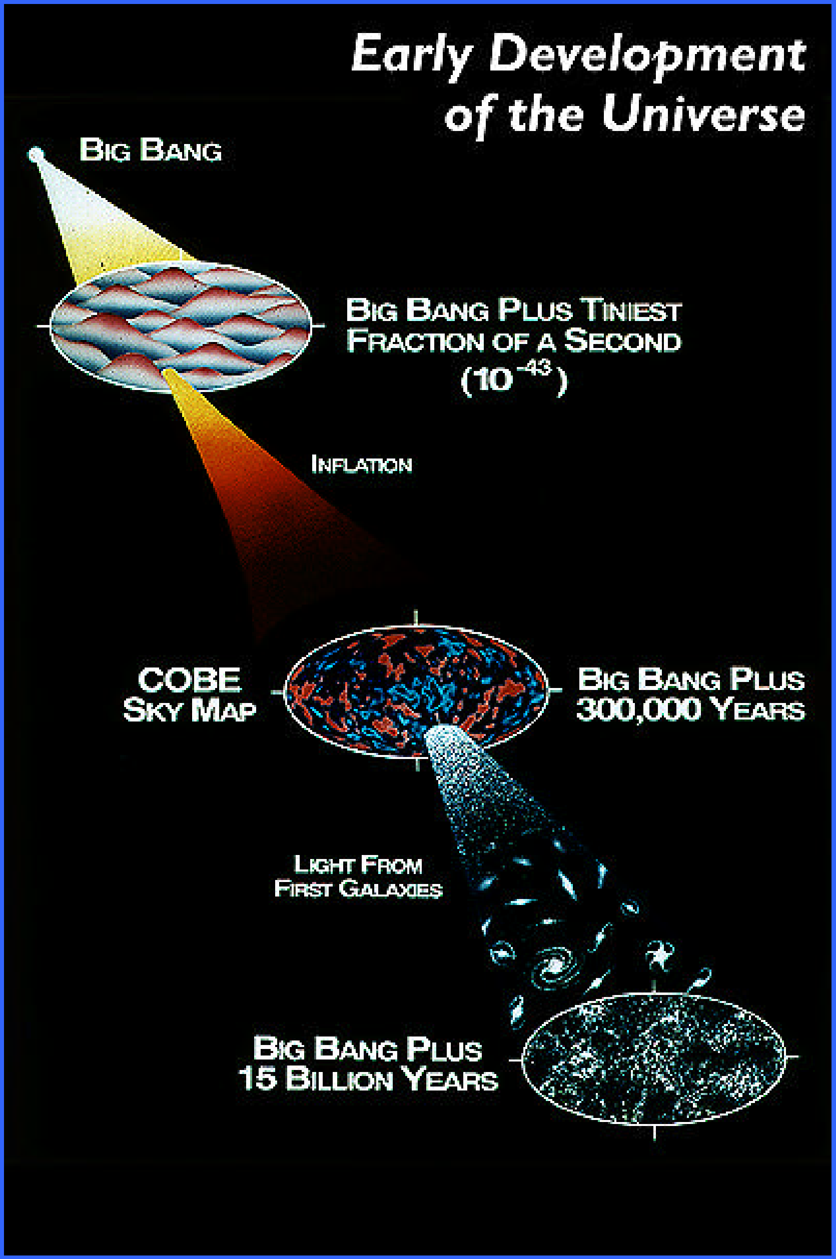
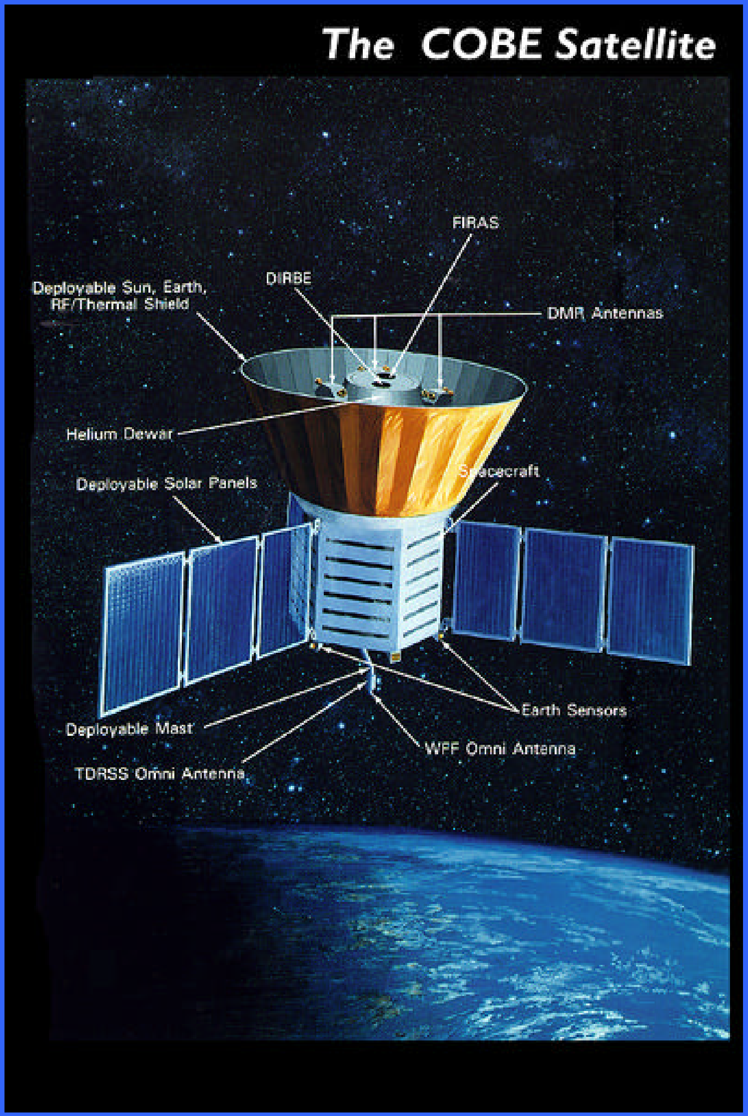
COBE Slide 1

Early development of the Universe. The Cosmic Background Explorer (COBE) satellite was designed to measure the diffuse infrared and microwave radiation from the early Universe, to the limits set by our astrophysical environment. The COBE was developed by NASA's Goddard Space Flight Center with scientific guidance from the COBE Science Working Group.



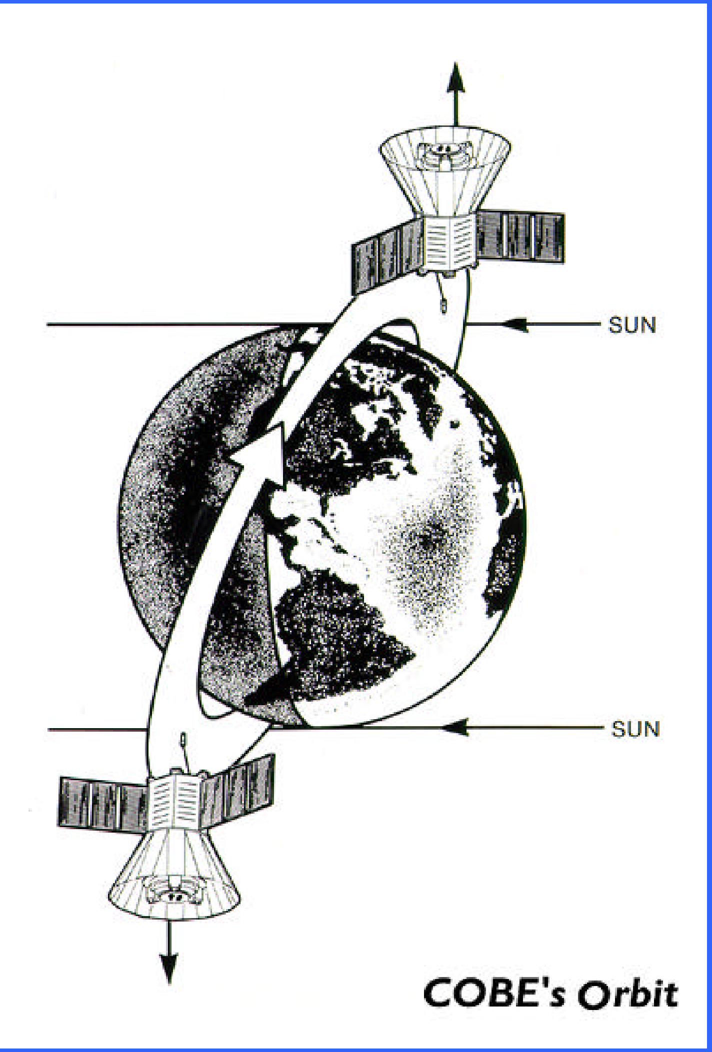
COBE Slide 2

Artist's conception of the COBE satellite in orbit, annotated with locations of scientific instruments, dewar, etc. The instruments are the Far Infrared Absolute Spectrophotometer (FIRAS), which made a precise measurement of the spectrum of the cosmic microwave background radiation; the Differential Microwave Radiometers (DMR), which detected for the first time and was used to characterize faint fluctuations in the cosmic microwave background corresponding to density structure in the early Universe; and the Diffuse Infrared Background Experiment (DIRBE),which obtained data that can be used to seek the cosmic infrared background and study the structure of the Milky Way Galaxy and the interstellar and interplanetary dust. The COBE was launched on November 18, 1989. All three instruments performed well while the helium cryogen supply lasted, until September 21, 1990. Thereafter, the FIRAS ceased operating, as did the DIRBE at wavelengths longer than 4.9 μm (micrometers, or "microns"). However, the DMR continued to operate normally, and the DIRBE continued to collectnear-infrared data with diminished sensitivity until these instruments were finally turned off on December 23, 1993.

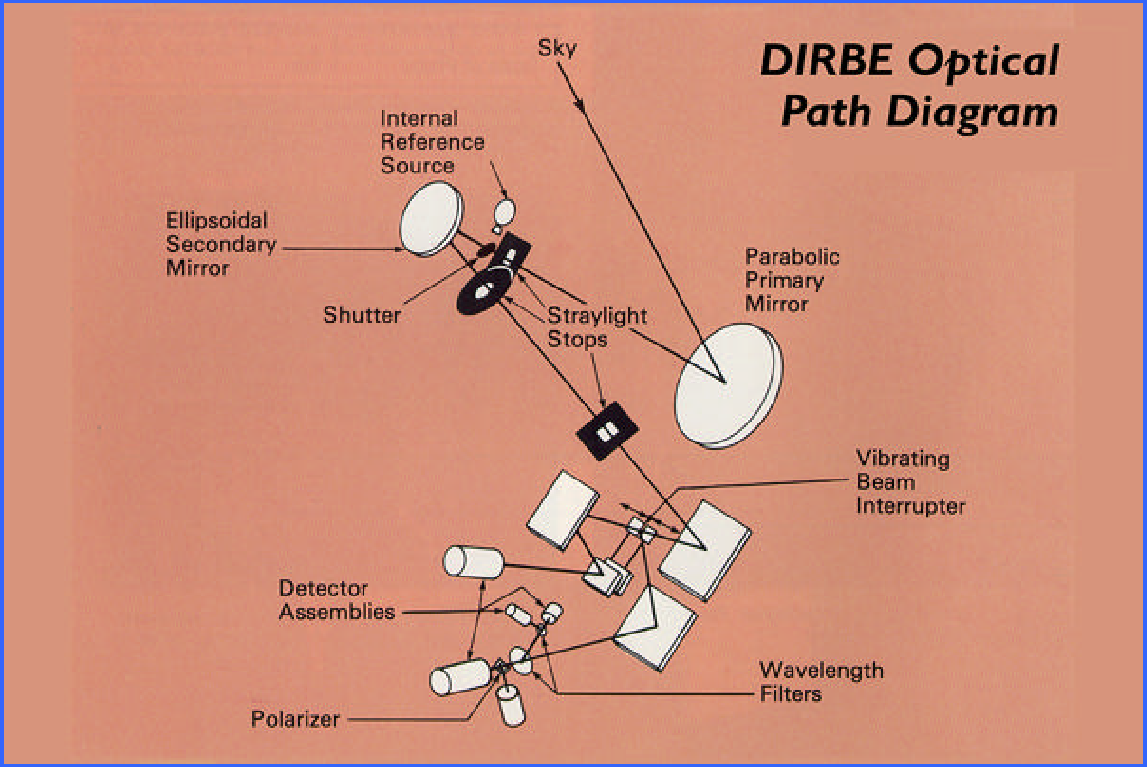


COBE Slide 3

The COBE orbit and spin axis orientation. The orbit nearly passes over the Earth's poles at an altitude of 900 km (559 miles). The orbital plane is inclined by 99 degrees to the Equator, causing the orbit to precess (turn) to follow the apparent motion of the Sun relative to the Earth. (The precession is caused by the Earth's equatorial bulge, which in turn results from the Earth's daily rotation about its axis.) Thus, the spin axis stays pointed almost perpendicular to the direction of the Sun and in a generally outward direction from the Earth. As the COBE orbits the Earth once every 103 minutes, it views a circle on the sky 94 degrees away from the Sun, and as the Earth moves around the Sun over the course of a year the COBE gradually scans the entire sky. The spacecraft rotates at 0.8 rpm. The FIRAS instrument is aligned with the spin axis. The DIRBE and DMR instruments point "off axis" and observe half the sky every orbit.



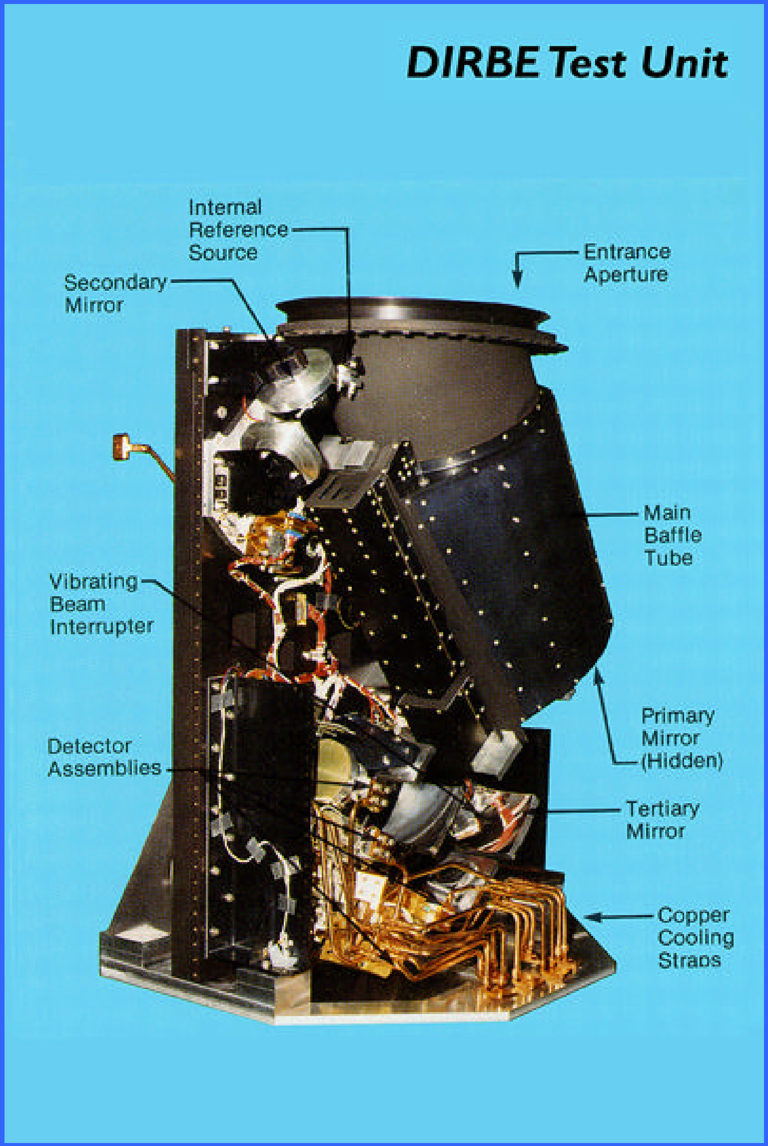
COBE Slide 4



DIRBE optical concept showing mirrors, filters, detectors, and beam interrupter. The DIRBE uses an unobscured off-axis Gregorian telescope to collect light and bring it to a focus on 16 infrared detectors. The instrument was designed to minimize response to objects outside the desired 0.7 degree square field of view. The vibrating beam interrupter allows continuous comparison of the sky brightness with the cold (2 degree Kelvin) interior of the instrument. The responsivity of each detector is monitored on a regular basis using the on-board internal reference sources. The same square field of view is observed simultaneously at each of ten wavelengths (1.25, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140, and 240 μm), and polarization is measured at the three shortest wavelengths.

