THE COSMIC BACKGROUND EXPLORER SATELLITE - COBE

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NASA's first dedicated cosmology satellite is scheduled to be launched in 1989 from the Western Space and Missile Center in California. It is the culmination of over a decade of labor by a number of groups working together at the Goddard Space Flight Center. The COBE satellite is designed to increase substantially our knowledge of the Cosmic Background Radiation(CBR), the relic radiation left over from an early phase of the universe. The data collected by COBE will help astrophysicists to understand the thermal history of the universe and the processes that led to the formation of the large scale structures(galaxies, clusters of galaxies, etc.) in the present universe. This article discusses the scientific objectives of the mission and the unique features of the satellite.

Cosmic Background Radiation was discovered nearly twenty five years ago by Penzias and Wilson of Bell Laboratories. The story of this serendipitous discovery is well known. While attempting to measure the galactic radiation halo at 7.35 cm wavelength, they observed a weak, noise-like radiation entering their horn antenna, uniform within their experimental uncertainties from every direction in the sky. In their discovery observation paper published in 1965, Penzias and Wilson stated "the radiation is consistent with a blackbody of temperature 3 K(ed note 3 degrees above absolute zero) unpolarized and free from seasonal variation". This observation is probably the most important observation related to cosmology since Hubble's discovery of the apparent velocity of recession of galaxies. An immediate explanation of the cosmological origin of this radation was made by Dicke, Peebles, Roll, and Wilkinson of Princeton University. They had not only anticipated this discovery, but were in the process of building a radiometer to search for this "Primeval Fireball", as they called it, at the time of the discovery at Bell Laboratories.

The theoretical basis for the CBR is related to the problem of understanding the relative abundances of all the chemical elements in the universe. As early as 1946, George

Gamow proposed that the early stages of the universe were sufficiently hot to enable nuclear reactions to occur. Efforts over the next several years by Gamow and his collaborators, Alpher and Herman, laid the theoretical groundwork for understanding element synthesis during a hot phase of the expanding universe. This model of the universe has come to be called the "Hot Big Bang". Alpher and Herman reasoned that a bath of photons was needed in order to photo-dissociate some of the forming deuterium needed for helium production to prevent too much helium from forming in an early era of nucleosynthesis. In this way, they predicted a radiation with a current temperature of about 5 K bathing the universe. This radiation is thought to be the radiation detected by Penzias and Wilson. Alpher and Herman also predicted that higher temperatures would lead to a lower helium abundance, and lower temperatures would lead to higher abundances.

In the simplest model of the Hot Big Bang, matter and radiation were tied together by interactions during the earliest times in the history of the universe. At very high energies or high temperatures, matter and radiation are very much alike and form a substance called a plasma. As the universe expanded and cooled, the ability of the matter and radiation to interact became smaller. The last kind of interaction to occur between radiation and matter consisted of free electrons colliding with the photons of the radiation. When the universe had cooled to the point where almost all the electrons had recombined with protons to form hydrogen, several hundred thousand years after the big bang, the radiation was almost completely decoupled from the matter and free to evolve independently.

The the plasma, before this era of decoupling, reached a state of near thermodynamic equilibrium. All sources of free energy had been converted into heat by the collisions between particles. Under these conditions, radiation takes on a form called a Planck black-body spectrum after Max Planck who first theoretically derived the shape of the spectrum. This form of radiation emitted from any object at temperatures above absolute zero (0 K) under certain conditions. The red glow from a very hot object is an example of approximately blackbody radiation. (The radiation is almost perfectly blackbody if an object is inside a very hot oven which has reached thermal equilibrium.)

The matter-radiation decoupling left the radiation locked into this spectrum. The expansion of the universe shifted the radiation to longer wavelengths but left the nature of the spectrum alone. This had the effect of making the apparent temperature lower and lower as the universe aged. While the matter went on to form stars and galaxies, the radiation remained nearly unchanged during most of the history of the universe!

