THE COSMIC BACKGROUND EXPLORER SATELLITE (COBE)

NASA's first dedicated cosmology satellite will be launched in 1989 and is the culmination of over a decade of work by a number of groups. It will substantially increase our knowledge of the Cosmic Background Radiation and the thermal history of the early universe and will help us understand the processes that led to the formation of structure in the present universe.

It has now been nearly twenty five years since the discovery of the cosmic background radiation (CBR) by Penzias and Wilson of Bell Laboratories in 1965 and the immediate explanation of its cosmological origins by the Princeton group; Dicke, Peebles, Roll, and Wilkinson who were, at that time, beginning their own search for the radiation. In this quarter of a century a handful of groups have pursued this cosmic holy grail in an effort to unlock some of the secrets of the early universe and its evolution. Nature has not given its secrets easily. The measurements are difficult, often requiring and stimulating the development of new techniques and technologies. In their original 1965 paper Penzias and Wilson stated "the radiation is consistent with a blackbody of temperature 3 K unpolarized and free of seasonal variation" (isotropic). We can now say with much greater certainty that these statements are true to such a high precision in some cases that new theories, such as the inflationary scenario, are needed to reconcile theory and measurement.

The existence of the radiation was first predicted in 1948 in the nucleosynthesis work of Alpher and Herman as a possible relic of a hot phase in the universe. Unfortunately this work was largely unknown to physicists and astronomers who could have detected the radiation significantly earlier than 1965. Alpher and Herman reasoned that to prevent too much helium from forming in an early nucleosynthesis era a bath of photon could prevent this by photodissociating the forming denterium needed for helium production. These photons are the radiation energy that later becomes the background radiation. In this way, they predicted, a radiation with a current radiation temperature of about 5K. They also predicted that higher temperatures would correspond to lower helium abundances and lower temperatures would correspond to a higher helium abundance. Remarkably this temperature is very close to the currently measured temperature of 2.7 K. In 1964 Doroshkervich and Novikov similarly pointed out that a remnant radiation with a temperature between 1 and 10 K should exist.

This newly discovered radiation was quickly seen as a serious, though not necessarily fatal blow, to the steady state theory which perceives the universe as homogeneous not only in space but also in time (the universe has always existed) with matter being constantly created through a "C" field and subsequently expanding to be consistent with the Hubble recession. The incorporation of a universal background radiation was an unnatural and ad hoc addition to the steady state model. On the other hand the radiation fits naturally into the so called (hot) big bang model where the universe begins in a very hot dense initial state and subsequently expands. Just as expanding gas cools so does the expanding radiation (heat) from the initial explosion ultimately cool to become the present 2.7 K radiation.

In the simplest model of the Hot Big Bang, the radiation which bathes the universe is pure blackbody or thermal radiation, having a classical Planck distribution established at a time when matter and radiation were in close physical contact. This condition existed for several hundred thousand years before the universe expanded and cooled sufficiently to allow the matter and radiation to decouple or pass freely through one another. "Decoupling" occurred when the temperature dropped to $\sim$ 4000 K thereby allowing protons and electrons to combine and form hydrogen atoms. Before this time, free electrons were plentiful and photon-electron scattering kept the radiation in equilibrium with the matter. Folis, provided there are no additional sources of radiation or heating. Hence, the presently observed radiation should have a blackbody spectrum, with a temperature approximately 1500 times smaller than the temperature(4000K) at which electrons and protons combined. In fact, the current value of the background temperature can be interpreted as a measure of the expansion of the universe.

If this very simple model were perfectly true the background radiation would not be of much interest since it would be an isotropic, unpolarized blackbody. It is, however, the deviations from this simple scenario that are of importance for they tell us about the processes that occurred from the time of decoupling, about one million years after the big bang, to the present time, 10-20 billion years after the big bang. In particular our ideas of galaxy formation are fundamentally influenced by measurements of the CBR.