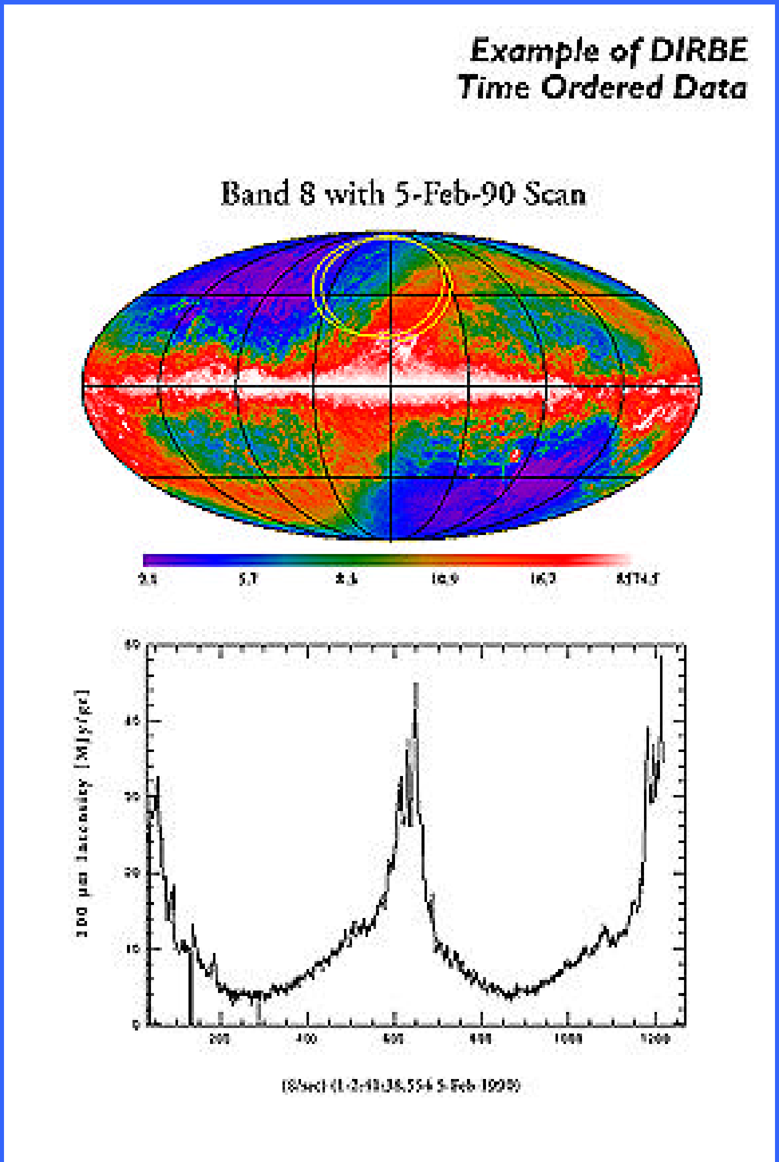
COBE Slide 5

DIRBE test unit showing optics and copper straps used to keep detectors cold. Optics were surrounded with baffle tubes to stop stray light.

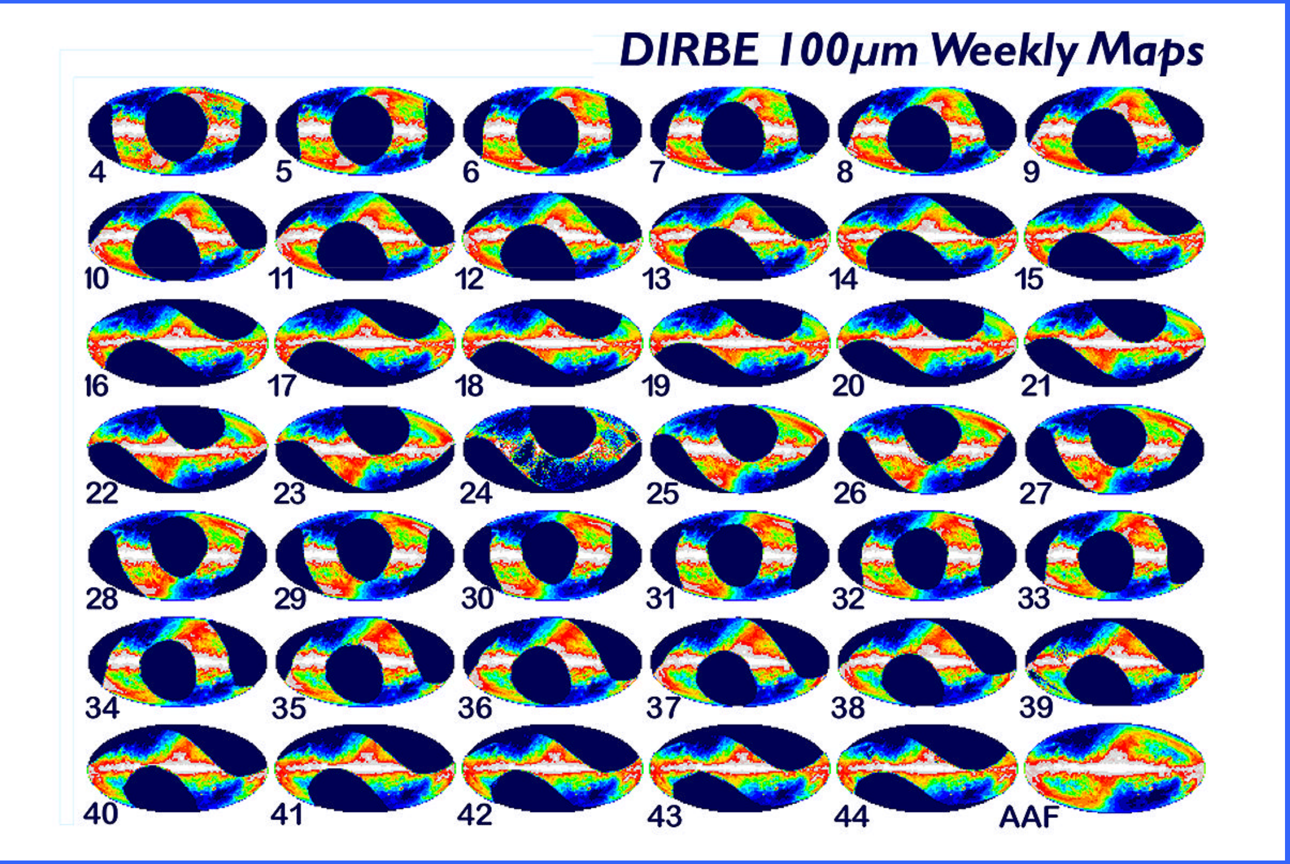


COBE Slide 6

DIRBE scan track superposed on 100 μm Annual Average Map and 100 μm intensity from the corresponding segment of time-ordered data. DIRBE scanned the sky in a helical pattern that resulted from the spin and orbital motion of the COBE satellite and the "look direction" of the telescope, which was 30 degrees from the spin axis. The scan segment depicted covers two COBE spin cycles, or about 150 seconds, during a time when the DIRBE field of view swept through the Sco-Oph region (bright area above the Galactic center in the figure) and passed near the North Galactic Pole, where the emission is faint. The brightness of the sky at 100 μm measured during this interval is shown as a graph of intensity vs. time, as given in the DIRBE Time-ordered Data product. On the abscissa, the unit of time is 1/8th of a second. The bumps at about 470 and 1040 time units correspond to ecliptic plane crossings; zodiacal emission is at a maximum in the ecliptic plane.

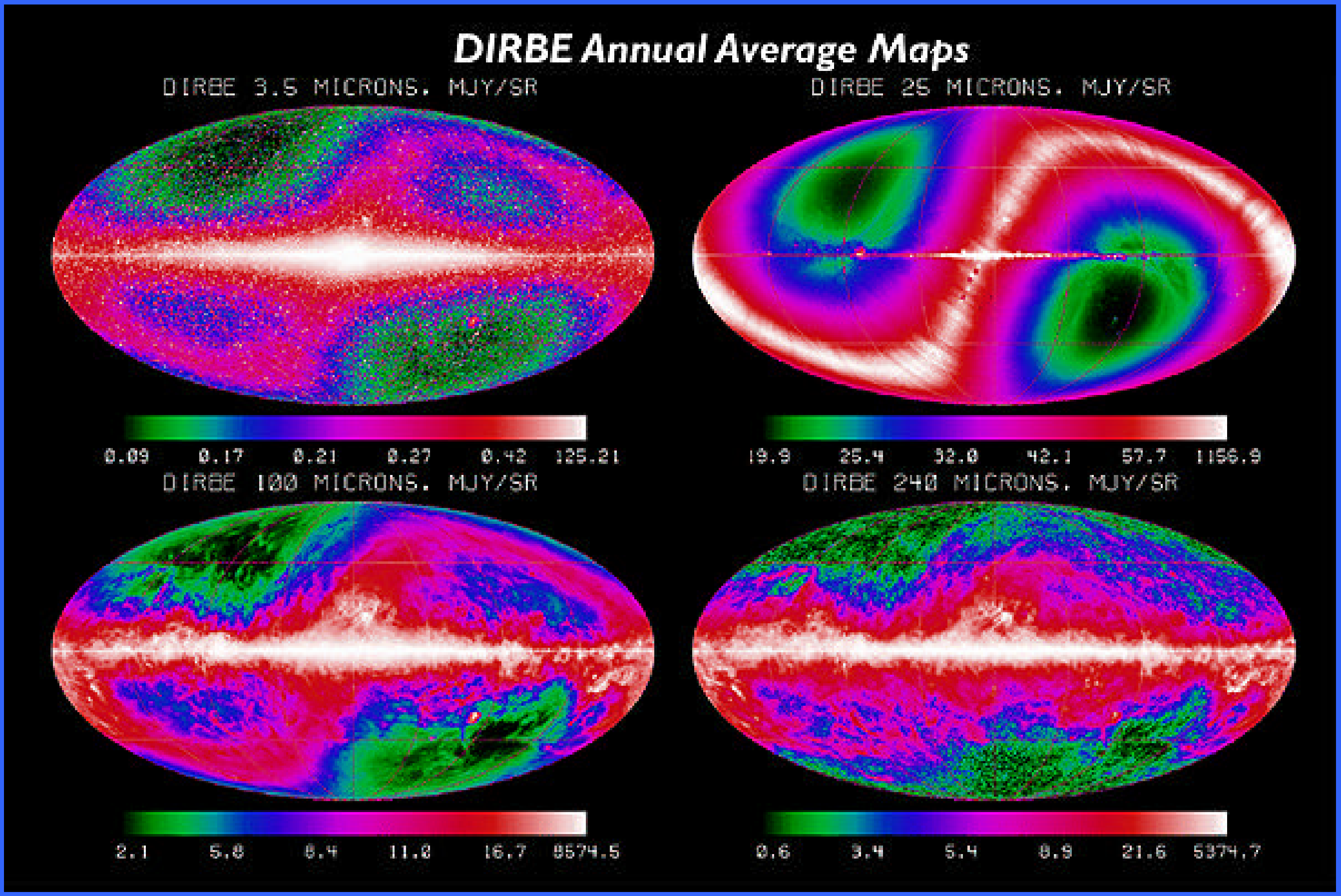


COBE Slide 7



100 μm Weekly Sky Maps for mission weeks 4 to 44, and the 100 μm Annual Average Map. Shows sky coverage each week of the DIRBE mission over the period during which the COBE cryogen supply lasted. As the Earth, with COBE in orbit, revolved around the Sun, DIRBE viewed the sky from an ever-changing vantage point in the solar system, enabling light reflected and emitted by the interplanetary dust cloud to be modeled.

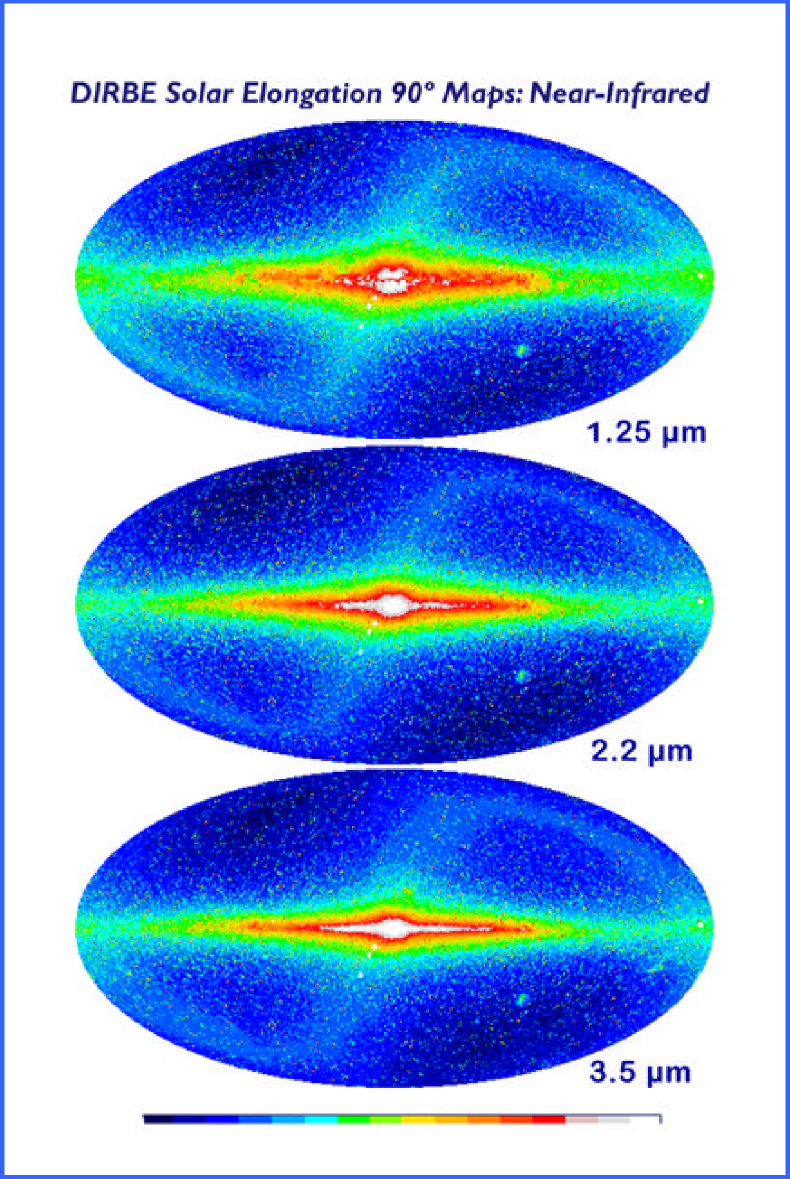
Cobe Slide 8



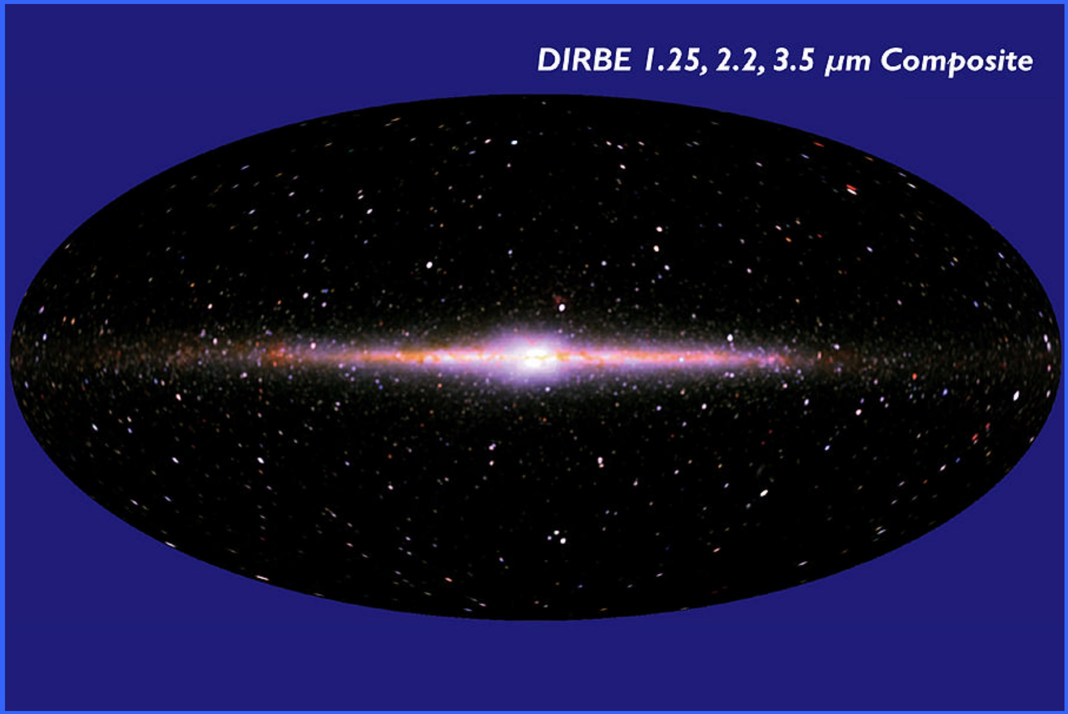
Annual Average Maps at 3.5, 25, 100, and 240 μm. Galactic coordinate Mollweide projection maps of the entire sky at four wavelengths showing emission from stars and dust in the Galactic plane (horizontal feature) and light scattered and emitted by dust in the solar system (S-shape).

COBE Slide 9

1.25, 2.2, and 3.5 μm Solar elongation angle = 90 degree Maps. Galactic coordinate Mollweide projection maps of the entire sky as seen by the DIRBE at a fixed angle relative to the Sun. Stars concentrated in the Galactic plane (horizontal feature) dominate the images at these wavelengths. Dust in the Milky Way absorbs and scatters starlight, producing the dark band that runs through the Galactic center in the 1.25 μm image; this "extinction" effect diminishes with increasing wavelength.