In the simplest model of the Hot Big Bang, the radiation which bathes the present universe is blackbody(thermal) radiation with a classical Planck spectrum (intensity of radiation as a function of wavelength or frequency) This distribution was established early in the history of the universe when matter and radiation were strongly coupled by scattering processes. This condition existed for several hundred thousand years before the universe expanded and cooled sufficiently (< 4000K) to allow the free electrons and protons to recombine (to form neutral hydrogen), thereby greatly reducing the number of free electrons available to scatter the CBR photons. The interval of time when this occurred is called the era of decoupling because after this time the radiation and matter did not interact significantly. After the era of decoupling, and in the absence of further interactions with matter, blackbody radiation will retain a Planck spectrum but with a decreasing temperature as the universe expands. The fact that the observed temperature of the CBR is ~ 3 K provides evidence that the universe has expanded since this time!

The possibility of measuring this radiation had been largely overlooked prior to the discovery, except by Robert H. Dicke and his group at Princeton, and by Doroshkervich and Novikov in the Soviet Union. The Russians pointed out in 1964 that microwave measurements would be very important for checking the theories of Gamow, Alpher, and Herman. As frequently occurs in science, Dicke independently rediscovered the concepts of the Hot Big Bang nearly fifteen years after the original suggestion. This time, however, he connected theory and experiment by noting that the radiation might be observable.

Aside from its importance in element synthesis early in the history of the universe, it might be surmised that the CBR is a curious but uninteresting phenomenon because no interactions of merit have occured since the era of decoupling. If our simple model of the CBR were perfectly true, the background radiation would carry no information since it would be isotropic, unpolarized, and have a blackbody spectrum. It has been recognized almost since the CBR was first discovered, however, that the CBR could be used as a tool to answer some of the most difficult questions about the history of the universe precisely because the initial form of the radiation is so close to isotropic and thermal.

Experimental measurements have overall confirmed the simple picture of the hot big bang origin of the CBR. Existing measurements have already influenced our ideas of galaxy formation by failing to detect any small scale anisotropy. Subtle distortions of the CBR, if detectable, can reveal unique and important characteristics of processes that have taken place as the universe evolved. Like the Rosetta stone which gave the world the key to the long-forgotten language of ancient Egypt, the CBR may contain answers to the most difficult questions about the evolution of the universe. How and when did galaxies form? Did stars form before galaxies? What is the nature of the dark matter that may constitute over 90observable universe? Is the whole universe rotating relative to absolute space? What were the physical conditions of the universe at the time the CBR radiation decoupled from the matter?

To answer these questions we must understand what processes might distort the spectrum of the CBR. The basic mechanism for creating distortions before the era of decoupling is to inject free energy into the plasma. This would have the effect of driving the plasma out of thermal equilibrium which is in contrast to the simple model of the pristine CBR. The equilibrium state would slowly be restablished after such an event but if the radiation-matter decoupling occured before complete return to equilibrium, evidence of this energy injection would be imprinted on the CBR.

After decoupling, the background radiation has been traveling in space throughout most of the history of the universe. During this time, the radiation could have encountered conditions which changed its pristine blackbody characteristics after the decoupling event. In particular, the spectrum and angular distribution of the radiation may have been altered, and these alterations might remain today as fossils of earlier epochs in the development of the present structure of the universe. This is true dispite the fact that the matter and radiation are nearly independent. If for example, a large region of space had a large column density of hot electrons injected by some process, the CBR passing through this region would suffer a small spectral change. This change could be large enough to be detected.