Numerous researchers have searched for distortions in the CBR, however the faintness of the signal coupled with interference from the Earth s atmosphere have precluded any definitive findings beyond the few mentioned below. In 1974, NASA initiated a project to measure the CBR using a dedicated, Explorer-class spacecraft. This spacecraft, named COBE, an acronym for Cosmic Background Explorer, is scheduled to be launched from the Vandenberg Western Space and Missile Center in California in 1989.

Detailed measurements of the CBR give us the opportunity to answer important questions about the history of the universe. Largely unchanged, the spectrum and spatial distribution of the radiation remains as a fossil of an early epoch in the development of the present universal structure and composition. The later development of the matter which eventually led to the the formation of stars, galaxies, and clusters of galaxies could have left their own unique imprints.

Two fundamental properties of the CBR which can be investigated are its spectrum and its angular distribution. The first is the spectrum: How much flux is there at each wavelength of the incoming radiation? Overall, the radiation has the spectrum of a black body (Planck). While the emission from most objects only approximates the ideal Planck emitter, an oven which has come to a constant temperature with no large holes for the radiation to leak out is very close to an ideal Planck source. The spectrum of a black body depends on only one property–its temperature. The fact that the CBR has a spectrum which is very close to that of a black body indicates that the radiation was emitted from matter which was nearly in thermal equilibrium just like the oven which has come to a constant temperature. This is a very striking result since the universe today, filled with hot stars and cold planets, gas and dust, is not at all in thermal equilibrium.

The second property of the CBR which can be investigated is its angular distribution. How does the radiation change from point to point on the sky? Here again the answer is striking. Except for an effect which is very likely to be due to the motion of the earth (and therefore not a fundamental property of the CBR), the radiation is the same in all directions to about ten parts in one million. It is said to be isotropic. Experiments looking for variation in the CBR from point to point on the sky are often called anisotropy experiments. Together with the Planckian spectrum, this fact tells a surprising story about the conditions of the universe in its early history. It was in thermal equilibrium and everywhere the same temperature– a smooth primordial soup.

Deviations from a thermal (Planck) spectrum can be caused by any process which injects or removes free energy into the radiation field. Examples of processes that inject energy in the radiation are decays of hypothetical massive particles produced in the big bang, decaying turbulence, early galaxy formation injecting light and heated dust, line emission from the cascading of electrons to form neutral hydrogen from the previously ionized plasma, and Compton scattering (and its inverse) of electrons and the CBR photons. This last process is expected to significantly distort the spectrum if during the period of early galaxy formation bright young stars emit enough ultraviolet photons to reionize the neutral plasma. This process is also important in the small scale anisotropy and spectral distortions produced by the observed hot intra cluster gas. The effect in this context is commonly called the Sunyaev-Zeldovich effect.

Some models of the early universe predict that there might be a considerable amount of turbulent motion in the matter-radiation soup near the time of the decoupling event. The effect of this on the spectrum would be that the signal of any region of the sky would be the combination of several temperatures because the turbulent motion would impart a different doppler shift for each region moving with different velocity. The resulting spectrum would be the sum of Planck spectra with slightly differing temperatures. The sum would not look like a Planckian spectrum. This deviation from a Planckian spectrum would not have the same characteristics as the deviation resulting from the production of free energy. Therefore by carefully measuring the CBR spectrum we can determine whether either or both of these conditions might have existed at the time of decoupling.

Still different kinds of deviations from a Planck spectrum might be in evidence from the weak interaction of the radiation with the matter after the decoupling. The interaction is dominated by the scattering of the CBR photons on free electrons in a process called Compton scattering. The weakness of the interaction is the result of the low energy of the photons and the low density of free electrons in the universe as a whole.