COBE Slide 10

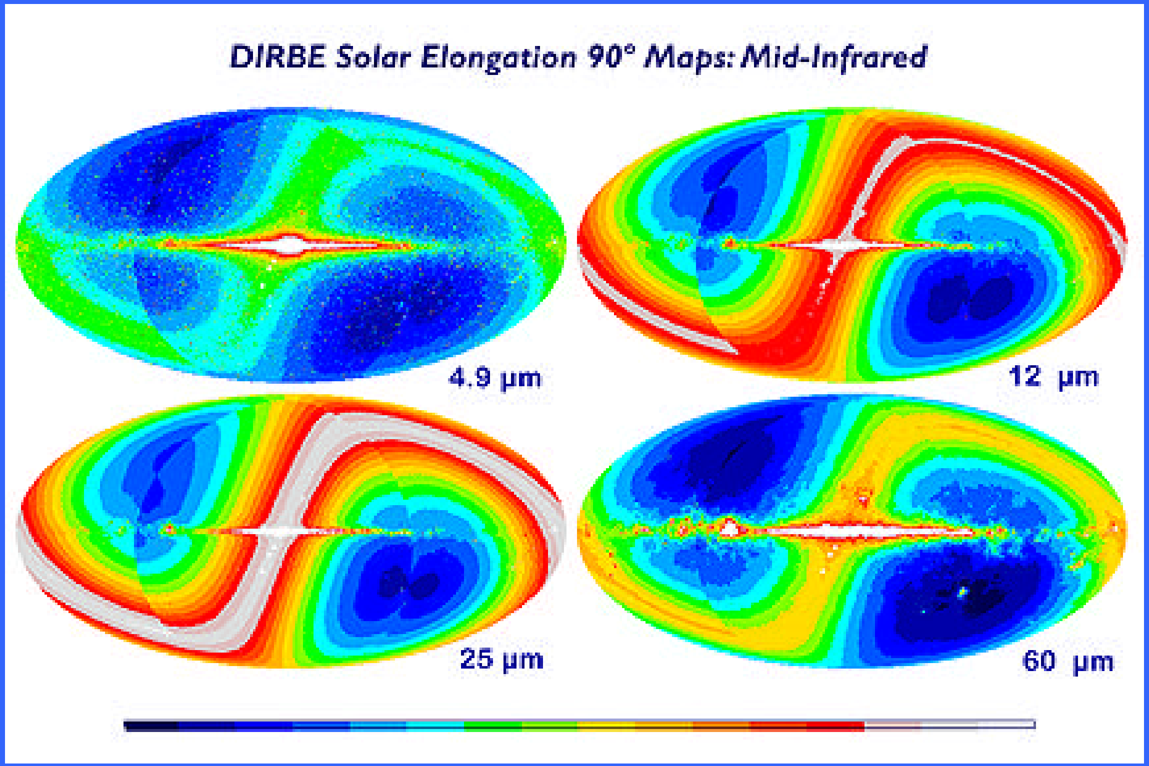


False-color image of the near-infrared sky as seen by the DIRBE. Data at 1.25, 2.2, and 3.5 μm wavelengths are represented respectively as blue, green and red colors. The image is presented in Galactic coordinates, with the plane of the Milky Way Galaxy horizontal across the middle and the Galactic center at the center. The dominant sources of light at these wavelengths are stars within our Galaxy. The image shows both the thin disk and central bulge populations of stars in our spiral galaxy. Our Sun, much closer to us than any other star, lies in the disk (which is why the disk appears edge-on to us) at a distance of about 28,000 light years from the center. The image is redder in directions where there is more dust between the stars absorbing starlight from distant stars. This absorption is so strong at visible wavelengths that the central part of the Milky Way cannot be seen. DIRBE data will facilitate studies of the content, energetics and large scale structure of the Galaxy, as well as the nature and distribution of dust within the Solar System. The data also will be studied for evidence of a faint, uniform infrared background, the residual radiation from the first stars and galaxies formed following the Big Bang.

COBE Slide 11

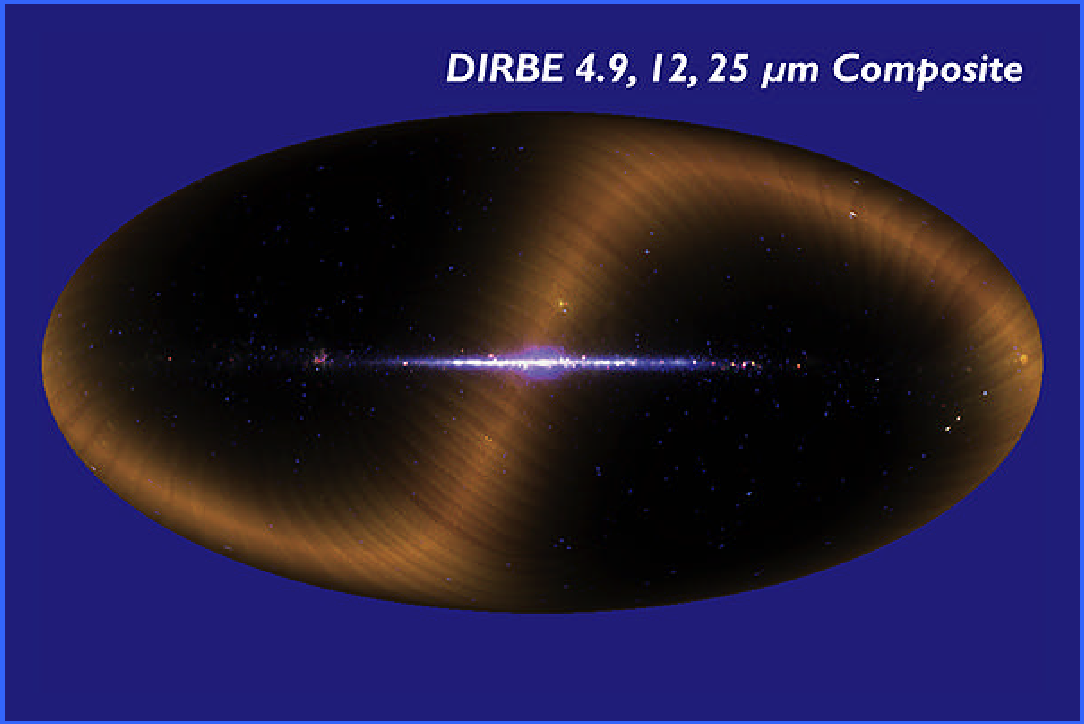
1.25, 2.2, 3.5 μm composite image of Galactic center region. Shows asymmetric shape of the bulge at the center of the Milky Way. The image is a Mollweide projection covering 60 degrees in Galactic longitude by 20 degrees in Galactic latitude and centered on the Galactic center.

COBE Slide 12



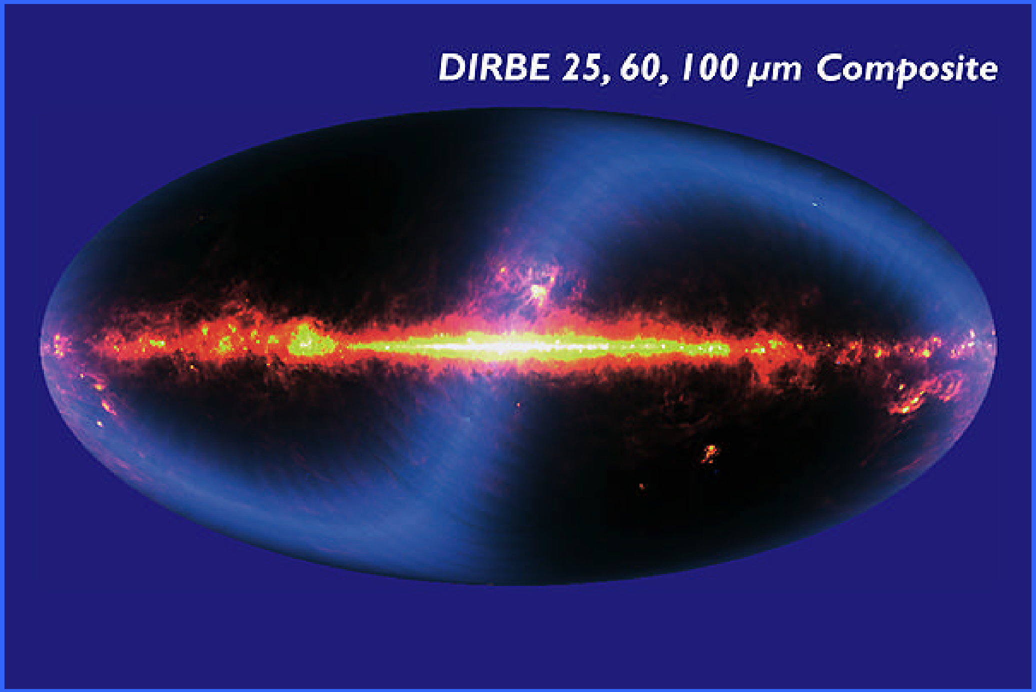
4.9, 12, 25, and 60 μm Solar elongation angle = 90 degree Maps. Thermal emission from star-heated dust in the Milky Way and interplanetary dust heated by the Sun dominates the images at these wavelengths. The S-shaped feature is the ecliptic plane, in which, like the planets, the interplanetary dust is concentrated. The oval-shaped brightness discontinuity is an artefact of the way the maps were prepared, not a feature in the infrared sky. The discontinuity corresponds to a path difference through the interplanetary dust cloud as adjacent positions in the sky were observed from DIRBE's vantage point in Earth orbit with the Earth on opposite sides of the Sun.

COBE Slide 13



This image combines data from the DIRBE obtained at infrared wavelengths of 4.9, 12 and 25 μm. The sky brightness at these wavelengths is represented respectively by blue, green, and red colors in the image. The plane of the Milky Way Galaxy lies horizontally across the middle of the image with the Galactic center at the center. Emission from interplanetary dust in our solar system is very prominent, as shown by the orange "S-shaped" curve which follows the ecliptic plane. The thin lines forming bands within the curve show the structure of streaming dust grains the result of colliding asteroids. At these wavelengths, the broad plane of the Milky Way, which appears as blue and pink, reveals stars and interstellar cool dust in the disk of the Milky Way. To make the contributions from the Solar System as uniform as possible, the images are made from observations when the Sun angle (solar elongation) was 90 degrees from the viewing direction. DIRBE is the first space instrument designed to make a comprehensive sky survey in the search for an ancient fossil known as the cosmic infrared background (CIB) radiation - the remnant from the formation of the earliest objects in the Universe created 5 to 12 billion years ago. Extensive modeling is required to isolate the CIB from the infrared foregrounds from the Solar System and Galaxy.

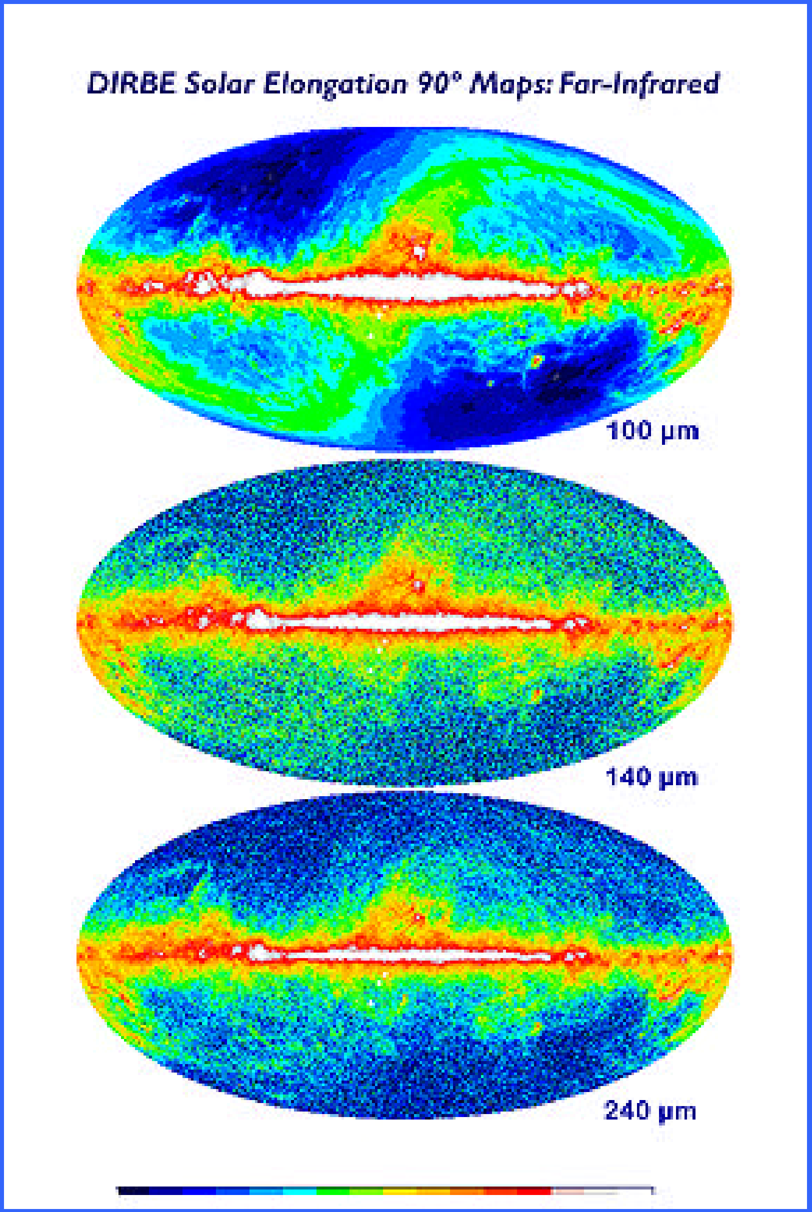
COBE Slide 14



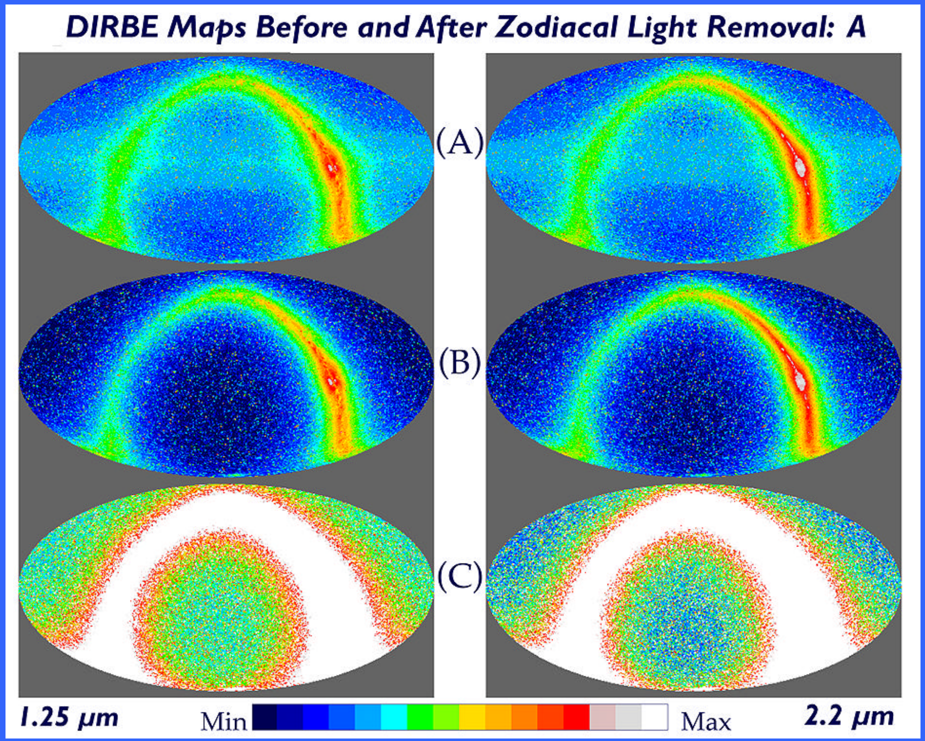
This image combines data from the DIRBE obtained at infrared wavelengths of 25, 60 and 100 μm. The sky brightness atthese wavelengths is represented respectively by blue, green, and red colors in the image. The plane of the Milky Way Galaxy lies horizontally across the middle of the image with the Galactic center at the center. The image is dominated by the thermal emission from interstellar dust in the Milky Way. The wispy-looking dust features are called "infrared cirrus." The structured, warmer emission from interplanetary dust, shown in blue, is also prominent. The image shows a number of well-known dusty regions in the Milky Way, such as the Orion molecular clouds (below the plane, far right) which are active "stellar nurseries" in our Galaxy. Two neighboring galaxies, the Large and Small Magellanic Clouds also can be distinguished (below the plane, approximately halfway between the center and right edge of the image).

COBE Slide 15

100, 140, and 240 μm Solar elongation angle = 90 degree Maps. Thermal emission from relatively cool interstellar dust warmed by stars in the Milky Way dominates at these wavelengths. At high Galactic latitudes, interstellar "cirrus" clouds are apparent. Emission from the solar system dust ("zodiacal emission") is strongest at 25 μm but remains in evidence in the 100 μm image, and to a lesser degree at the longer wavelengths.

