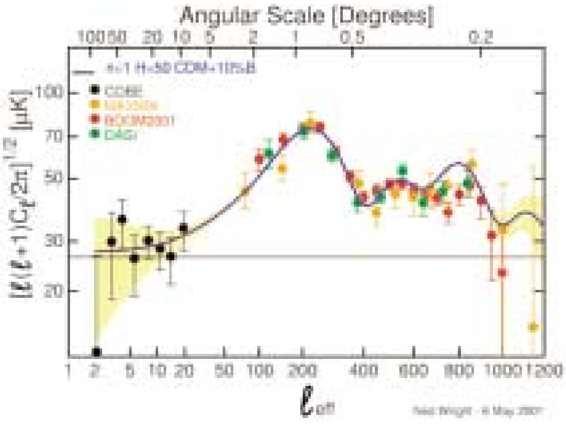

Figure 6. CMB anisotropy angular power spectrum.

COBE CIB measurements constrain models of the cosmological history of star formation and the build-up over time of dust and elements heavier than hydrogen, including those of which living organisms are composed. Dust has played an important role in star formation throughout much of cosmic history.

The impact of COBE

The COBE discoveries, particularly the COBE DMR discovery of CMB anisotropies, galvanized cosmology for the larger public as well as the science community, as a result of the significant new scientific results, with the anisotropies promising to be a new powerful cosmological probe, generating attention, interest and impact.

Immediately following the COBE DMR announcement and subsequent press coverage a large number of people moved into cosmology and in particular CMB-related cosmology. The first noticeable results were the theoretical papers exploring the outstanding potential that precise observations of the CMB anisotropy angular spectrum had for testing cosmological models and determining key cosmological parameters. At the same time new experimental programs were started and existing experimental programs invigorated. In addition to the science community, agencies and governments took note of the attention and promise of CMB cosmology and as a result two new satellite missions were started. NASA's MAP (Microwave Anisotropy Probe) and the joint European Space Agency (ESA) and NASA Max Planck Explorer. The design and personnel on MAP are essentially direct descendants of COBE DMR. MAP was launched in 2001 getting to Earth–Sun L2 in September 2001 and making observations. The Planck mission is broader and more ambitious but can trace many of its approaches and training to COBE. Planck is scheduled for launch in 2007.

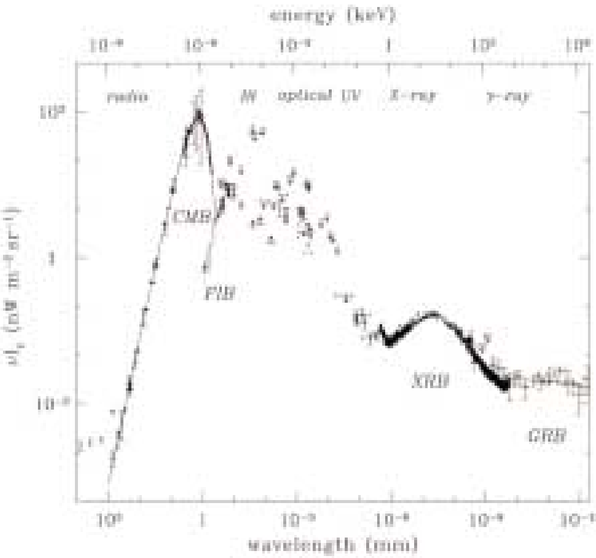

Figure 7. AUTHOR TO PROVIDE CAPTION AND INDICATE WHERE IT SHOULD BE CITED IN THE TEXT.

Figure 8. Our Milky Way Galaxy as observed by the COBE DIRBE in wavelength bands at 1,2 and 3 μm presented in the optical. The stars making the central Galactic bulge at the nucleus and the brownish regions of dust and gas show clearly.

Figure 9. Full version of our Milky Way Galaxy as observed by the COBE DIRBE in wavelength bands at 1,2 and 3 μm presented in the optical. The stars making the central Galactic bulge at the nucleus and the brownish regions of dust and gas show clearly.

The CMB promise began to be fulfilled by the MAXIMA, BOOMERANG and DASI experiments which extended the COBE observations of the anisotropy angu-

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lar power spectrum to smaller angles (⅙° for MAXIMA) and showed that there was a first acoustic peak at about the 1° angular scale followed apparently by a second and third at angular scales of ½° and ⅓° respectively. The location and position angular scale of the first acoustic peak are strong evidence that the geometry of the universe is flat (or very nearly so) and the location and width of the first peak are strong support for INFLATION. The additional peaks indicate that gravitational instability is truly the source of large-scale structure and provide a good measure of the baryon content of the universe as about 5% of that needed to make the universe flat. This is in good agreement with big bang NUCLEOSYNTHESIS of primordial light elements and indicates that the rest must be some form of non-baryonic dark matter and dark energy.

COBE served as a wellspring of new cosmological discoveries and as a training ground for a new generation. NASA's Goddard Space Flight Center management recognized the opportunity for hiring and training a new generation of engineers, scientists and technical personnel as well as a chance to further the careers of existing staff. Likewise, for university groups COBE was a training ground for a new generation of postdoctoral fellows and graduate students. These people have gone on to new-generation experiments, other fields and missions, including John Mather (COBE project scientist), who became head of the NGST team.

In all COBE was a tremendously successful mission in terms of its science, programmatic, public and personnel impacts.

George Smoot

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