18

K.M. GÓRSKI* AND A.J. BANDAY**

COBE, dark matter and large-scale structure in the Universe

PREAMBLE

NASA's first dedicated cosmological space mission, the Cosmic Background Explorer (*COBE*), has provided comprehensive full-sky observations of both microwave and far-infrared frequencies. Each of the three instruments onboard – the Far Infrared Absolute Spectrometer (FIRAS), the Differential Microwave Radiometers (DMR), and the Diffuse Infrared Background Explorer (DIRBE) – has contributed significantly to our fundamental understanding of the universe. FIRAS has measured the Planckian nature of the relic blackbody radiation to unprecedented accuracy, thus establishing stringent constraints on the thermal history of the universe. DMR has discovered full sky structure in the temperature of the blackbody radiation over a range of angular scales down to $\sim$10 degrees, thus establishing stringent limits on the evolution of large-scale structure in the universe and providing us with our first glimpse of the initial conditions for structure formation. DIRBE has provided the first evidence for the existence of a cosmic infrared background, thus providing important constraints on the integrated cosmological history of star formation in various pregalactic objects, protogalaxies, and galaxies, and the subsequent conversion of starlight into infrared emission by dust.

Thus *COBE* has become a *tour de force* of modern cosmological studies; it has influenced physical cosmology with its results dramatically, and established a splendid legacy for the community with its unparalleled view and interpretation of the multiwavelength sky.

* European Southern Observatory, Garching bei München, Germany; Warsaw University Observatory, Warszawa, Poland
** Max-Planck-Institut für Astrophysik, Garching bei München, Germany

K. M. Górski and A. J. Banday, The Century of Space Science, 399–421

1 LARGE-SCALE STRUCTURE OF THE UNIVERSE BEFORE *COBE*

Following closely upon the launch of the *COBE* satellite in November 1989, the January 1990 issue of "Scientific American" presented an article "The Cosmic Background Explorer", which announced the following: "NASA's cosmological satellite will observe a radiative relic of the Big Bang. The resulting wealth of data will be scoured for clues to the evolution of structure in the universe". In this article we describe how the outcome of this remarkable mission did indeed provide important scientific results which helped in a very major way to improve our understanding of the universe. However, to start our story at the beginning, let us first recall what was the status of our knowledge about the universe before *COBE*, and why *COBE* was needed for subsequent exploration of the universe.

It is very well known that our modern understanding of the universe as a physical system rests on three major pillars of observational cosmology:

- **Universal Expansion:** On cosmological distance scales, astronomical objects recede from one another with velocities proportional to their separations – a remarkable discovery by Hubble in the 1920s. As we now know, the universe on the largest scales is very nearly homogeneous and expands isotropically.
- **Primordial Nucleosynthesis:** The observed universal abundances of light elements proved inconsistent with the idea that they were produced in stars. This puzzle was explained in the 1940s by Gamow, Alpher, and Bethe in the context of an initially hot and dense phase in the early

evolution of the expanding universe. This necessarily required that a residual relic thermal radiation permeated the universe, and its temperature was theoretically expected to be $\sim$4–5 K.

- **Microwave Background Radiation:** The relic thermal radiation of temperature $\sim$3 K was serendipitously discovered by Penzias and Wilson (1965) and immediately recognized by Dicke *et al*. (1965) as the "missing link" between the primordial fire-ball of the young Big Bang universe and its present day mature phase dominated by evolved astronomical objects. This discovery delivered a direct proof of the dense and hot early stage of evolution of the universe.

These three phenomenological ingredients laid a solid foundation for the Hot Big Bang model, which became nearly unanimously accepted as the framework for our understanding of the universe at large. The Cosmic Microwave Background (CMB) radiation itself has subsequently become the subject of increasingly vigorous theoretical and observational studies. It was recognised very rapidly following its discovery that the CMB should contain "fossilized" imprints of the processes which could, or even had to, occur in the early universe, and that such signatures of past events should be pristine in comparison with the clues provided to us through the studies of nearby, well evolved astronomical objects. Hence, both the nature of the CMB electromagnetic spectrum, and its possible deviations from a perfectly thermal (Planckian) form, and the CMB anisotropy, or dependence of its temperature on the direction of observation on the sky, very quickly became attractive theoretical and observational research targets, which were pursued relentlessly up until the *COBE* mission, and, indeed, even more so afterward.