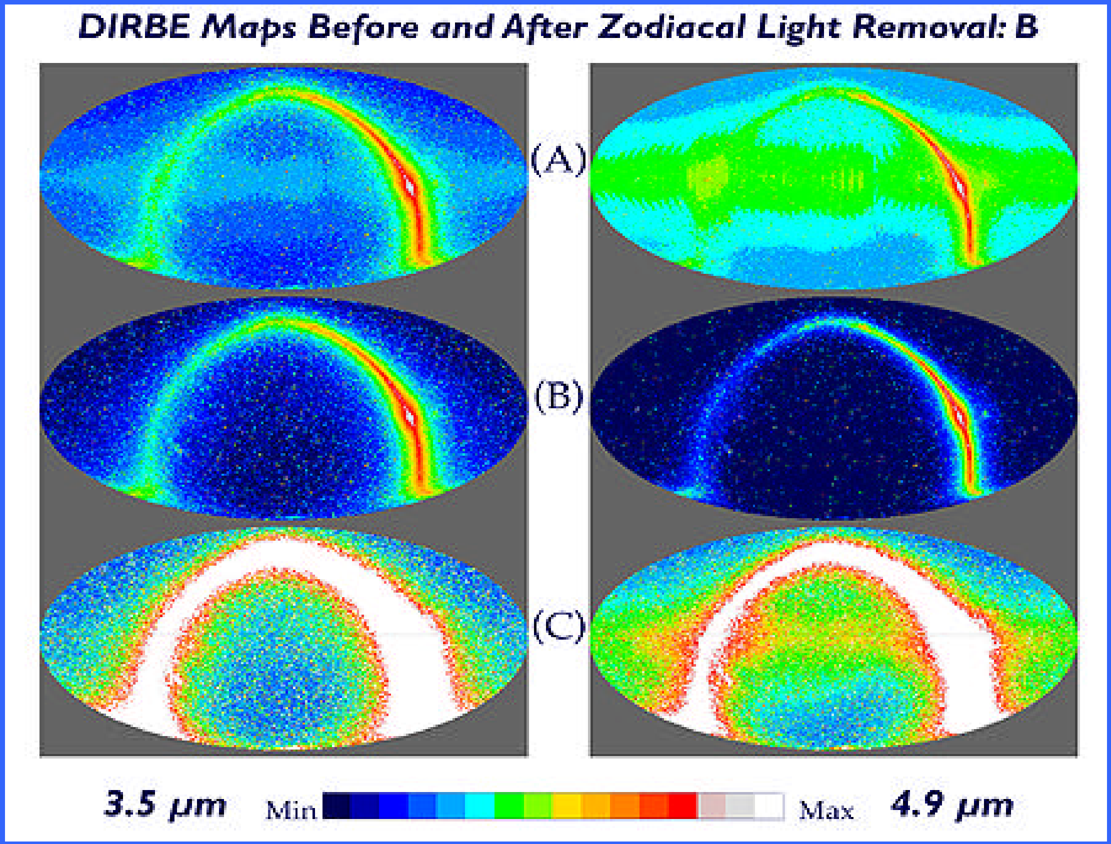


COBE Slide 16



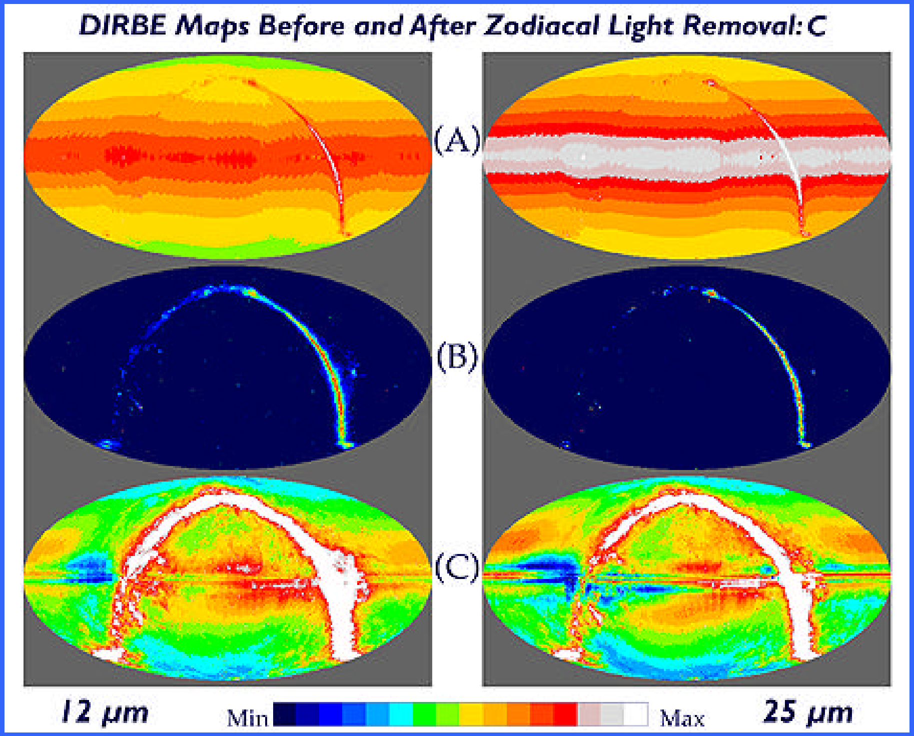
DIRBE 1.25 and 2.2 μm maps of the sky as observed (top) and following subtraction of a detailed model of the zodiacal light (middle and bottom), which at these wavelengths is Sunlight scattered by interplanetary dust grains. The maps are Mollweide projections in geocentric ecliptic coordinates. In this projection, the Galactic plane is seen as a bright arc across the sky, and the zodiacal light is concentrated in a horizontal band which runs through the middle of the map. At each wavelength, the top and middle maps are shown on the same brightness scale; the maps on the bottom are shown at a narrower brightness range in order to accentuate imperfections in the zodiacal light model. These imperfections are most evident at mid-infrared wavelengths where the interplanetary dust signal is strongest (12, 25, 60 μm). Such defects notwithstanding, all of the emission seen in the middle and bottom maps is either Galactic (stars in the Milky Way) or extragalactic in origin. The main scientific goal of the DIRBE is to measure the brightness of the extragalactic component of this residual emission, which is presumed to be isotropic (i.e., uniform over the sky). The DIRBE zodiacal light model is described by Kelsall et al. 1998,ApJ, in press.

Cobe Slide 17



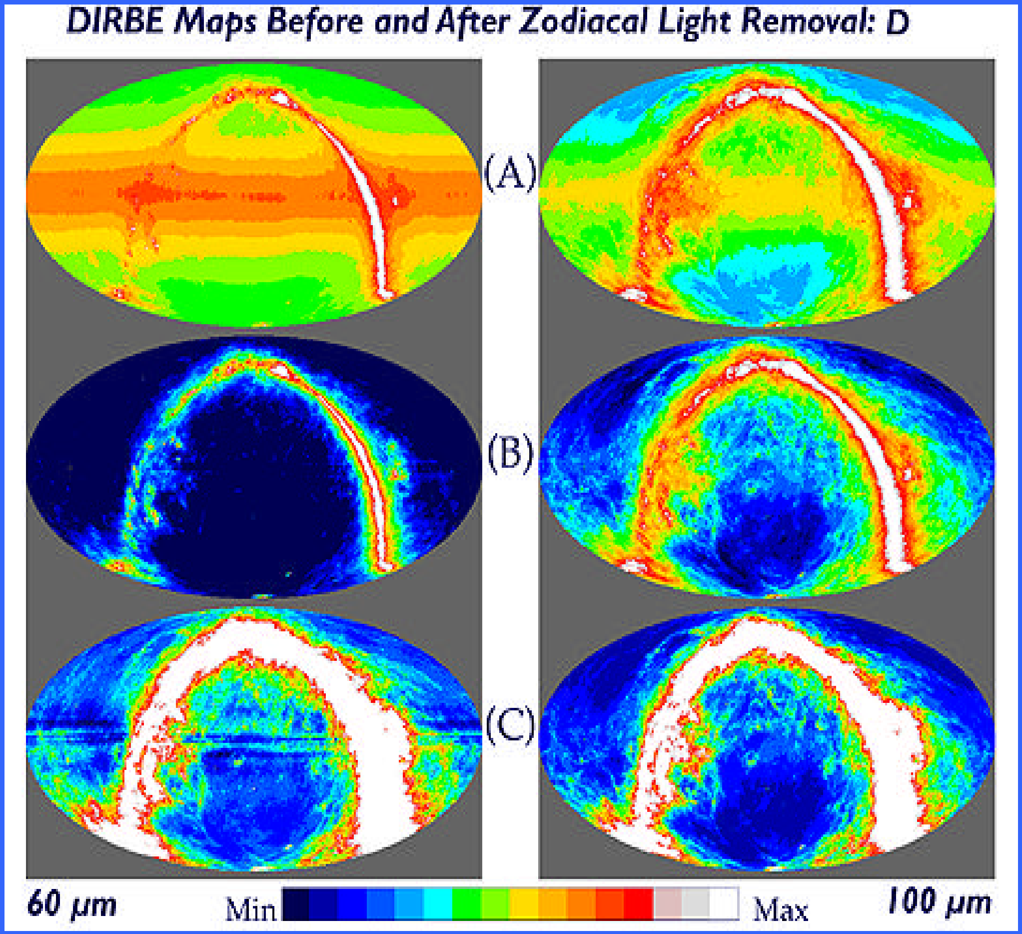
DIRBE 3.5 and 4.9 μm maps of the sky as observed (top) and following subtraction of a detailed model of the zodiacal light (middle and bottom). At these wavelengths, "zodiacal light" includes both thermal emission from and Sunlight scattered by interplanetary dust grains (see Kelsall et al. 1998, ApJ, in press). The Slide 16 caption above contains information about the map projection and brightness scales. The residual emission at 3.5 and 4.9 μm (middle and bottom maps) comes predominantly from stars in the Milky Way. Imperfections in the zodiacal light model are evident in the 4.9 μm map on the bottom, where the brightness scale was compressed in order to emphasize low-brightness features.

COBE Slide 18



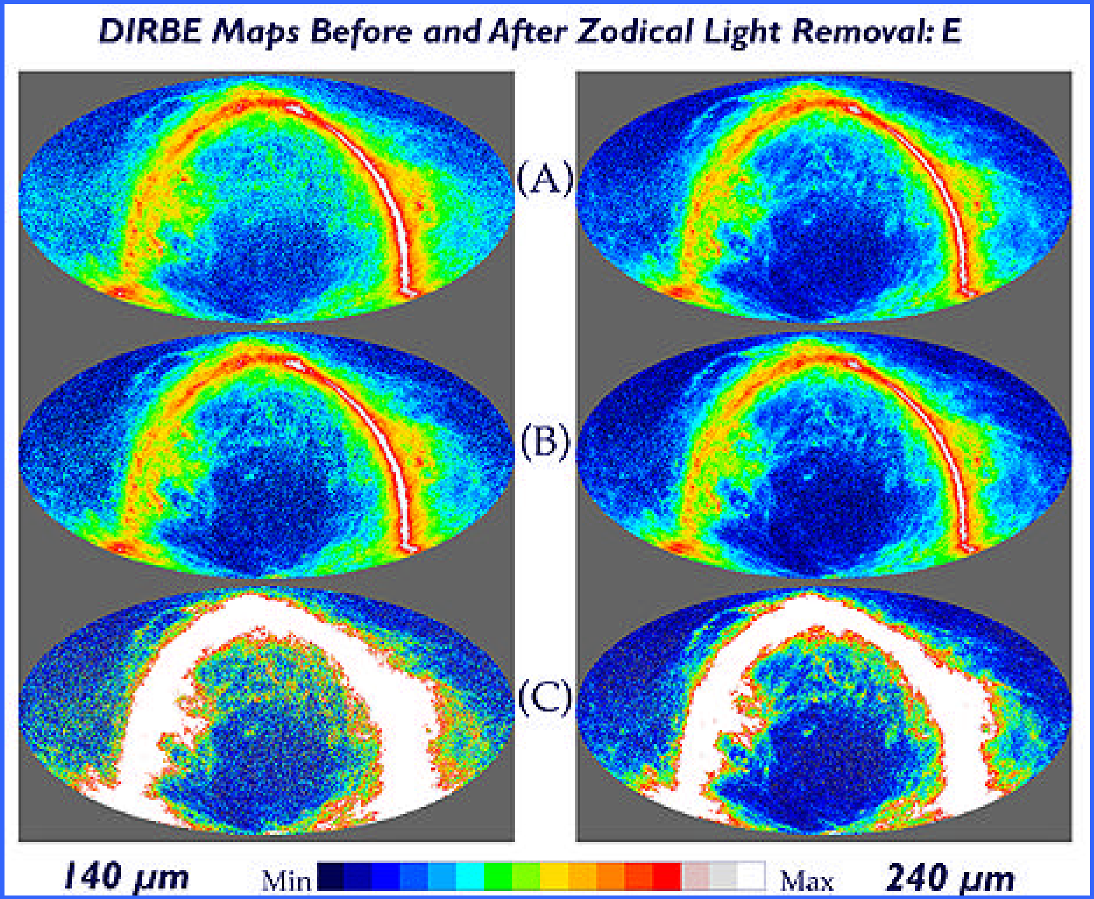
DIRBE 12 and 25 μm maps of the sky as observed (top) and following subtraction of a detailed model of the zodiacal light (middle and bottom), which at these wavelengths is thermal emission from interplanetary dust grains heated by absorbed Sunlight (see Kelsall et al.1998, ApJ, in press). The Slide 16 caption above contains information about the map projection and brightness scales. The residual emission at 12 and 25 μm (middle and bottom maps) comes predominantly from interstellar dust in the Milky Way which, like the interplanetary dust, absorbs starlight and gives off thermal emission. The emission from interstellar dust is strongest at longer infrared wavelengths (> 60 μm) than the interplanetary dust emission (peak emission at about 25 μm) because typical interplanetary grains are warmer than their interstellar counterparts. This is because interplanetary grains are relatively close to the Sun compared to the distance between the average interstellar grains and the nearest stars. Imperfections in the zodiacal light model are evident in both of the bottom maps, where the brightness scale was compressed in order to emphasize low-brightness features.

COBE Slide 19



DIRBE 60 and 100 μm maps of the sky as observed (top) and following subtraction of a detailed model of the zodiacal light (middle and bottom), which at these wavelengths is thermal emission from interplanetary dust grains heated by absorbed Sunlight (see Kelsall et al. 1998, ApJ, in press). The Slide 16 caption above contains information about the map projection and brightness scales, and the Slide 18 caption describes some of the relevant astrophysics. Galactic interstellar dust emission is quite strong at these wavelengths, while zodiacal emission is relatively weak, as can be seen in the maps on the top. Imperfections in the zodiacal light model are evident at 60 μm but markedly less apparent at 100 μm, as can be seen in the maps on the bottom.

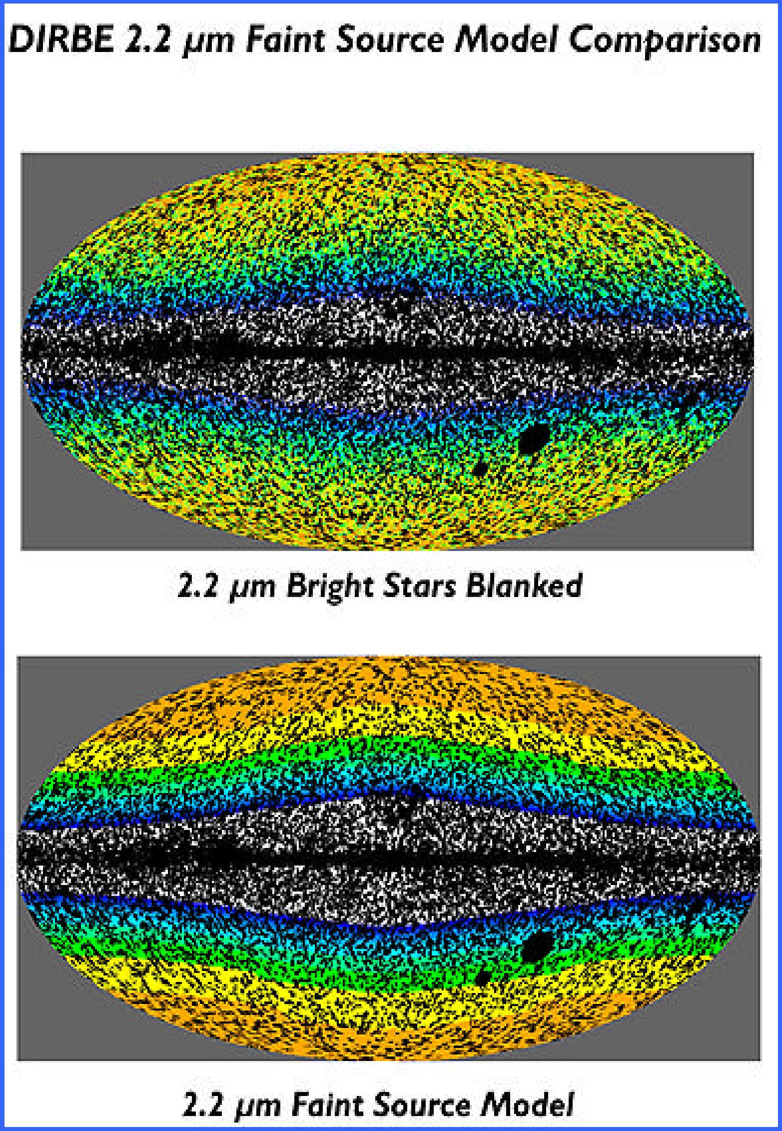
COBE Slide 20



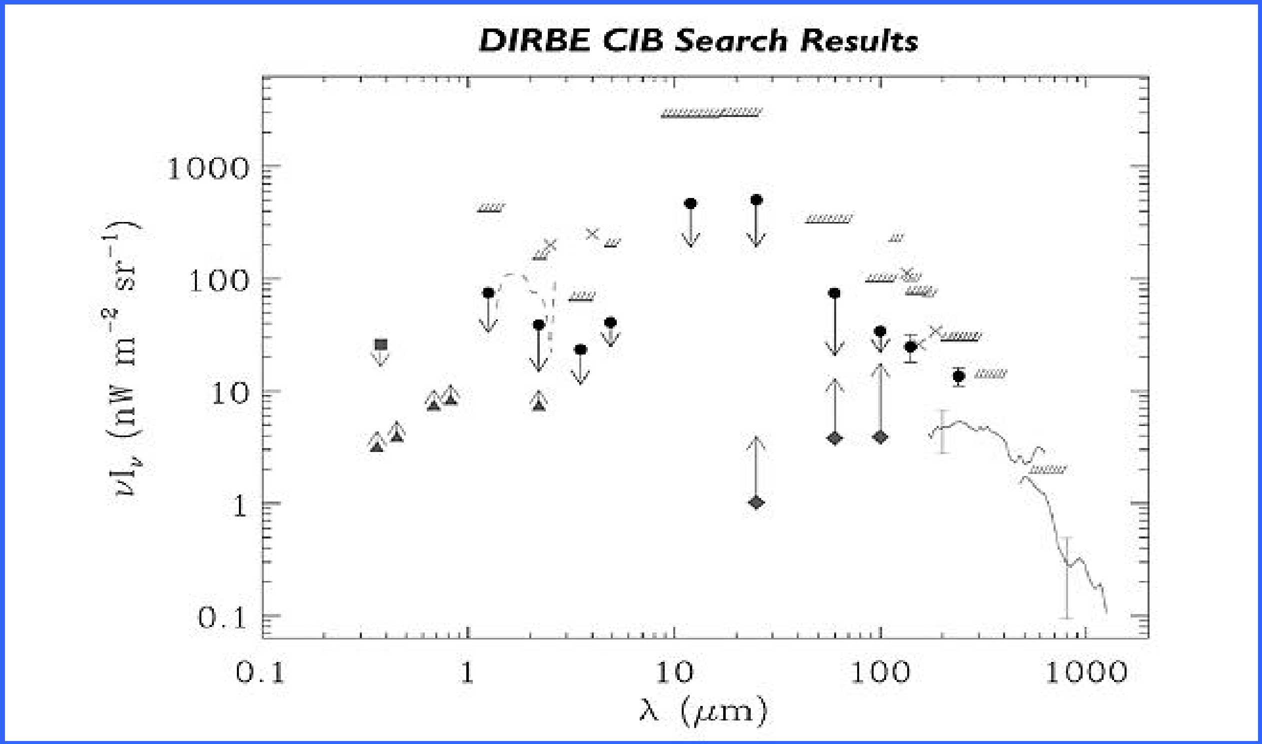
DIRBE 140 and 240 μm maps of the sky as observed (top) and following subtraction of a detailed model of the zodiacal light (middle and bottom; see Kelsall et al. 1998, ApJ, in press). The Slide 16 caption above contains information about the map projection and brightness scales, and the Slide 18 caption describes some of the relevant astrophysics. Galactic interstellar dust emission is much stronger at these wavelengths than zodiacal emission, as can be seen in the maps on the top.Even on a stretched brightness scale (bottom maps), imperfections in the zodiacal light model are not apparent. Detector noise from the DIRBE instrument is significant at these wavelengths and gives rise to the speckled appearance of the maps.