Spectral deviations of a different type might have been produced close to and after the time of decoupling. For example, the recombination radiation produced when the hydrogen atom recombines with an electron can distort a blackbody spectrum at very short wavelengths, as shown in Figure 2b. Other distortions could be produced if the universe was re-heated after the era of decoupling, perhaps by the gravitational potential energy released during the formation of stars and galaxies. If the energy were sufficient to re-ionize some of the gas in the universe, then Compton scattering from the free electrons would again occur. Consequently, the spectrum would shift toward shorter wavelengths(Figure 2c) at least in the regions where the gas was ionized. Significant deviation from the blackbody spectral shape would occur at wavelengths shortward of about 1 mm if the universe contained a low density hot plasma.

Quite independent of ionization, it is possible to imagine sources which produce enough radiation at certain wavelengths to impart significant changes to the CBR. Astrophysical dust, for example, may be heated by some source to temperatures above that of the CBR . This dust might absorb the visible and ultraviolet light and reradiate it at infrared wavelengths where the universe is more transparent. These very small particles are built of elements heavier than helium such as carbon, silicon and oxygen. Since heavy elements were formed by nuclear burning in the early stars, the dust could not have formed before the first generation of stars. The red-shifted spectrum of early dust emission would tell us about the nature and time when the first star and/or galaxy formation took place.

The spatial distribution of the CBR can also vary from point to point in the sky due to a variety of effects including a) relative motions between the restframe of the CBR and the Earth, b) irregularities in the surface of last scattering, c) scattering since the era of decoupling, d) non-uniform expansion of the universe, e) rotation of the universe as a whole, and f) long wavelength gravity waves. Experiments designed to search for spatial variations in the CBR are called anisotropy experiments(e.g. The Cosmic Background Radiation and the New Aether Drift, R.A. Muller, Sci. Am. May, 1978). The first of these effects has already been measured(Figure 3) through the use of balloons, aircraft, and satellite. It is due to a remakable feature of blackbody radiation. When viewed in a frame of reference that is moving relative to the emitter, blackbody radiation retains its characteristic Planck distribution but it's temperature changes. If the observer and the emitter are traveling towards one another, the shift in temperature is toward higher temperatures; if they are travelling apart the temperature shift is toward lower temperatures. The magnitude of the temperature shift is proportional to the velocity of the observer divided by the speed of light, just as for the Doppler shift. Modern microwave CBR measurements now routinely detect a non-cosmological component caused by the earth's motion through space. These data show a dipole anisotropy with a distribution consistent with the earth's motion in a direction towards the Virgo cluster of galaxies with a velocity of 300 km/sec, or 1/1000 the speed of light. The corresponding temperature shift is approximately .003 K. Just as the earth's motion with respect to the CBR's frame of reference can be detected, spatial distortions in the CBR may arise from differential kinematic motions in different parts of the universe. Depending on the angular scale of these effects, some of COBE's experiments may detect evidence of these large scale motions of matter in the universe.

There are good reasons for believing that anisotropies due to irregularites in the regions of last scattering must exist, but they have not yet been detected. The present-day universe is far from uniform on any size scale accessible to measurement. The universe is lumpy on scale sizes from micron size dust particles, to planets, to stars, to galaxies, and to galaxy superclusters. The largest scale lumps associated with galaxies and clusters, presumably, began with small variations of the matter density and grew, in time, due to gravity (See e. g. Large Scale Structure in the Universe, Silk, Szalay, Zel'dovich, Sci Am. Oct, 1983). Theoretical studies have shown that some small density perturbations would need to be present at the time of decoupling, if gravity alone were responsible for creating the galaxies and galaxy clusters we now observe. Since the CBR we observe today reflects the distribution of matter at the time of last scattering (end of the era of decoupling), the primordial clumps which are the progenitors of present-day large-scale structure must cause anisotropies in the CBR. They must be observable at some level of sensitivity, unless they have been erased by unknown processes. The experimental results so far are quite interesting. Except for the dipole anisotropy due to the motion of the earth, the radiation is the same in all directions to better than a part in ten thousand, which is the current observational limit for scale sizes less than 1 degree in extent.