There are, however, regions in space where the free electron density might be high enough to have a measurable effect on the CBR. It is thought that there might have been an epoch where a large number of very massive stars were formed which burned quickly and at high temperature. While the light from these stars would not be large enough to significantly change the background radiation, they might have produced enough ultra-violet radiation to ionize a significant fraction of the hydrogen in their vicinity. Alternatively, regions where galaxies are just beginning to form are characterized by a large inflow of material into a small volume. In such a region it is likely that the energy of infall is converted to heat in a shock front. The shock temperature is also high enough to ionize the hydrogen. In fact, almost any process which has the ability to ionize large volumes of hydrogen will produce many free electrons. These could have a high enough column density to cause a measurable spectral distortion.

In addition, some clusters of galaxies are known to have a gas of electrons in their gravitational potential. X-ray measurements from the Einstein Satellite show a spherical distribution of emission which is likely to come from hot intracluster electrons. The density electrons and size of the clusters is sufficient to have a measurable effect on the spectrum in the direction on the cluster.

Quite independently of free electrons, it is possible to imagine radiation sources which produce enough light at the same wavelengths as the CBR that they would impart significant changes to the background. Among these is emission from dust which is heated to temperatures above that of the CBR by some source of energy. This dust, while so tenuous that it cannot absorb much of the CBR, could emit enough power to have a measurable effect on the total background spectrum.

Dust in the astrophysical sense consists of small grains built of elements heavier than helium such as silicon and oxygen. Because these elements are produced in significant quantities only in stars, radiation from dust cannot exist before the formation of stars. The era of early star and galaxy formation is not known but measurements of the spectrum of the background radiation will give us a much better picture of when this occurred.

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 emitter of the CBR and the Earth, b)irregularities in the surface of last scattering, c)scattering since the era of decoupling, and d)rotation. Experiments designed to search for spatial variations in the CBR are called anisotropy experiments. The first of these effects has already been measured. It is due to a remarkable feature of black-body radiation. When viewed in a frame of reference moving relative to the emitter, black-body radiation retains it's characteristic Planck distribution but with a different temperature. 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. Modern microwave CBR measurements now routinely detect a non-cosmological component caused by the earth's motion (Fig ?) through space. These data show an anisotropy with the correct distribution to be explained by the earth's motion and the motion is in a direction towards the Virgo cluster of galaxies with a velocity of 300 km/sec or 1/1000 the speed of light. 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 irregularities of the surface of last scattering must exist, however they have not been detected yet. The present-day universe is far from uniform on any size scale accessible to measurement. On scale sizes from micron size dust particles, to planets, to stars, to galaxies, and to galaxy superclusters, the universe is lumpy. Presumably, these lumps began with small variations of the matter density, and they 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 cluster we now observe. Since the CBR we observe today reflects the distribution of matter at the time of 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 on the CBR. They must be observable at some level of sensitivity, unless they have been erased by some unknown process. The experimental results are quite surprising. Except for anisotropy due to the motion of the earth the radiation is the same in all directions to nearly ten parts in a million, the current observational limit.

In addition to the lumpy nature of the universe, it is quite 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 or all parts of the universe started with the same initial conditions. As no a priori justification exists for assuming identical initial conditions everywhere, this is a plausible condition. In the case of the CBR, regions of the sky which are separated by more than about 2 degrees in angle have, in fact, never been in contact in the classical 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 emission of the CBR radiation we now observe. 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 is the temperature of the CBR so uniform on large angular scales?

Our own galaxy is filled with dust and gas in the interstellar medium and the solar system contains interplanetary dust. For the COBE experiments, these components represent an unavoidable source of background clutter, keeping us from clearly studying the components of the radiation coming from afar. A model of the galactic emission from the high energy electrons losing energy in galactic magnetic fields must be determined and removed from the low frequency microwave data to uncover the cosmological components. At infrared and millimeter wavelengths the thermal emission of galactic and interplanetary dust and the scattered sunlight from interplanetary dust are another source of unwanted background. At short infrared wavelengths, the integrated light from stars themselves becomes a significant correction if a cosmological component is to be determined. The large spectral and spatial coverage provided by the COBE experiment's design and long operational lifetime permit high precision models to be obtained to correct the data for these "local" effects. While these "local" sources of radiation must be removed from the COBE data to obtain the cosmological components, the background corrections determined by the COBE experiments will provide some of the most detailed data available on these "local" emission sources. Figure ? shows the "local" emission that the COBE experiments will encounter. In spectral regions where the CBR is not the dominant emission, we expect to be able to remove the background sources at the level of about 1underlying cosmological component of the radiation.