COBE Slide 21

At near-infrared wavelengths, following the subtraction of zodiacal light (see Slide 16), map pixels containing discrete bright sources are masked and the DIRBE Faint Source Model is used to subtract residual Galactic starlight in order to detect or place an upper limit on the brightness of the cosmic infrared (extragalactic) background emission (Arendt et al. 1998, ApJ, in press). Here the upper map shows the residual sky brightness at 2.2 μm after zodiacal light subtraction and bright source masking (dark spots in maps). In this projection, the Galactic plane runs horizontally through the map. Ideally, if the zodiacal model were perfect, only the collective emissions of (faint) stars in the Milky Way and the sought-after extragalactic light (cosmic infrared background) would remain in this map. The lower map shows the DIRBE Faint Source Model. To facilitate comparison, both maps are shown on the same brightness scale and with the same pixels masked. Clearly, most of the residual 2.2 μm emission in the upper map is attributable to stars in the Milky Way.



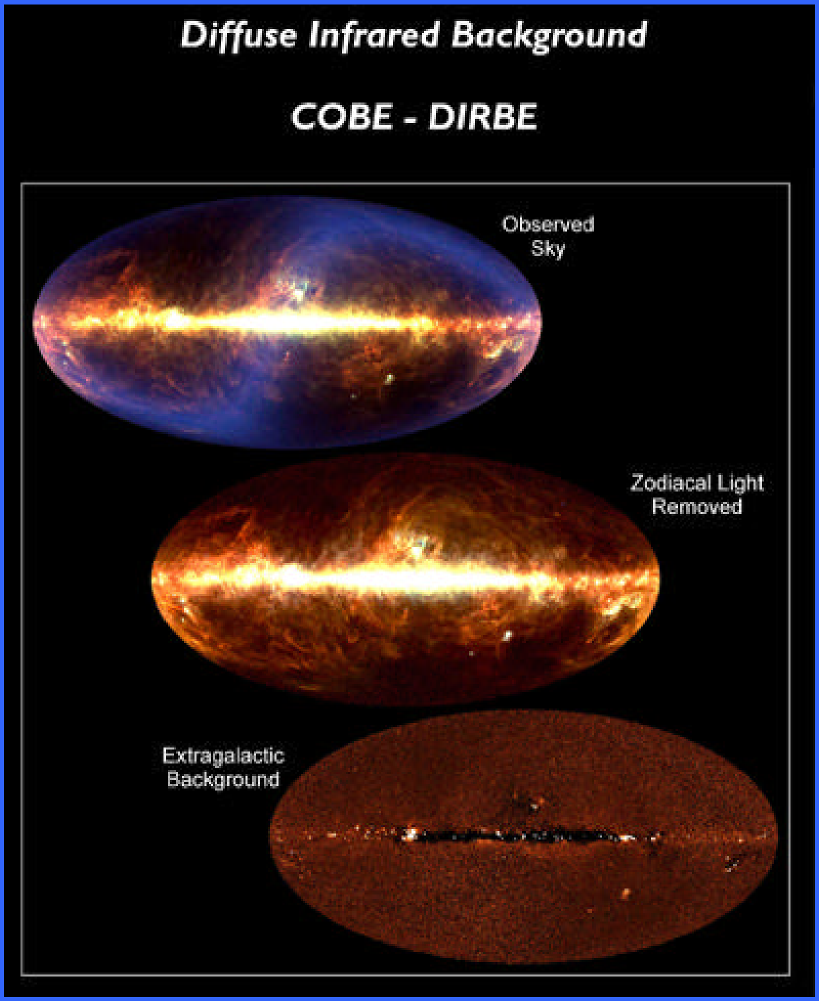
COBE Slide 22



Results of the DIRBE search for the Cosmic Infrared Background (CIB) after removal of foreground emissions from the solar system and the Milky Way (see Hauser et al. 1998, ApJ, in press). The two black circles with error bars represent DIRBE detections of the CIB at 140 and 240 μm. (These detections were the subject of a press release.) Circles with downward-pointing arrows represent DIRBE 2 [Image] upper limits at 1.25 - 100 μm; the tips of the arrows indicate the measured residual values after foreground subtraction. Prior to subtracting the foreground emissions, DIRBE observations of the darkest regions in the sky in each wavelength band were interpreted as conservative upper limits on the CIB brightness (hatched horizontal lines). The other symbols represent limits or tentative detections of the CIB from non-DIRBE data sources.

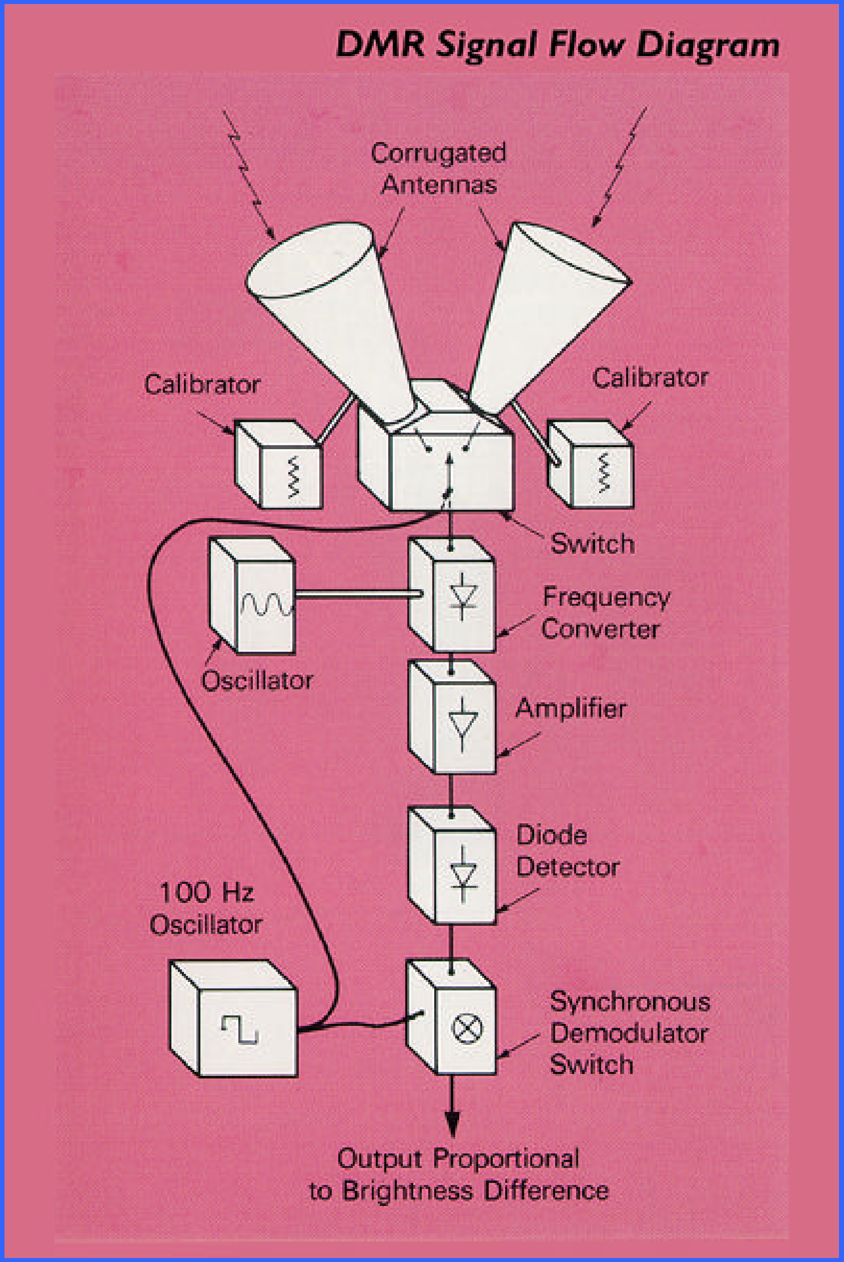
COBE Slide 23

An illustration of the foreground emission subtraction process resulting in the DIRBE detection of the Cosmic Infrared Background at 240 μm. The map at the top is a false-color image showing the observed infrared sky brightness at wavelengths of 60 (blue), 100 (green) and 240 μm (red). The bright white-yellow horizontal band across the middle of the image corresponds to emission from interstellar dust in the plane of our Milky Way Galaxy (the center of the Galaxy lies at the center of the map). The red regions above and below this bright band are "infrared cirrus" clouds, wispy clouds of relatively cool Galactic dust. The blue S-shaped figure follows the ecliptic plane and represents emission from interplanetary dust in the solar system. The map in the middle is a 60-100-240 μm false-color image depicting the sky after the foreground glow of the interplanetary dust has been modeled and subtracted; this image is dominated by emission from interstellar dust in the Milky Way. After the infrared light from our solar system and Galaxy has been removed, what remains is a uniform Cosmic Infrared Background. This is illustrated in the bottom image, which shows just the residual 240 μm brightness. The line across the center is an artifact from removal of the Galactic light. The DIRBE team reports detection of this cosmic background light also at 140 μm, and has set limits to its brightness at eight other infrared wavelengths from 1.25 to 100 μm (see Slide 22). Credit: STScI OPO - PRC98-01; M. Hauser and NASA.

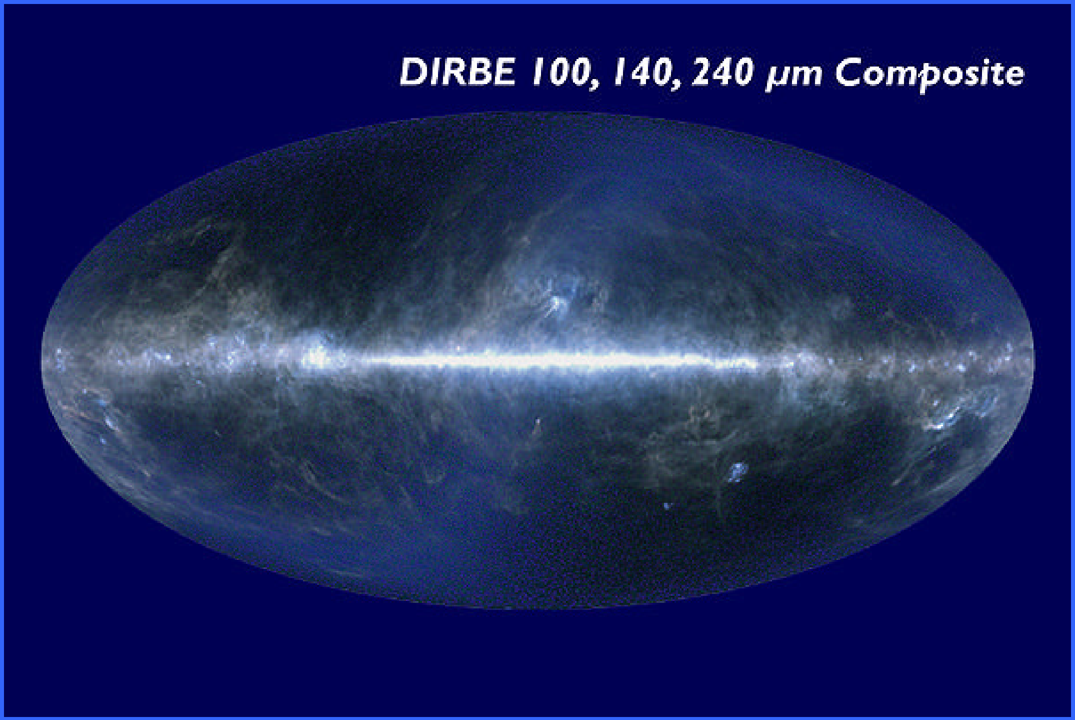


COBE Slide 25

Signal flow in the DMR instrument, which was designed to detect and enable the characterization of temperature differences ("anisotropy") in the cosmic microwave background radiation. The DMR design is similar to that used in instruments flown on balloons and aircraft. The receiver input is connected alternately to two separate antennas that point at different parts of the sky. If the two parts of the sky are not equally bright, the detected signal will change slightly when the switch is moved from one antenna to the other. The entire apparatus is rotated to show that the difference comes from the sky and not from differences in the two antennas. The DMR instrument has three separate receiver boxes, one for each wavelength (3.3, 5.7 and 9.6 millimeters). Each box has two separate andindependent receivers tuned to the same frequency, to improve the sensitivity of the measurement and to protect against a failure. The antennas in a pair are pointed 60 degrees apart and 30 degrees away from the spin axis of the COBE spacecraft. Each antenna receives microwave light from a 7 degree diameter beam. The Microwave Anisotropy Probe (MAP), a new NASA mission, will measure the cosmic microwave background anisotropy at ten times higher spatial resolution.