In addition to the observed lumpy nature of the luminous matter in the present universe, it is possible that the temperature describing the radiation is not everywhere exactly the same. Matter at large separation is not expected to be at the same temperature unless some mechanism has brought these regions into contact so that their temperatures may equilibrate. Alternatively, all parts of the universe started with the same initial conditions. This would be a remarkable condition for which there is no known justification. In the case of the CBR, regions of the sky which are separated by more than about 2 degrees in angle have never been in contact in the standard Big Bang model. These regions are said to be causally disconnected because, even traveling at the speed of light, heat or information of any kind could not have gotten from one region to another from the time of the Big Bang singularity to the present. We would therefore expect these regions to have a temperature determined by the initial conditions of that region of space, which we assume cannot be identical in every decoupled region of the universe. One of the fundamental questions in cosmology, sometimes called the horizon problem, is why the temperature of the CBR is so uniform on large angular scales. The inflationary model of the very early universe solves this problem by postulating that the entire observable universe was at one time in thermal contact.

Having given the reasons why the CBR provides a probe of the early universe, we now turn to the experimental approachs that has been developed to study it. Measurements of the CBR spectrum up to now (Figure 1) show that the radiation closely approximates that of a 2.7 K Planck blackbody radiator over a large range of wavelengths. These measurements have been carried out over the two decades since the discovery of the CBR and give support to the overall validity of the simple model we have outlined here. Very recent measurements, however, indicate the presence of significant distortions from a blackbody spectrum at submillimeter wavelengths. These measurements were carried out by experimentors from Nagoya University and the University of California at Berkeley using instrumentation carried 300 km above the surface of the earth by a sounding rocket. Confirmation of these distortions await additional measurements, but these data may be the begining of an era of finding distortions on the CBR spectrum and discovering important clues to the evolution of the universe.

Previous measurements of the CBR from airplanes, balloons, and rockets have encountered a variety of problems. The principal problem for the submillimeter and infrared spectral regions is the earth's atmosphere. Although it is highly transparent at visual wavelengths, it is nearly opaque throughout much of the wavelength range of interest, typically 0.1 - 10mm. Due to the numerous molecular absorption bands in oxygen(O2), ozone(O3) and water(H2O), the atmosphere at best gives ground-based observers only narrow selected windows in this wavelength range through which to observe the CBR. The experience gained from measurements performed over the last two decades, combined with additional considerations outlined below, argue strongly for performing the measurements from a satellite, located well above the bulk of the earth's atmosphere.

The concept of using a satellite to measure the CBR was developed by a team of scientists and engineers representing 6 different institutions(Goddard Space Flight Center, JPL, MIT, Princeton University, UC Berkeley, UC Santa Barbara, UC Los Angeles). They decided that the overriding consideration for achieving a successful CBR measurement was that the observations must be able to distinguish between the distant and cosmologically significant CBR, and the radiation from the intervening and nearby sources such as those from our own galaxy. Our own galaxy is filled with dust and gas in the interstellar medium, and our solar system contains interplanetary dust. These gas and dust components produce radiation which intermingles with the radiation from the CBR. They provide an unavoidable and undesirable source of radiation which must be removed to reveal the CBR.

A goal at the outset was to design an experiment whose sensitivity over the entire sky would be set by the local astrophysical background (i.e. galactic emission, zodiacal light, etc.), rather than by the inherent sensitivity of the instruments or by our local environment(ie. earth's atmosphere, emission from the earth or sun, etc.). Figure 5 shows the "local" emission that we expect will be encountered while attempting to measure the CBR. Also shown are the intensity of a 2.7 K blackbody curve, and a guess about the background of primeval galaxies.