Having explained the scientific objectives for studying the CBR, we now turn to the experimental approach that has been developed to study the CBR. This approach was developed by a team of scientists and engineers representing 6 different institutions(Goddard SFC, JPL, MIT, Princeton University, UC Berkeley, UC Santa Barbara) working together at the Goddard Space Flight Center. The overriding consideration was that the experiment had to be designed to distinguish between the distant and cosmologically significant radiation, and the radiation from the intervening and nearby sources such as that from our own galaxy. An early conclusion of the science team was that a meaningful understanding of the CBR could only be obtained by a set of comprehensive measurements covering a wide range of frequencies and covering the entire sky. 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 seen as the necessary set of measurements which would allow us to untangle the data, and to study the CBR itself. With these considerations in mind, the objectives of the COBE experiment can be simply stated. They are to measure the spectrum and angular distribution of the background radiation(including the diffuse infrared emission) over the entire sky, and to separate the contribution of the relatively nearby sources of radiation from the more distant and cosmologically interesting radiation. The fundamental objectives of the COBE satellite are to make these measurements and to return the data to the Earth.

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 xx shows our estimate of the predicted intensity of interstellar dust, interplanetary dust (zodiacal light), and galactic radiation which both interfere with and obscure the background radiation we are attempting to measure. Also shown are the intensity of a 2.7 K blackbody curve, and a guess about the background of primeval galaxies.

To meet the goals and objectives, the COBE satellite has three distinct, but complementary experiments. Each experiment measures a different regime in the background radiation, but the results are symbiotic, each instrument aiding in the interpretation of the other two. The three instruments are: 1)DMR — the Differential Microwave Radiometer will measure the large scale anisotropy in the background radiation; 2)FIRAS — the Far Infrared Absolute Spectrometer will measure the flux (intensity) as a function of wavelength; and 3)DIRBE — the Diffuse Infrared Background Experiment will measure the infrared background expected from early galaxy formation processes. Although DIRBE will not in general measure the CBR it is extremely important for our understanding of processes in the more recent history of the universe when structure becomes dominant (i.e. early star formation, and galaxy formation).

The Differential Microwave Radiometer experiment is actually three pairs of instruments designed to measure very slight temperature differences (anisotropy) that might exist in CBR. Since the ultimate sensitivity goal of the DMR is to measure temperature differences at a level of 1 part in 10^5 it is crucial to eliminate other sources of radiation such as emission for our galaxy. To accomplish this three different wavelengths are measured simultaneously and for redundancy each wavelength band has a simultaneously operating additional channel. The wavelengths chosen were 3.3, 5.7, and 9.5 mm or 90, 53, 31 GHz (1 GHz = 1 billion cycles per second). These wavelengths were chosen to give an optional mix of technologically achievable sensitivity and the ability to remove the "local" galactic emission. For increased sensitivity the 3.3 and 5.7 mm channel critical components are cooled by radiation to about 130K, while the 9.5 mm channel runs at about 300K (room temperature). A schematic of the DMR is shown in Figure XX. The antennas are critical in that they should reject the radiation from the earth to prevent a false signal. This has plagued many previous ground based, balloon borne and even a satellite experiments. The desired overall sensitivity goal is about 10^{-5}K so the signal contributed by the earth should be much less than this. Since the earth is very large (size) source for a low earth orbit satellite (it basically fills the backward hemisphere) rejection, relative to on axis acceptance, should be $10^9 - 10^{10}$ to be conservative. Fortunately the technology to build such antennas is possible. By forming small (quarter wavelength) grooves inside the antenna, the diffraction pattern can be controlled to provide this rejection. Figure XX shows a boresight view of one of the DMR horns along with its beam pattern. Beyond about 60 degrees from boresight the measured pattern is measurement noise. The beam pattern from each horn is approximately gaussian in distribution with 7 degrees defining the distance between half power (3 db) points.