It is beyond the scope of this contribution to review systematically the steady progress of observational and theoretical cosmology from the discovery of the CMB until the *COBE* mission, but let us try to mention the essential developments.

- **Large-scale structure of the galaxy distribution:** It has been assessed that galaxies not only form groups and clusters, but their tendency to aggregate in space extends to even larger scales of superclusters (separated by voids), and perhaps beyond. For a long time the extreme scales of detectable inhomogeneity in the 3-D galaxy distribution coincided with the largest scales surveyed, which rendered a determination of the scale of transition to the expected homogeneity of the universe at large somewhat elusive. A rigorous quantitative description of the galaxy distribution in space has been developed, including number counts, correlation functions, and power spectra. During the 1980s, astronomical measurements of the spatial distribution of galaxies matured sufficiently to put strong constraints on theories of galaxy and large-scale structure formation.

- **Dark matter in the universe:** Ever since Zwicky's realisation in the 1930s that clusters of galaxies consisted predominantly of matter in some nonluminous form, the "missing mass" or later "dark matter" problem was one of the most serious puzzles in astronomy. The following observational picture was built over time: astronomical objects of increasing size (galaxies, groups, clusters, superclusters) appear to contain more and more mass that does not manifest itself via luminosity, but can be detected due to its gravitational effects. The amount of this hidden mass is large – perhaps about 20–30% of what is required to render the universe spatially flat. This fraction is sufficiently large that (1) it clearly exceeds the census of baryons in the universe, i.e. the dark matter in known astronomical objects is unlikely to be comprised entirely of ordinary matter, and (2) it invites speculation that perhaps the universe indeed is spatially flat, and therefore that the required dark matter content for the whole universe must still be larger than for individual astronomical objects. This finding tied in with a rich supply of theoretical candidates for weakly interacting massive particles, which could dominate the matter content of the universe, and the idea that perhaps the dynamically detected matter (comprising both luminous, baryonic objects and dark material) is more clumped than the remaining more smoothly distributed dark matter (the so called biasing effect). An alternate speculation involves the idea of a cosmological constant, or vacuum energy density, which was originally introduced by Einstein, and thereafter enjoyed various degrees of popularity with astronomers trying to determine the global properties of the universe. Indeed, the currently available combination of CMB anisotropy, large scale structure, and high-redshift supernovae observations can be interpreted as supportive of these cosmological constant dominated models of the universe.

- **CMB phenomenology:** Immediately after the discovery of the CMB radiation, it was realised that the background radiation should be carefully measured to search for

1. any deviations of its electromagnetic spectrum from thermal, and
2. the expected deviations from isotropy in the angular distribution of its temperature on the sky.

Both effects, if found, would provide invaluable clues to our understanding of physical processes occurring in the early universe. It would be the case regarding spectral distortions because only significant energy releases (e.g. bulk annihilation of exotic particles at some epoch) at very high redshift could measurably perturb the Planckian spectrum of the CMB. It would also be the case regarding CMB anisotropy because it could reveal to us the early predecessors of presently observable structures in the universe, as outlined below.

It was well understood that the primary dynamical factor that must have driven the evolution of structure in the universe was gravitational instability. To understand how the presently existing structure in the universe has arisen, it is necessary to postulate the existence of perturbations in the primordial spatial distribution of matter, which over time were amplified by their self-gravity. The logical appeal of the proposition to use the expected minute CMB anisotropies to study directly the matter distribution in the universe as it just emerged from its embryonic stage was built upon the following considerations:

1. the universe is opaque beyond redshift ~1000, thus one may think of CMB photons as having been emitted from the last scattering surface at the epoch corresponding to such a redshift (typically about a few hundred thousand years after the Big Bang); hence the CMB photons, which are influenced very little by the nearly transparent universe at redshifts <1000, bring to us precious information about the conditions as far away and early on in the universe as we can ever probe with electromagnetic radiation;
2. gravitational instability in an expanding universe is a slow process (described by power law functions of time, rather than the familiar Jeans exponentials in a non-expanding medium), hence the amplitudes of large scale inhomogeneities observed today must have then been small but not negligible;
3. the temperature of the CMB radiation photons when they were emitted at the epoch of last scattering was physically related to the perturbations of the matter distribution via both the gravitational potential of inhomogeneities (the so called Sachs-Wolfe effect), the emitting plasma velocity (or the Doppler effect), and the thermal effects in gravitationally compressed or rarified plasma. Thus one is led to conclude that the physical conditions at the time of the last scattering of the CMB photons are necessarily "imprinted" on a sky map of CMB temperature anisotropy.

With such understanding firmly established, all that still remained to be done was to measure these CMB temperature fluctuations.

Surely, the excitement related to the opening of a window in the background radiation through which direct observations of the truly embryonic stages of evolution of the large scale structure of the universe could be attempted was missed by neither experimentalists nor theoreticians in cosmology. But the required measurements proved to be an incredibly hard task, as we can only now appreciate in hindsight. A brief, and somewhat unjust, summary of the experimental CMB anisotropy efforts that were conducted for more than two decades up until the *COBE* mission is simple: there were no detections of cosmological anisotropy, only upper limits. The only exception was the measurement of the CMB dipole temperature pattern, at an amplitude of ~0.1% of the mean, superposed on the isotropic background (Smoot *et al*. 1977). This effect, however, was expected and explained as being dominated by our own motion (i.e. a combination of motions of the solar system in the Galaxy in the Local Group) with respect to the rest frame defined by the CMB radiation, and, hence, a local rather than cosmological effect. Despite this apparent lack of a tangible result, there was ongoing and steady progress stimulated by the increasingly stringent limits on theoretical predictions of expected CMB anisotropy depending on particular scenarios of evolution of structure in the universe. In fact, the search for evidence of anisotropy in the CMB by the experimental community became somewhat akin to the quest for the Holy Grail.

• **Mainstream theoretical cosmology in the 1980s:** The rapid development of theoretical and observational cosmology after the discovery of the CMB radiation resulted in very impressive support for the Hot Big Bang model as a basic paradigm for understanding the universe at large. However, there were still some nagging paradoxes left which could not be answered simply within the framework of the model. Among those were the following:

1. overall homogeneity and isotropy of the universe – why are the very distant regions in the universe, which were never in causal contact (i.e. could not have interacted at any time during the history of the standard Hot Big Bang universe), so similar as suggested by the apparent isotropy of the CMB?
2. flatness of the observed universe – why is the average density of the universe so close (within a factor of a few) to the critical density, which makes the universe spatially flat, just right now, when we (the human race) exist?
3. where did the initial perturbations which seeded structure formation come from?

All these questions could be by-passed with a reference to the initial conditions for the evolution of the universe. This, however, satisfied practically no-one, so when the idea of inflation appeared in the early 1980s, it was rapidly embraced as a compelling explanation for the shortfalls of the standard cosmological model. Inflation postulates that the evolution of the early universe is driven by a scalar field, called the inflaton, which dominates the energy density. Random regions, which get trapped in a state of false vacuum (or a local minimum of the potential energy) of the inflaton, end up expanding very rapidly due to an effectively negative pressure (hence the term inflation). A typical inflating region ends up so big that the currently observed astronomical universe would be just a small fraction thereof. Hence, the explanation of homogeneity and isotropy of the universe that we see. Near flatness is explained because, again, our astronomical universe would be just a small sector of an original arbitrarily curved manifold stretched to enormously large size. Density perturbations which seeded the presently observed structures were generated due to zero-point quantum fluctuations of the inflaton. Even though inflation is not a verified theory its logical appeal is huge, since it is apparently solves a number of seemingly unrelated paradoxes at the price of introducing just one new puzzle – what is the physical nature of the inflaton?