An early conclusion of the science team was that the separation of local sources of radiation from the CBR can only be obtained by having a set of comprehensive measurements covering both the entire sky and a wide range of wavelengths. Such a data set will allow the determination of models of the local sources of radiation, which in turn can be used to separate the local radiation sources from the CBR. The thermal emission of galactic and interplanetary dust, and the scattered sunlight from interplanetary dust can be modelled in this way as well as both gas emission and synchrotron emission from the high energy electrons interacting with the galactic magnetic fields. At short infrared wavelengths, the integrated light from stars themselves becomes a significant correction, and this can be modelled and extropolated to wavelengths of interest for the study of CBR. (Figure 4 of galactic emission model and zodiacal light). Precision measurements of the spectrum and angular distribution of the CBR, as well as an all-sky survey of the diffuse emission in the infrared, were chosen by the science team to be the necessary set of measurements which would permit the separation of local sources from the CBR and provide the necessary data to study the CBR itself. The requirement for an all-sky, precision survey argues once again for an orbiting satellite. Ground based observations need to contend with the variability and opacity of the atmosphere, The orbiting satellite provides all-sky coverage without the need to replicate or move instruments from place to place on the ground. It also provides the integration times needed for sensitivity, and the stable thermal and noise environment needed for the instruments.

To meet the goals and objectives outlined by the science team, the COBE satellite employs three distinct but complementary instruments. Each instrument measures a different regime in the background radiation. The instruments are symbiotic, however, the measurements from each instrument aiding in the interpretation of the other two. The three instruments are: 1) DMR — the Differential Microwave Radiometer, which will measure the large scale anisotropy in the background radiation; 2) FIRAS — the Far Infrared Absolute Spectrometer, which will measure the spectrum (intensity as a function of wavelength);

and 3) DIRBE — the Diffuse Infrared Background Experiment, which will measure the infrared background expected from early galaxy formation processes. Although DIRBE will not measure the CBR specifically, it is extremely important for our understanding of processes in the more recent history of the universe when structure became dominant (i.e. early star formation, and galaxy formation). The Table shows the details of each instrument.

The DMR instrument contains six heterodyne radiometers designed to measure very slight temperature differences that might exist in the CBR. The six radiometers operate simultaneously at three different wavelengths, with two radiometers at each wavelength for redundancy. The wavelengths used are 3.3, 5.7, and 9.5 mm. These wavelengths were chosen to give an optimum combination of technologically achievable sensitivity and the ability to remove the local galactic emission. For increased sensitivity, critical components of the 3.3 and 5.7 mm radiometers are passively cooled by radiation to about 140K, while the 9.5 mm radiometers operates at about 300K. A schematic diagram of the DMR is shown in Figure 6.

Each DMR radiometer contains two horn-type antennas aimed 60 degrees apart in the sky. The spatial resolution of each antenna is about 7 degrees. The spinning satellite, discussed below, sweeps these antennas along trajectories that follow small circles in the sky. The full sky is swept out in approximately six months. The radiometers operate by rapidly (100 Hz) comparing the power received in each antenna, and reporting the difference in power at the receiver output. These differences in power can be converted to temperature differences in the sky. Each radiometer has about the same sensitivity, being able to measure about 25 mK (0.025 K) temperature difference in a one second measurement. The sensitivity of the individual DMR instruments is about 0.2 mK per beamwidth after 1 year of observations. By combining observations over the entire sky, it will be possible to measure temperature variations as small as 10 micro Kelvin. The speed of the earth around the sun, 30 km/sec, produces a temperature distortion of approximately 300 micro Kelvin, well within the observational limits of COBE. This effect will need to be removed from the data inorder to arrive at the CBR.

The DMR antennas form a critical part of the instrument. They must reject, almost completely, the off-axis radiation from the earth and sun to prevent spurious signals from appearing in the data. Stray radiation from the earth and sun has plagued many previous ground-based, balloon borne and satellite experiments. Since the solid angle subtended by the earth is very large for a low earth orbit satellite (it nearly fills half the sky), rejection relative to on-axis acceptance must be greater than 10^8. Fortunately the technology to build antennas that can provide this rejection capability is possible. Figure 7 shows a boresight view of one of the DMR horns along with its beam pattern. For angles larger than about 60 degrees from boresight the resulting measurements are dominated by measurement noise. The angular distance between points in the beam pattern at which the value of the pattern is one half it peak value is 7 degrees (full width at half maximum).