The DMR rapidly (100 Hz) compares the temperature of radiation measured by each antenna and provides a measure of its difference at its output. The two antennas of each channel are 60 degrees apart. All DMR channels have the same geometry and beam size. Each channel has about the same sensitivity of being able to measure about 25 mK (0.025

K) temperature difference in a one second measurement. Since these measurements are statistically independent the overall sensitivity goes inversely as the square root of time. So, for example, in 100 seconds a temperature of 25/sqrt100 = 2.5 mK could be discerned. Other limitation such as the fact that the radiometers do not measure only two points in the sky but the entire sky plus the galactic emission prevent this full sensitivity from being realized. The sensitivity of the instrument is estimated to be about .0002 K per beamwidth after 1 year of observations. By combining observations over the entire sky, it should be possible to measure temperature variations as small as 10 micro Kelvin. Our understanding of the galactic emission at this level is not precise enough to predict this. Indeed one of the products of the DMR data will be a much better understanding of the galactic emission.

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, each less than 5 xx 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(parabolic Winston) 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 xx. The two components are allowed to reflect from movable mirrors which redirect the radiation back to the beam splitter which then allows the two beams to recombine 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 Diffuse Infrared Background Experiment is designed to search for the radiation characteristic of primordial galaxy formation. Since the era of galaxy formation is highly uncertain and since the emission of forming galaxies is unknown, DIRBE is designed to cover a very broad range of wavelengths. It has 10 bands in a range of 1 - 300 microns. The DIRBE is actually a small off-axis Gregorian telescope with a primary mirror diameter of 30 cm. The view axis of the telescope is tilted 30 degrees relative to the spacecraft spin axis so that as the COBE spins (at 0.8 RPM) the DIRBE will map out a portion of the sky. 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. For this purpose special paints, baffles and beam stops are used. Another problem is that since the COBE satellite is in a relatively low orbit it will pass through the intense trapped particle radiation areas known as the Van Allen belts. These particles desensitize some of the detectors enough that after passing through the radiation the detector must be warmed up slightly (annealed) to restore their sensitivity. This will occur every orbit or about every 100 minutes.

DIRBE has a crucial role in determining where the spacecraft, and DIRBE in particular, is pointing at any given time. The coarse spacecraft pointing is determined by gyros and magnetometers on board. The gyros will drift with time and the magnetometers depend on a somewhat imprecisely known earth magnetic field. Together they cannot provide the necessary precision. So DIRBE itself will determine the pointing information by using known objects as reference sources as they pass through the field of view. Between known objects the positions will be interpolated with the aid of the gyros. In all DIRBE will detect a very large number of known objects (several hundred thousand). In addition the solar systems interplanetary dust scatters the light from our sun in such a way that a diffuse glow will be seen concentrated along the ecliptic plane (plane of primary planet orbits). 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.

Previous measurements of the large scale CBR from airplanes, balloons, and rockets have encountered a variety of problems. A principal problem for the submillimeter and infrared spectral region 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 for studying the CBR typically 0.1 - 10mm. The atmosphere at best gives ground based observers only narrow selected windows through which to observe the CBR. This is due to the numerous molecular absorption bands in oxygen(O2), ozone(O3) and water(H2O). The experience gained from these measurements, combined with additional considerations that we outline below argue strongly for performing the measurements from a spacecraft, located well above the bulk of the earth's atmosphere.