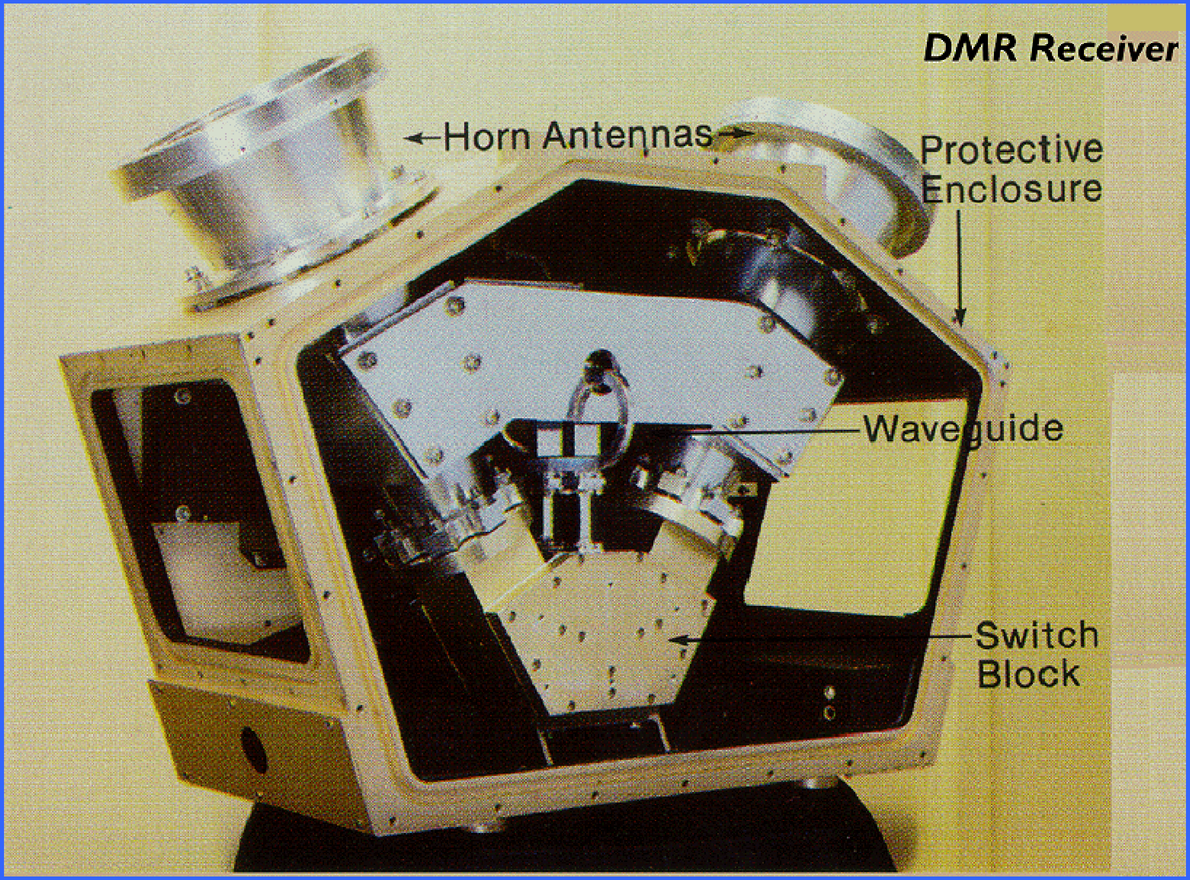


COBE Slide 24



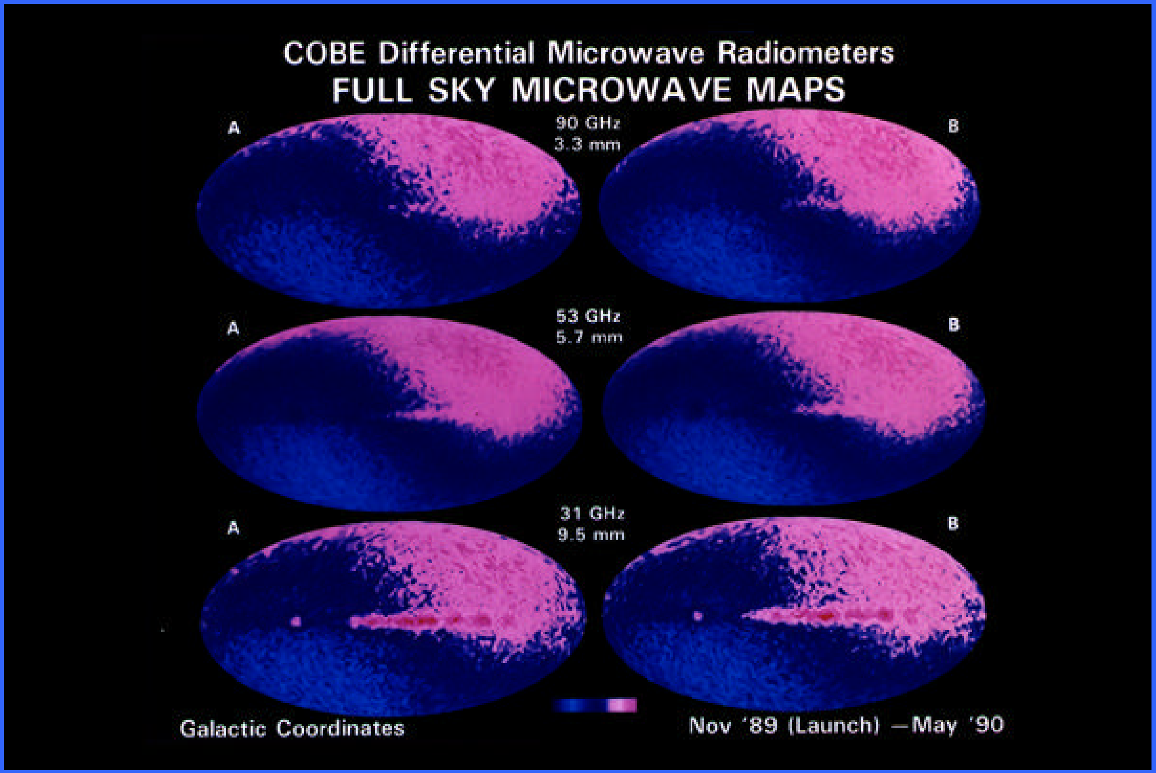
This image combines data from the DIRBE obtained at infrared wavelengths of 100, 140 and 240 μm - the longest wavelengths measured by this instrument. The sky brightness at these wavelengths is represented respectively by blue, green, and red colors in the image. This image shows where there is more material (appears brighter) and where this material is coldest (appears redder). The plane of the Milky Way Galaxy lies horizontally across the middle of the image with the Galactic center at the center. Most of the infrared radiation seen in this image originates from cold dust (approximately 20 K, or 20 degrees Centigrade above absolute zero) located in clouds of gas and dust between the stars in the Milky Way Galaxy. The wispy-looking dust features are called "infrared cirrus." The region of the Orion Nebula with active star formation approximately 1,500 light years distance from the Sun appears on the right of the image below the plane of the Milky Way. Neighboring galaxies, the Large and Small Magellanic Clouds, appear as faint "blobs" below and slightly to the right of the Galactic center. Much of the picture appears to be the same color, indicating that there is not a large variation in the dust temperature. Because the brightness of the Solar System and Galaxy tends to decrease with increasing wavelength, these long wavelength DIRBE measurements are particularly valuable for searching for the cosmic infrared background.

COBE Slide 26



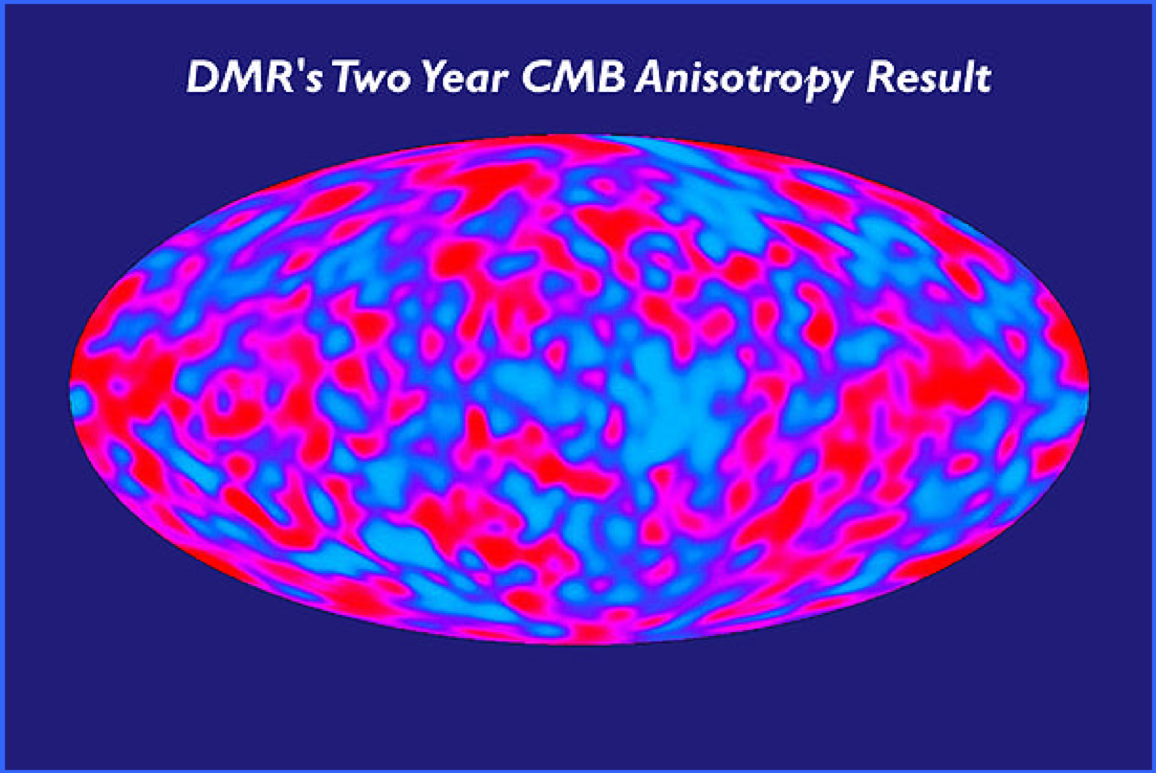
The 9.6 mm DMR receiver partially assembled

COBE Slide 27



Early DMR sky maps depicting data obtained from the independent ("A" and "B") channels at each of the three observed microwave wavelengths: 3.3, 5.7 and 9.6 mm (corresponding frequencies are 90, 53 and 31.5 GHz, or thousand MHz, respectively). Like the maps depicted in slides 20 - 23, these maps were smoothed with a 7 degree beam, yielding an effective angular resolution of 10 degrees. Each map is an all-sky Mollweide projection in Galactic coordinates. The plane of the Milky Way Galaxy is horizontal across the middle of each map. The asymmetry, or "dipole," that dominates the appearance of these maps is a smooth variation between a relatively warm (bright) area in the upper right to a relatively cool (faint) area in the lower left. The dipole asymmetry is due to the motion of the solar system relative to distant matter in the Universe. Although the signal attributed to this variation is very weak - only one thousandth the brightness of the sky - it is about a hundred times stronger than the cosmic microwave background anisotropy which the DMR was designed to detect and so must be subtracted before the anisotropy can be seen.

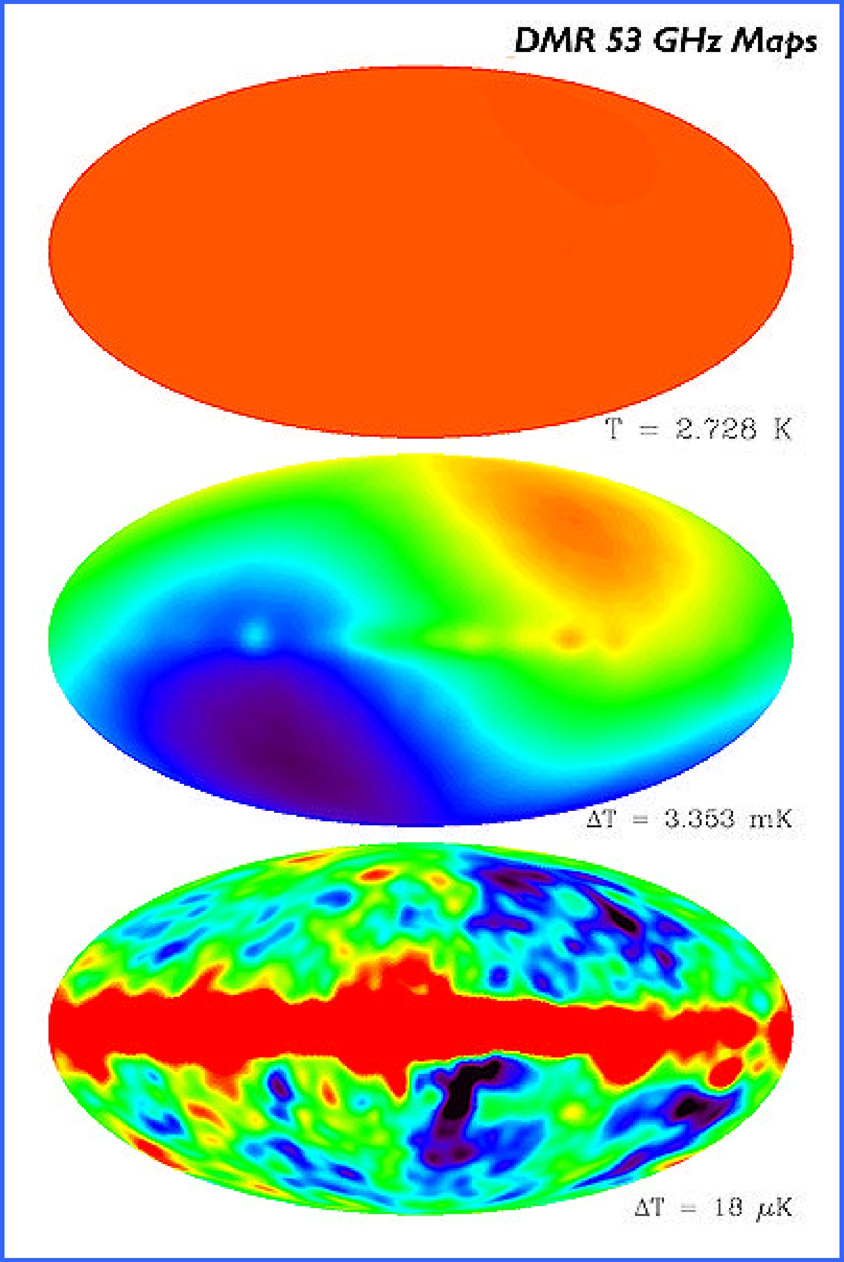
COBE Slide 28



Following subtraction of the dipole anisotropy and components of the detected emission arising from dust (thermal emission), hot gas (free-free emission), and charged particles interacting with magnetic fields (synchrotron emission) in the Milky Way Galaxy, the cosmic microwave background (CMB) anisotropy can be seen. CMB anisotropy tiny fluctuations in the sky brightness at a level of a part in one hundred thousand was first detected by the COBE DMR instrument. The CMB radiation is a remnant of the Big Bang, and the fluctuations are the imprint of density contrast in the early Universe (see slide 24 caption). This image represents the anisotropy detected in data collected during the first two years of DMR operation. Ultimately the DMR was operated for four years. See slide 19 caption for information about map smoothing and projection.

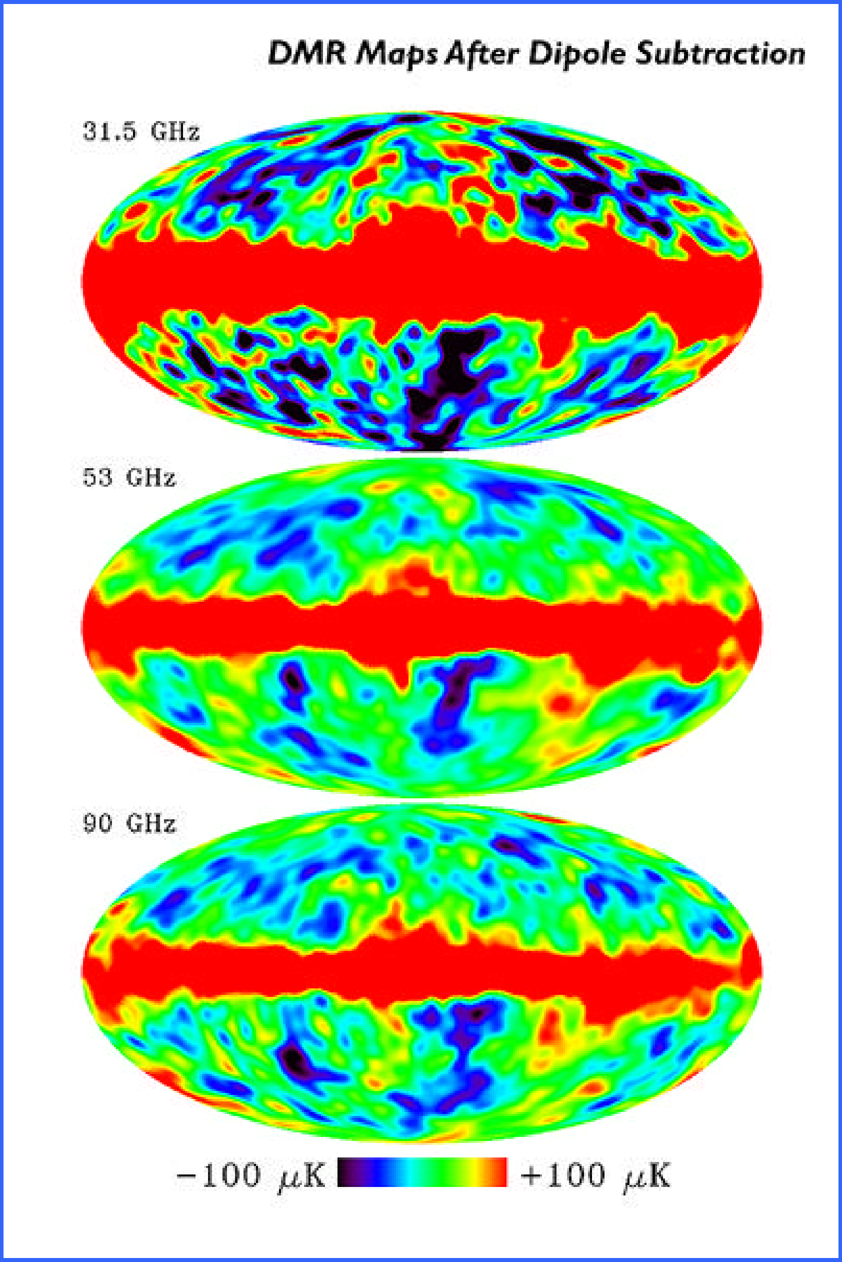
COBE Slide 29

Maps based on 53 GHz (5.7 mm wavelength) observations made with the DMR over the entire 4 year mission (top) on a scale from 0 - 4 K, showing the near-uniformity of the CMB brightness, (middle) on a scale intended to enhance the contrast due to the dipole described in the slide 19 caption, and (bottom) following subtraction of the dipole component. Emission from the Milky Way Galaxy is evident in the bottom image. See slide 19 caption for information about map smoothing and projection.