It should be now clear, even with this rather sketchy description of the development of experimental and theoretical cosmology after the discovery of the CMB, that there were important questions about the universe which could be answered with accurate measurements of the attributes of the relic radiation. A hard-learned lesson from early ground-based and balloon-borne experiments was of the enormous difficulties involved with attempts to perform such measurements successfully, and that the better approach would be a well-planned experiment in space. An opportunity to realise such a project was provided by NASA in 1976, when it selected the Cosmic Background Explorer, *COBE*, for a design study.

2 THE *COBE* PROJECT

Perhaps the first issue to address is the simple question, why a satellite? The most succinct response to this can be found in the proceedings of a meeting held in Copenhagen from June 25–29, 1979. "The Universe at Large Redshifts" contained a brief paper by Ray Weiss designed to serve as an introduction to a more complete review of the *COBE* mission (Mather and Kelsall 1980). Nevertheless, the most relevant issues for the reader to understand are indeed recorded there. Based on the integrated experiences of the *COBE* team members with ground-based, balloon-borne and air-borne experiments to measure the background radiation, and more importantly the limitations of these platforms, the arguments in favour of a space-borne experiment were then, and remain today, as follows:

1. Freedom from atmospheric emission and fluctuations in that emission.
2. Full sky coverage with a given single instrument.
3. A benign and controlled thermal environment to reduce systematic errors.
4. The ability to perform absolute primary calibration in flight without the necessity of windows to avoid condensation of the atmosphere on calibrators and instruments.
5. Sufficient time both to peform tests for systematic errors and to gain the increase in sensitivity permitted by extended observation time.

To achieve the full benefit of space observations, the goal of the mission and instrument design was to ensure that the scientific measurements conducted by *COBE* were ultimately limited by the ability to model the various astrophysical components and distinguish them from the cosmological information sought. This goal thus drove the mission strategy, spacecraft and operations design and choice of instruments.

2.1 Satellite overview

The need to minimise, control and measure the impact of systematic errors led to the requirements for an all-sky survey, a minimal survey period of 6 months, and constraints on the amount of interference from local sources of radiation such as the Earth, Sun, Moon and radio emission from the ground. The orbit, spacecraft attitude, and instrument enclosures were therefore carefully selected to avoid direct exposure to the Earth and Sun, and maintain a stable thermal environment for the instruments. For *COBE*, depicted in Figure 1, a 900 km altitude, Sun-synchronous orbit was selected so that the orbit, with a duration of 103 minutes, precessed by 1 degree per day. In order to meet the scientific requirements of the mission (as will be discussed below), the spacecraft must also spin. A rate of 0.8 rpm was adopted, with the spin axis tilted back from the orbital direction by 96 degrees, so that residual atmosphere did not affect the instruments. The attitude of the spacecraft was controlled by inertia wheels and electromagnets, and determined from Sun sensors, Earth sensors and gyroscopes.

2.2 Instrumental design

Three complementary experiments were flown on the *COBE* spacecraft: the Far-Infrared Absolute Spectrometer (FIRAS) designed to measure the frequency spectrum of sky radiation from 100 microns to 1 cm (see Figure 2), the Diffuse Infrared Background Explorer (DIRBE) to map the sky from 1 to 300 microns, and the Differential Microwave Radiometers (DMR) to search for anisotropies in the CMB on scales larger than 7 degrees.

Due to the authors' involvement with the analysis and interpretation of the *COBE*-DMR data, and the aim of this contribution being the assessment of the impact of *COBE*'s results on our understanding of the large-scale structure of the universe, the remaining text is focused on the DMR instrument and the measurements of CMB anisotropy conducted with this instrument. Those readers interested specifically in the results of DIRBE and FIRAS are referred to NASA GSFC www page http://space.gsfc.nasa.gov/astro/cobe/ and references therein.

A differential radiometer is a device which outputs a voltage proportional to the difference in power received by

http://www.springer.com/978-0-7923-7196-0

The Century of Space Science
Bleeker, J.A.; Geiss, J.; Huber, M. (Eds.)
2001, XLIX, 1846 p., Hardcover
ISBN: 978-0-7923-7196-0