The FIRAS instrument, a polarizing Michelson interferometer, uses the phenomena of wave interference to measure the spectrum of the CBR over the wavelength range from 1 cm to 100 microns. Approximately 100 frequency channels are provided by the instrument over this wavelength range. Figure 8 shows a schematic diagram of the instrument. The FIRAS optical parts and detectors are located inside a liquid helium dewar(shared with DIRBE) which maintains them at a temperature less than 2 K. A trumpet shaped cone collects light from the sky and funnels it to a beam splitter which divides the radiation into two components as shown by the red and green wavy lines in Figure 8. The two components reflect from movable mirrors that redirect the radiation back to the beam splitter, which then recombines the two beams at each of two detectors. The two beams will recombine perfectly if the delay between the two beams is an integral number of wavelengths, but will cancel if the path difference is an odd number of half wavelengths. The wavelength can be measured by varying the position of the movable mirrors. As the mirror positions are changed, the varying intensity at each detector is called an interferogram. The interferogram contains the information about the intensity of the incoming radiation as a function of frequency. The accuracy of the FIRAS is achieved by a large blackbody calibrator, maintained at a temperature near that of the CBR, which can be inserted by command into the mouth of the cone.

The DIRBE instrument covers a very broad range of wavelengths. It has 10 bands in a range from 1 - 300 microns. The instrument is basically a small multi-mirror telesccope with a primary mirror diameter of 30 cm(Figure 9). The view axis of the telescope is tilted 30 degrees relative to the satellite spin axis, so that the DIRBE will map out a portion of the sky as the COBE spins. The field of view (beam size) is 0.7 degrees. The entire DIRBE is inside the large superfluid He cryostat and runs at about 2K to minimize radiation from the instrument and for increased detector sensitivity. Four different types of detectors are used; they are 1) photovoltaic (solar cells) Indium antiminide cells used in the short wavelength bands 2 & 3) silicon and germanium photo-conductors at intermediate wavelengths and 4) bolometers (thermometers) at the longer wavelengths. The DIRBE long wavelength channel overlaps the shortest FIRAS channels for comparison. Since scattered radiation from local celestial and galactic objects is a critical problem for DIRBE, extreme care has to be taken inside the telescope to minimize stray light scattering. Light baffles and beam stops are used for this purpose. Another problem is related to the COBE orbit, which will pass through the intense trapped particle radiation areas known as the South Atlantic Anomoly (SAA), where the energetic protons can desensitize some of the detectors. After passing through the SAA detectors must be warmed up slightly (annealed) to restore their sensitivity and allow quick recovery from the SAA proton exposure. This will occur once during every orbit of the satellite, about 100 minutes between these events.

The COBE satellite(Figure 10) weighs 2280 kg (5020 pounds) including the three instruments. In the launch configuration, the satellite is 4.4 m long and 2.2 m in diameter. A 9 panel, double sided, deployable solar array supplies over 700 watts of electrical power to the satellite. Two NI-CD batteries will supply power during short eclipse periods which occur during part of the year. The main instrument related components of the satellite are the three scientific instruments, a dewar, and the deployable thermal /RF shield. The dewar will contain(at launch) 600 liters of superfluid helium at a temperature of 1.6 K. The FIRAS and DIRBE instruments are located inside the dewar in order to cool the detectors and instrument components, thereby improving the sensitivity of these experiments. The DMR instrument is distributed around the outside of the dewar. The purpose of the thermal/RF shield is to protect the sensitive instruments and cryogenics from both solar and terrestrial radiation, and radio frequency interference. In order to satisfy the operating temperature requirements for the dewar and the DMR, the inner surface of the shield is kept cold, less than 240K, and is designed to be a good infrared reflector. Because the DMR instruments receive direct radiation from the shield, the shield is designed to be thermally stable over the spin period of satellite. The shield also reduces radio radiation incident on the backside by a factor of a million.