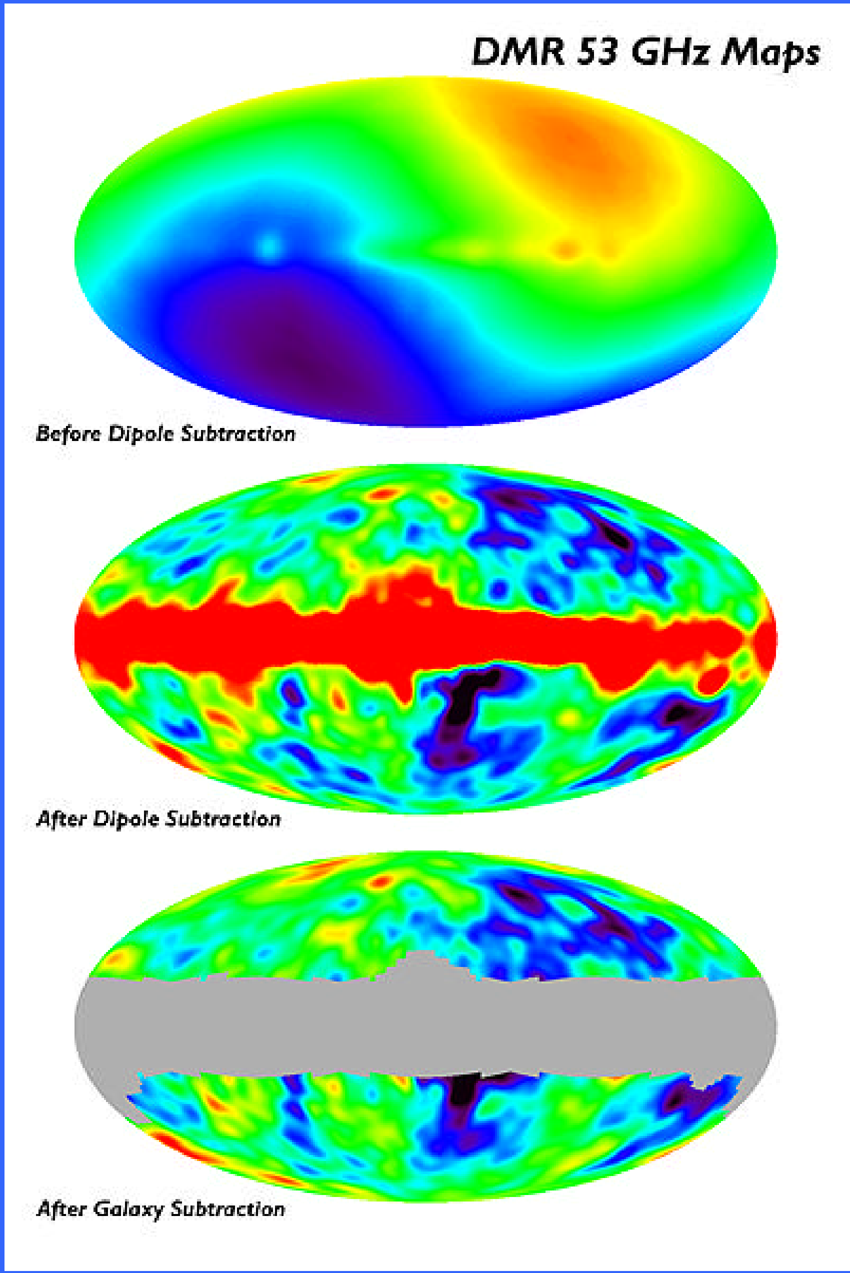
COBE Slide 30

Maps based on observations made with the DMR over the entire 4-year mission, at each of the three measured frequencies, following dipole subtraction. See slide 19 caption for information about map smoothing and projection.

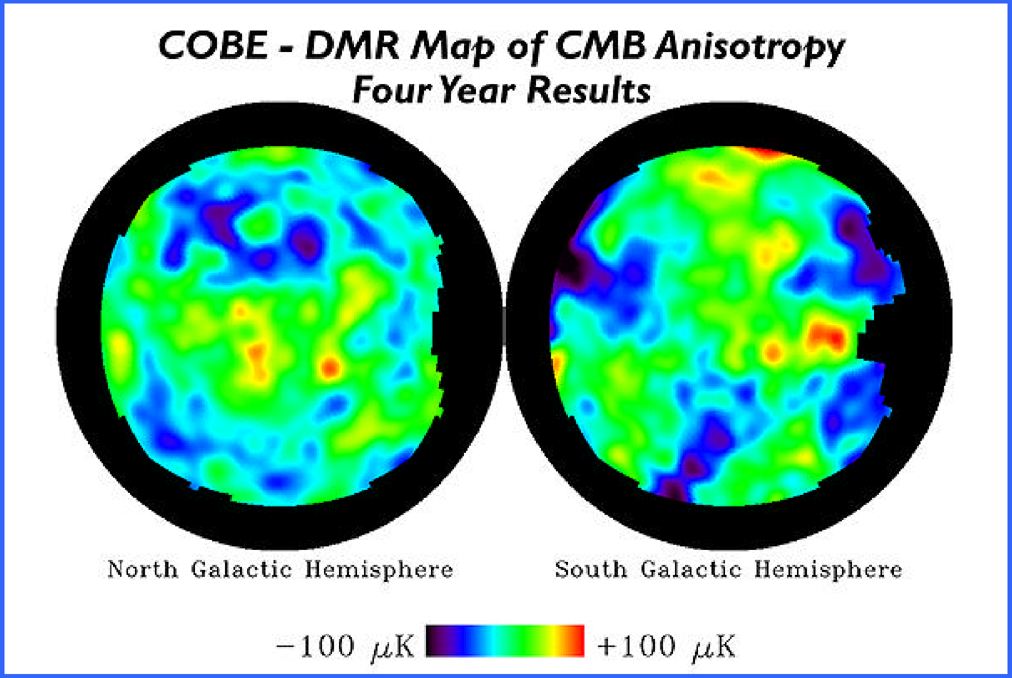


COBE Slide 31

The 53 GHz DMR sky map (top) prior to dipole subtraction, (middle) after dipole subtraction, and (bottom) after subtraction of a model of the Galactic emission, based on data gathered over the entire 4year mission. The Galactic emission model is based on DIRBE far-infrared and Haslam et al. (1982) 408 MHz radio continuum observations (see Bennett et al. 1996, ApJ, 464, L1). Bennett et al. excluded an area around the Galactic plane referred to as the "custom cut" region when they conducted their analysis. See slide 19 caption for information about map smoothing and projection.

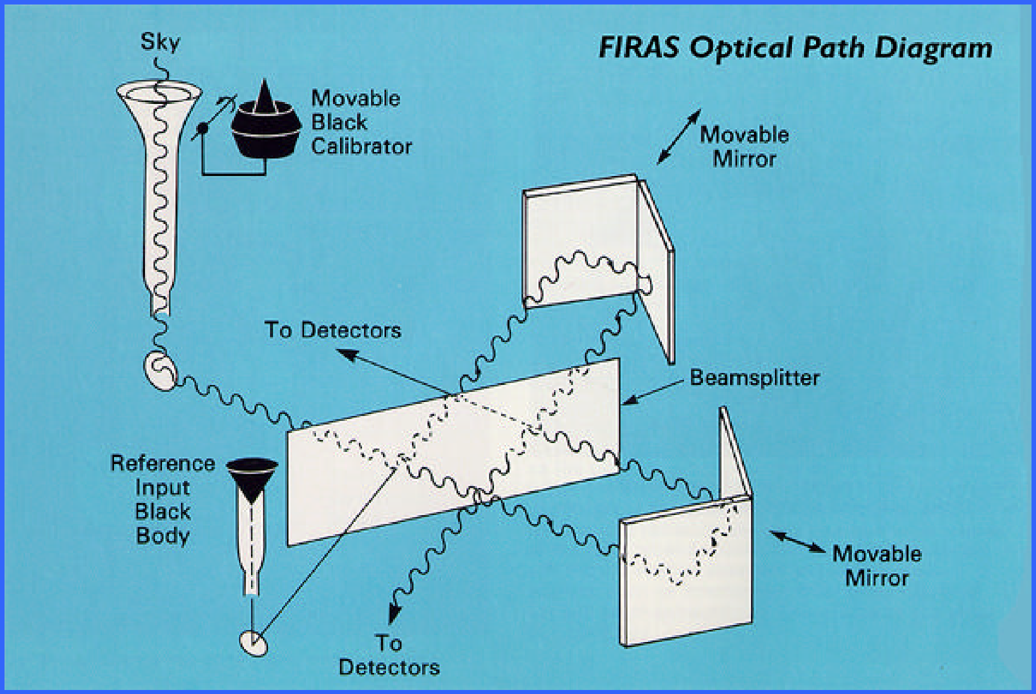


COBE Slide 32



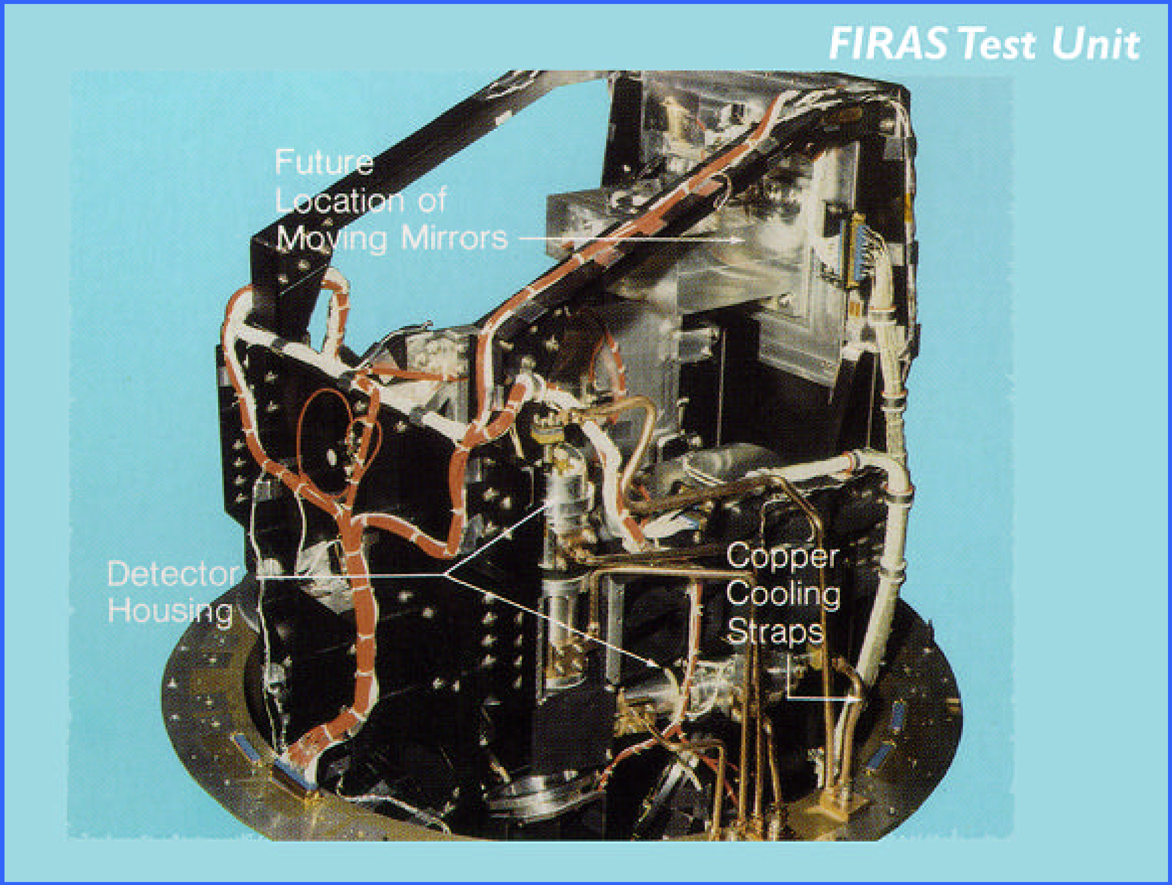
DMR "Map of the Early Universe." This false-color image shows tiny variations in the intensity of the cosmic microwave background measured in four years of observations by the Differential Microwave Radiometers on NASA's Cosmic Background Explorer (COBE). The cosmic microwave background is widely believed to be a remnant of the Big Bang; the blue and red spots correspond to regions of greater or lesser density in the early Universe. These "fossilized" relics record the distribution of matter and energy in the early Universe before the matter became organized into stars and galaxies. While the initial discovery of variations in the intensity of the CMB (made by COBE in 1992) was based on a mathematical examination of the data, this picture of the sky from the full four-year mission gives an accurate visual impression of the data. The features traced in this map stretch across the visible Universe: the largest features seen by optical telescopes, such as the "Great Wall" of galaxies, would fit neatly within the smallest feature in this map. (See Bennett et al. 1996, ApJ, 464, L1 and references therein for details.)

COBE Slide 33



Concept of FIRAS, showing light from the sky being focused through cone and sent to interferometer. The FIRAS instrument was designed to measure precisely the spectrum of the cosmic microwave background radiation over a wavelength range from 0.1 to 10 mm. The instrument measures the wavelength of the incoming radiation by using the phenomenon of wave interference. A Michelson interferometer is used to break the wave into two equal parts, to delay one part, and then to recombine them. The waves recombine perfectly (constructive interference) if the delay is a whole number of wavelengths, but cancel perfectly (destructive interference) if the delay is an odd number of half wavelengths. The wavelength can be measured by varying the delay and noticing where the interference is constructive and destructive. As the delay is changed, the varying intensity at each detector is called the interferogram. The interferogram contains the information needed to determine the intensity of the incoming light at a large number of wavelengths (i.e., a spectrum) simultaneously. This method provides an enormous advantage in sensitivity over more direct methods. The FIRAS uses a trumpet-shaped cone to collect light from the sky and funnel it into the instrument while rejecting light that arrives from unwanted directions. The field of view is 7 degrees, like the DMR, so a spectrum can be obtained at about 1000 independent parts of the sky. The accuracy of the FIRAS is achieved by a large blackbody calibrator which can be inserted by command into the mouth of the cone. (A blackbody is an object that absorbs all radiation that falls on it and radiates heat and light with an intensity that can be computed precisely if its temperature is known. For a related tutorial, see "About Temperature" by Dr. Beverly Lynds.) The temperature of the calibrator can be controlled to within 0.001 K. The detectors are thermometers which can easily detect temperature changes caused by changes of only a hundred trillionth of a watt in the incident power.

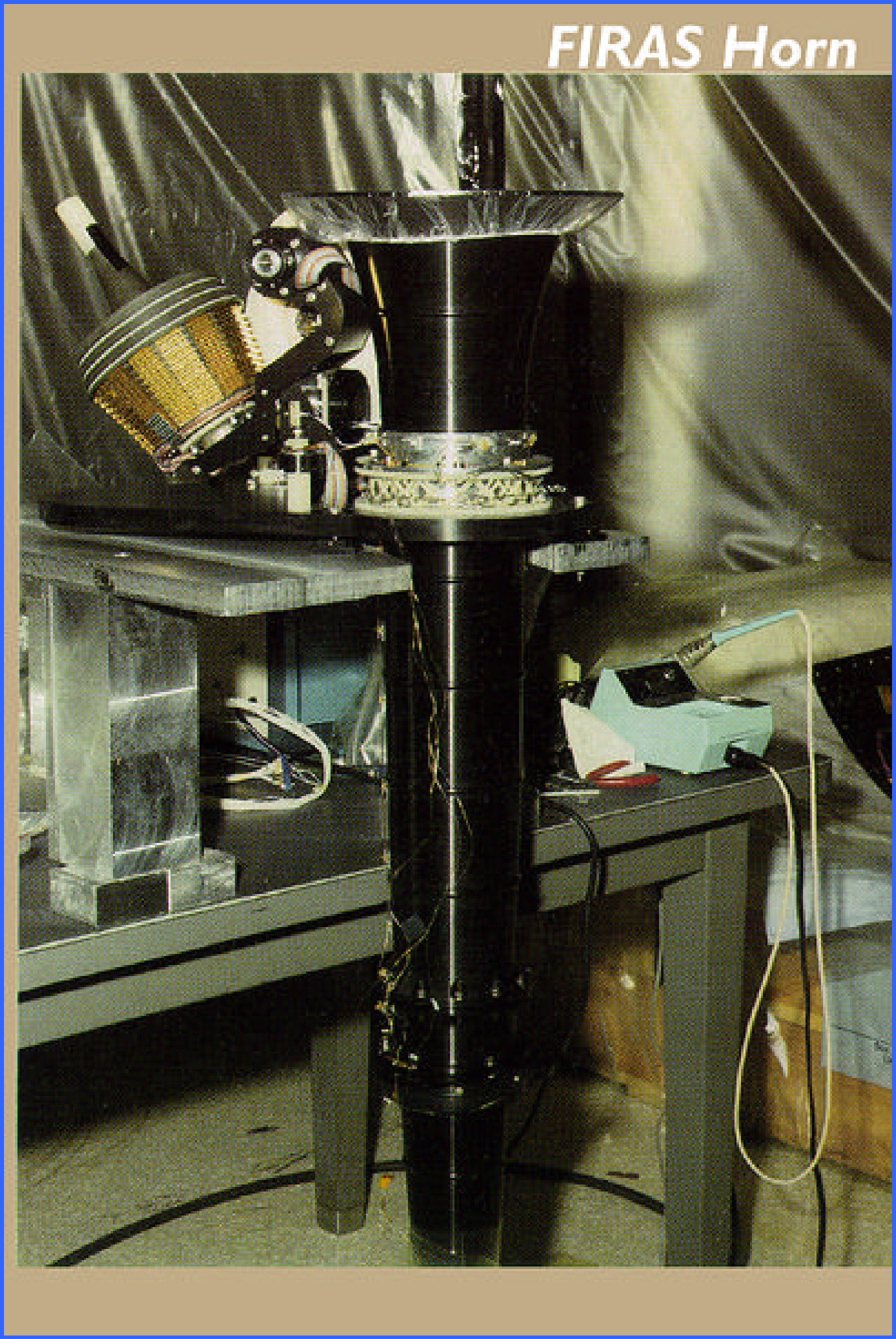
COBE Slide 34



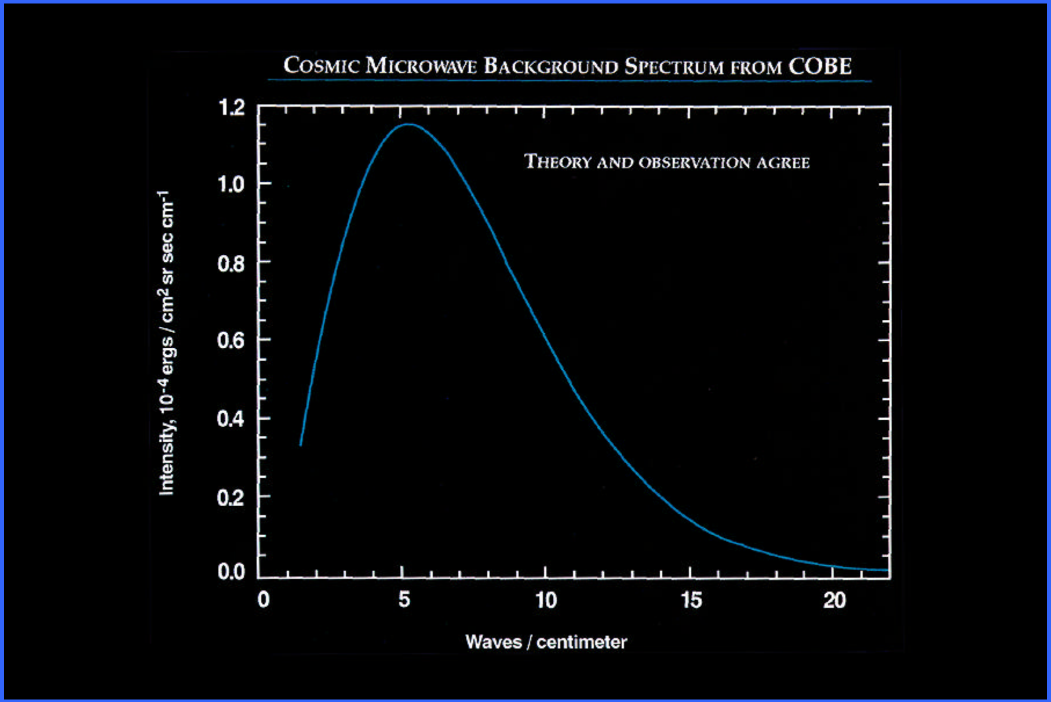
FIRAS test unit being prepared for vibration test. Horn, calibrator, and mirror mechanism are not shown.