To understand the requirements for a spacecraft environment, we turn first to the common observational requirements for the isotropy, spectrum, and diffuse IR experiments. These requirements are: 1)full sky coverage , 2)long observation times, 3)negligible interference from the terrestrial atmosphere, 4)modest pointing capability, 5)protection from the heat and light from the sun and earth, 6)low radio interference, 7)a controlled thermal environment, and 8)reliability. Full sky coverage is necessary to separate the local sources of radiation from the CBR, and to measure the intrinsic large angular scale structure of the CBR itself. 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. Full sky coverage is also required by the DMR isotropy experiment in order to p;provide closure or the ability to interconnect all of the differential measurements. There are several reasons for requiring extended observation time, all related to sensitivity and reliability. First, the sensitivity of the infrared and millimeter wave detectors require long integration times in order to reach the sensitivity limits imposed by the astrophysical environment. Secondly, even if sensitivity were improved, systematic effects which might be produced by subtle receiver drifts or thermal gradients might go unnoticed unless some measurements can be repeated.

Additional arguments for a spacecraft environment are also provided by individual instruments. For example, a requirement for the isotropy experiment is that it be able to measure the relative brightness temperature of the sky to a precision of $< .0001$ K. This requirement places stringent requirements on the stability of the atmosphere as well as on the gain stability of the receiver. In orbit, the atmosphere is eliminated as a problem and the sky itself can be used as a stable reference by measuring differences in received power between two parts of the sky. The thermal requirements for both the spectrum and diffuse IR experiments are also best achieved in space.

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

The redesigned COBE spacecraft weighs kg (5020 pounds) including the three instruments. In the stowed 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 spacecraft. Two 20 amp hour NI-CD batteries will supply power during eclipse periods. The main instrument related components of the spacecraft 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 cryogenic instrument area from radiation from the sun and earth, and to protect all instruments from 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 made to be a good infrared reflector(emissivity of surface $<.07$). Because the DMR instruments receive direct radiation from the shield, the shield must also be thermally stable. In a single spacecraft rotation, the product of the maximum temperature variation across the shield and the RF emissivity is less than 4 K. The shield provides more than 60 db of attenuation at 2.2 GHz.

A unique aspect of the COBE satellite is its attitude control system. The COBE spacecraft is a zero angular momentum system, that both spins and is three axis stabilized. Why and how does the spacecraft achieve this seemingly contradictory configuration. To understand the why, we first take a look at the orbit requirements. A prime requirement 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(mentioned above), and by careful selection of the orbit. The orbit chosen for COBE is circular and sun-synchronous with a 900 km altitude. 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 spacecraft is oriented so that the symmetry axis of the instruments is pointed 94 degrees from the sun and outward from the earth. (As the spacecraft moves around the earth, it must also rotate about its center of gravity in order to keep the direction of the earth.) 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 spacecraft will rotate at 0.8 revolutions per minute thereby providing a mechanism for sweeping the instrument reception patterns over the sky.

The launch sequence for COBE, from time of liftoff at the Western Test Range to its nominal orbit is shown in Figure xxx. The final orbital injection maneuver occurs approximately 1 hour after liftoff. The spacecraft then reorients itself in preparation for separation from the second stage booster. Following deployment of the sun shield, the booster separates from the spacecraft, and the momentum wheels are spun up. The solar array and spacecraft 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 spacecraft for its scientific mission.

Solar cells provide electrical power for the spacecraft during most of the mission. For the nominal COBE orbit, the satellite is in a shadow region for less than 17 minutes during each orbit. For these occasions, the spacecraft will be hidden from the sun by the earth, and onboard batteries will provide auxiliary power.

Data storage capacity on each the spacecraft's two tape recorders is about 70 MB. Each tape recorder can be played back in 13 minutes.

Communications with the COBE spacecraft 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.

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Conclusion

The COBE satellite promises to dramatically increase our knowledge of events in the early universe. Its unique ability to obtain full sky coverage with complimentary measurements from several different instruments will give us a much larger view than our previous glimpses. The COBE measurements combined with other measurements planned over the next several years may well revolutionize our ideas about the events that led to our present universe.