Initially, the COBE satellite was to be launched from a NASA Space Shuttle vehicle. The catastrophic failure of the Challenger, however, forced NASA to choose another launch vehicle. A Delta rocket was chosen in late 1986 as a replacement launch vehicle. As much of the COBE satellite had already been designed at the time of the Challenger accident, a great deal of additional effort was necessary to redesign the satellite. The main changes were to reduce the weight of the satellite by a factor of two and to reduce the original 4 meter envelope of the satellite to fit inside the 2 meter diameter Delta shroud. Fortunately, this was all accomplished without any reduction of the scientific payload.

A prime requirement for the COBE satellite is to observe the entire sky while keeping the sensitive instruments well shielded from the sun and the earth. Shielding is accomplished through both the use of a passive thermal/RFI shield, and by careful selection of the orbit. The orbit chosen for COBE is circular and sun-synchronous with a 900 km altitude (Figure 11). The orbit is further constrained by having the sun oriented approximately 90 degrees away from the orbit plane. To achieve the sun-synchronous motion, the orbit plane is inclined 99 degrees to the equator, thereby allowing the orbit plane to precess at the same rate as the apparent solar motion (1 deg/day). This precession motion allows the entire sky to be observed in 6 months. To both observe the sky and to keep the radiation from the sun and earth away from the instruments, the satellite is oriented so that the symmetry axis of the instruments is pointed 94 degrees from the sun and outward from the earth. The satellite will rotate at 0.8 revolutions per minute about the symmetry axis thereby providing a mechanism for sweeping the instrument reception patterns over the sky. As the satellite moves around the earth, it must also rotate about its center of gravity in order to keep the direction of the earth behind the sunshield.

The constant redirection of the spin axis forces the COBE satellite to use a unique attitude control system. The COBE satellite is three- axis stabilized, yet it spins and has zero angular momentum. Momentum wheels inside the satellite serve to cancel the momentum of the external spinning satellite. The satellite is stabilized on three axis through the use of reaction wheels using the sun and the earth as celestial references. After the fact pointing determinations will be made using the signals recorded by the DIRBE instrument as known reference stars pass the field of view of that instrument.

The launch sequence for COBE, from time of liftoff at the Western Test Range to its nominal orbit is shown in Figure 12. The final orbital injection maneuver occurs approximately 1 hour after liftoff. The satellite then reorients itself in preparation for separation from the second stage booster. Following deployment of the sun shield, the booster separates from the satellite, and the momentum wheels are spun up. The solar array and satellite communication antenna are then deployed. Throughout these maneuvers, the dewar cover remains on until approximately five days after launch at which time a command from the ground deploys the dewar cover, thereby readying the satellite for its scientific mission. Data storage capacity on each the satellite's two tape recorders is about 70 MB. Each tape recorder can be played back in 13 minutes. Communications with the COBE satellite are conducted through radio links with the Tracking and Data Relay Satellite System (TDRSS) and directly with a NASA ground receiving station at Wallops. The major down link data stream will be transmitted to the ground receiving station once per day.

The COBE satellite promises to dramatically increase our knowledge of events in the early universe. Its ability to obtain full sky coverage with complimentary measurements from several different instruments will give us a unique opportunity to separate the non-cosmological and cosmological background radiation. The COBE measurements combined with other measurements planned over the next several years may provide new data which could revolutionize our ideas about the events that led to our present universe.

FIGURES

Figure 1 - The observed spectrum of the Cosmic Background Radiation follows that of a blackbody with a temperature of approximately 2.7 K at wavelengths longer than a few millimeters. The original Penzias and Wilson data point is indicated by the solid bar at 7.5 cm wavelength. Recent short wavelength measurements, indicated by the open circles, show significant departures from the blackbody curve.

Figure 2 - Spectral Distortions of the background radiation

a) Excessive turbulence in the early universe could generate enough energy to distort the blackbody spectrum(solid line) to a non-blackbody spectrum as shown by the dashed line.

b) The universe cooled as it expanded. At temperatures close to 4000K, the free electrons combined with protons and emitted energetic photons in the process. These energetic photons outnumbered the energetic photons present in the blackbody spectrum and could have distorted the spectrum at wavelenghts less than .01 cm.

c) It is possible that the enire universe was reheated after the era of decoupling. This re-heating could have produced a hot gas which is not in equilibrium with the CBR. The presence of the hot gas would distort the spectrum as show by the dashed line.

Figure 3 - A partial map of the sky brightness made by a balloon borne predecessor of the DMR at 3.3 millimeters wavelength. The total variation of the sky brightness in this map is .006 K. The sky brightness is hotter(RED) in the direction toward which the Earth is moving, and cooler in the opposite direction(BLUE). This map was made by Lubin et al.

Figure 4 - Zodiacal light/ galactic emission model Figure yy shows measurements of the galactic radiation obtained with the IRAS satellite. Similar maps will be made from the COBE data, and used to subtract the galactic emission from the CBR.

This diffuse glow is known as zodiacal light and is primarily a problem at the shorter DIRBE wavelengths. This was also clearly seen by the IRAS satellite. After all these and other sources of non-cosmological radiation are accounted for it is the residual which is of greatest interest. For this would be evidence for the glow of the earliest galaxies to form.

Figure 5 - The COBE satellite will map the sky and measure the radiation emitted by a great variety of objects in addition to the relic CBR from the Big Bang. The figure shows the expected brightness of a number of sources of radiation that the COBE can measure. These include the CBR, dust grains orbitting around the sun(source of the zodiacal light), microscopic dust grains located between the stars, electrons moving in the space between the stars in our galaxy, and the light from the first stars and galaxies. The approximate sensitivities of the DMR, FIRAS, and DIRBE instruments is shown.

Figure 6 - DIFFERENTIAL MICROWAVE RADIOMETER for measuring the anisotropy of the cosmic background radiation is shown schematically in this diagram. The two corrugated horn antennas point at different parts of the sky, and are alternately connected to the receiver by the switch 100 times per second. The signal entering the receiver is translated to a lower frequency, amplified, and detected. The synchronous demodulator reports the difference in power received in the two antennas. Six instruments with this design, operating at three wavelengths (3.3, 5.7, and 9.6 mm) comprise the DMR instrument.

Figure 7 - DMR and FIRAS HORN ANTENNAS are shown on the right and left sides of the figure respectively. The DMR antennas are

Figure 8 - FIRAS INSTRUMENT FOR MEASURING THE CBR SPECTRUM is shown schematically in this figure. The trumpet shaped cone collects light from the sky

and funnels it to a beam splitter which divides the radiation into two components as shown by the (red and green) wavy lines. The two components reflect from movable mirrors that redirect the radiation back to the beam splitter, which then recombines the two beams at each of two detectors. The two beams will recombine perfectly if the delay between the two beams is an integral number of wavelengths, but will cancel if the path difference is an odd number of half wavelengths. The is intensity at each wavelength is measured by varying the position of the movable

Figure 9 - Schematic of DIRBE

Figure 10 - Artist rendition of the COBE SATELLITE in orbit, high above the earth. The locations of the three science instruments, DIRBE, DMR, and FIRAS are shown. The solar cell arrays are unfolded when the COBE reaches orbit.

Figure 11 - The COBE ORBIT passes nearly over the Earth's poles at an altitude of 900 km. Its spin axis is pointed almost perpendicular to the direction of the sun. This keeps the sun from shinning directly into the deployable RF/thermal shield.

Figure 12 - Launch Sequence