COBE Slide 35

FIRAS horn antenna with movable calibrator. Protective plastic covers were removed before launch.

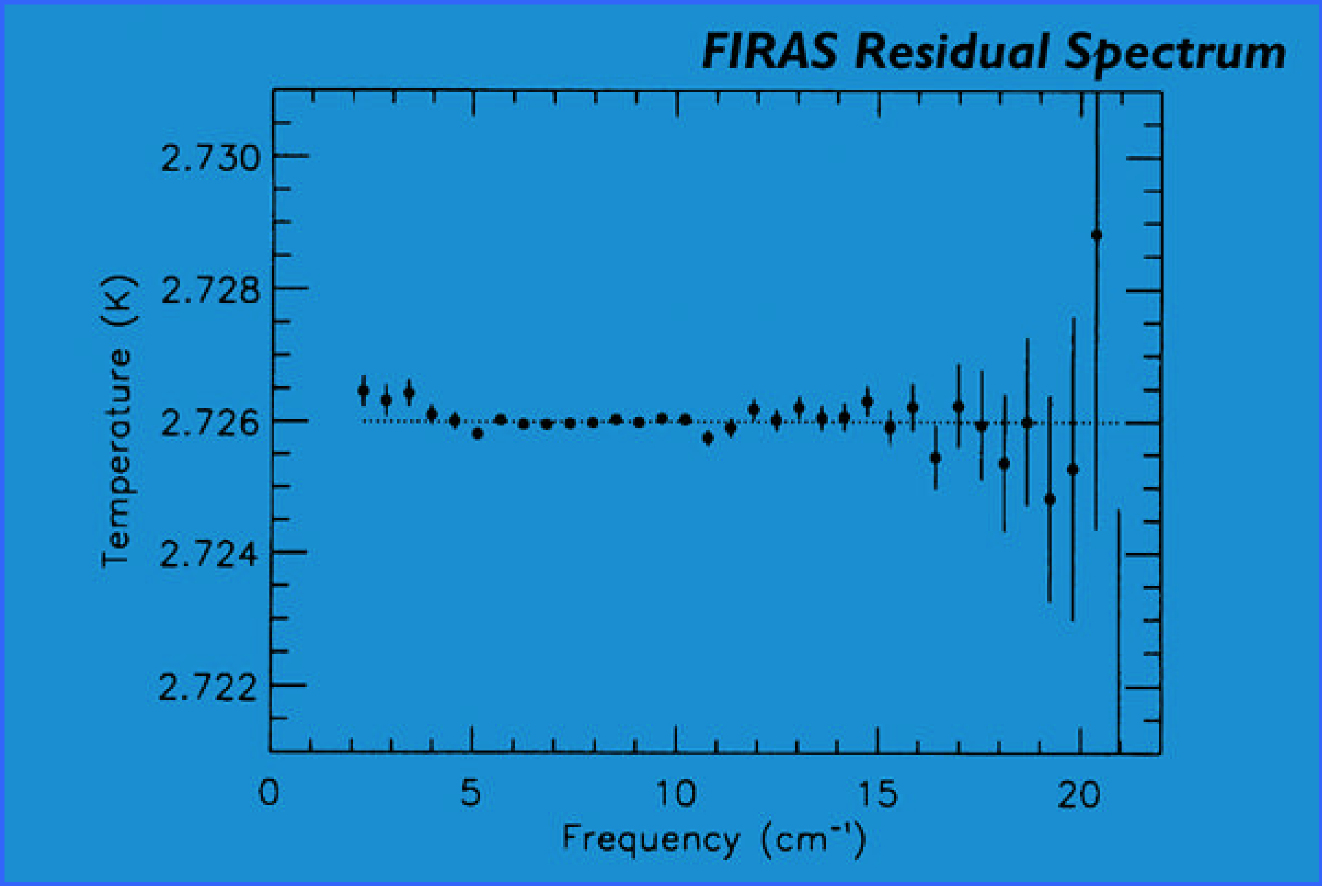


COBE Slide 36



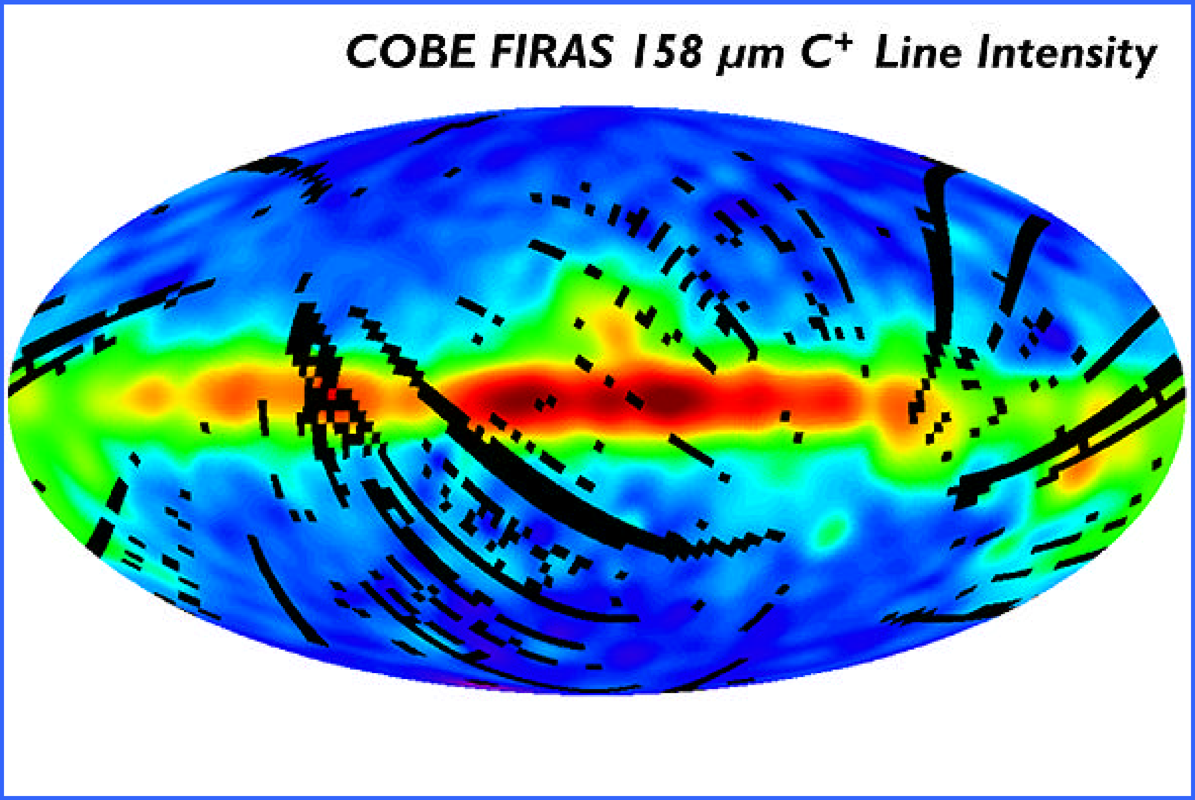
Cosmic microwave background (CMB) spectrum. The solid curve shows the expected intensity from a single temperature blackbody spectrum, as predicted by the hot Big Bang theory. The FIRAS data were taken at 34 positions equally spaced along this curve. The FIRAS data match the curve so exactly, with error uncertainties less than the width of the blackbody curve, that it is impossible to distinguish the data from the theoretical curve. These precise CMB measurements show that at least 99.994% of the radiant energy of the Universe was released within the first year after the Big Bang itself. All theories that attempt to explain the origin of large scale structure seen in the Universe today must now conform to the constraints imposed by these measurements. The results show that the radiation matches the predictions of the hot Big Bang theory to an extraordinary degree. See Mather et al. 1994, Astrophysical Journal, 420, 439, "Measurement of the Cosmic Microwave Background Spectrum by the COBE FIRAS Instrument," Wright et al. 1994, Astrophysical Journal, 420, 450"Interpretation of the COBE FIRAS CMBR Spectrum," and Fixsen et al. 1996, Astrophysical Journal, in press, "The Cosmic Microwave Background Spectrum from the Full COBE FIRAS Data Sets" for details.

COBE Slide 37



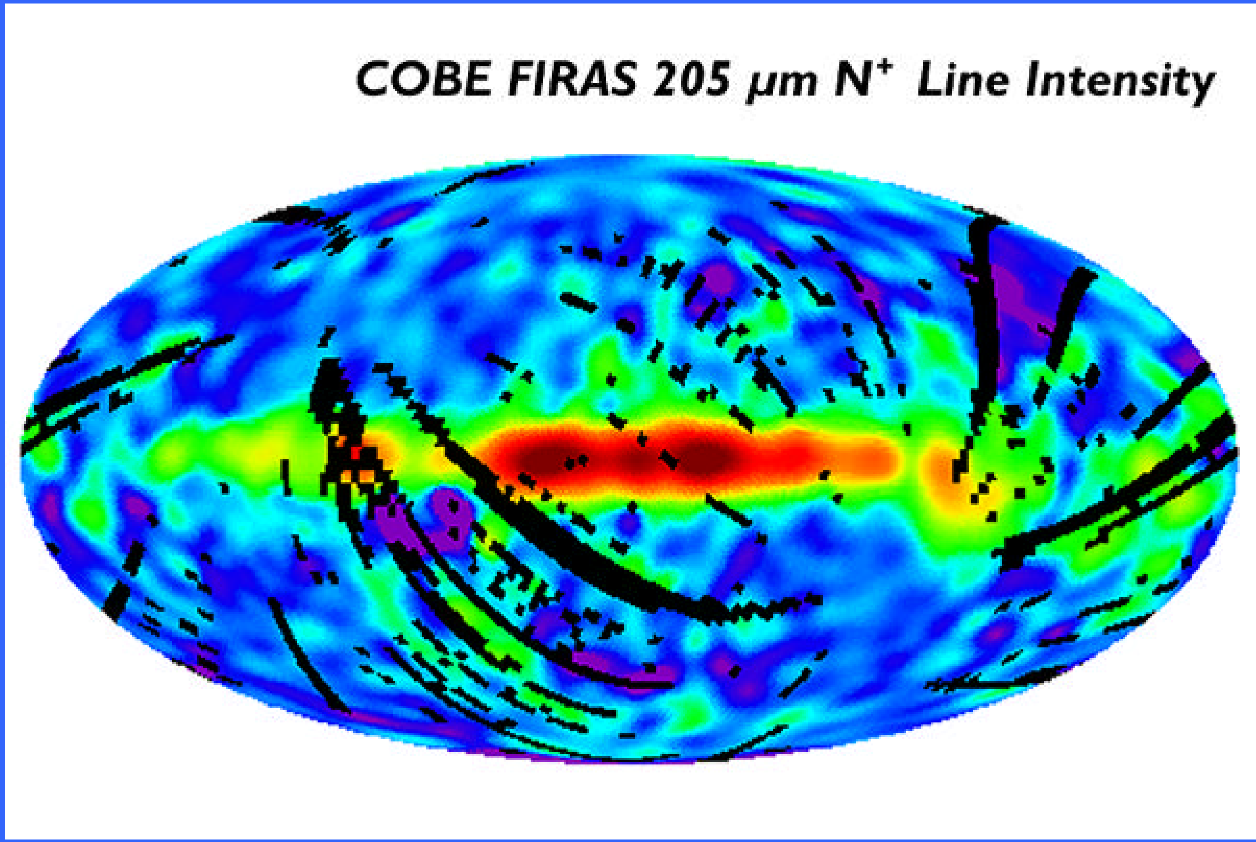
FIRAS measured cosmic microwave background radiation residual spectrum from Mather et al. 1994, ApJ, 420, 439. A Planck blackbody spectrum and a small Galactic emission component have been subtracted from the measured spectrum in order to make the residuals visible. To a very good approximation, the cosmic microwave background spectrum is the same as that of a 2.728 (+/- 0.004) degree Kelvin blackbody.

COBE Slide 38



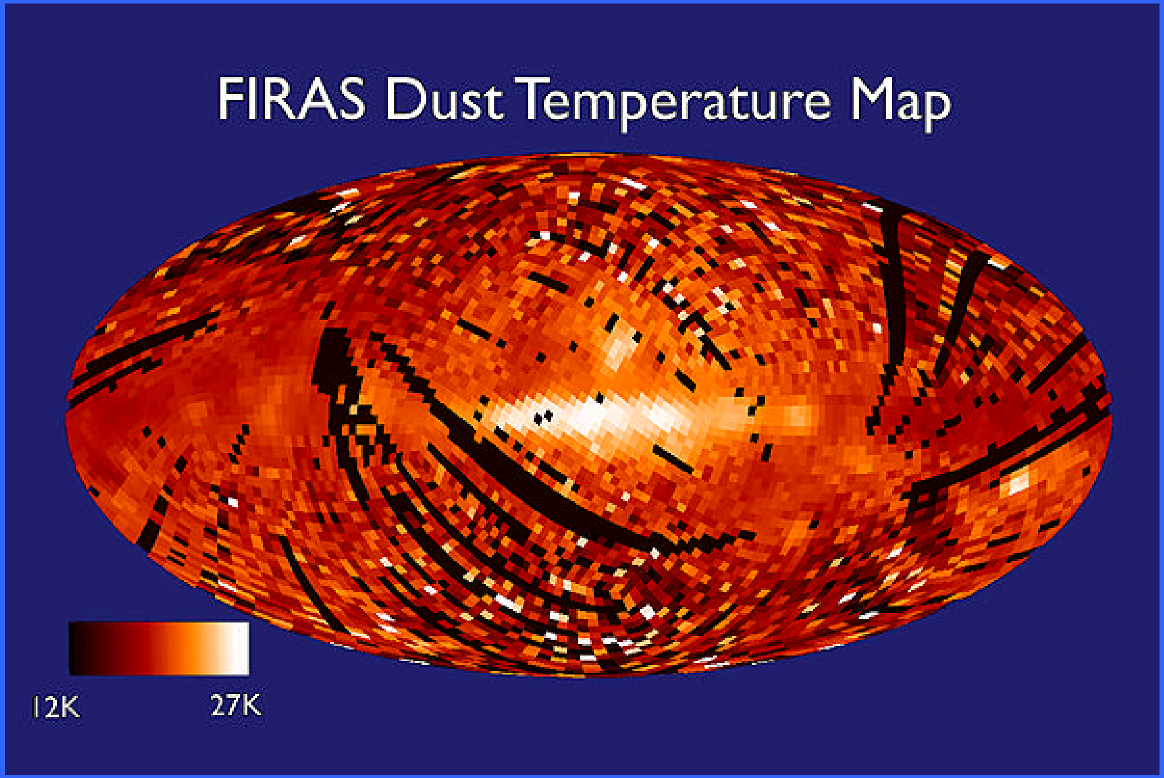
FIRAS map of C+ 158 μm spectral line intensity from Bennett et al. 1994, Astrophysical Journal, 434, 587, "Morphology of the Interstellar Cooling Lines Detected by COBE." The map is a projection of the full sky in Galactic coordinates. The plane of the Milky Way is horizontal in the middle of the map with the Galactic center at the center. The C+ line is an important coolant of the interstellar gas, in particular the "Cold Neutral Medium" (e.g., surfaces of star-forming molecular clouds). In contrast, the N+ line emission (see slide 31) arises entirely from the "Warm Ionized Medium" which surrounds hot stars.

COBE Slide 39



FIRAS map of N+ 205 μm spectral line intensity. (See slide 30 caption.)

COBE Slide 40



A map of the temperature of interstellar dust in the Milky Way Galaxy derived from FIRAS sub millimeter data. The map is a projection of the full sky in Galactic coordinates. The plane of the Milky Way is horizontal in the middle of the map with the Galactic center at the center. At high frequencies, the continuum in a FIRAS spectrum is dominated by thermal dust emission; at low frequencies, the cosmic microwave background dominates. A single-temperature dust model (with 1.55 adopted as the emissivity spectral index) was used to make this map. Different models can be used and assumptions made, and corresponding temperature and optical depth maps can be derived straightforwardly from the FIRAS Continuum Spectrum Maps (see "About the Data Products" in the FIRAS section of the COBE Home Page). Reach et al. (1995, ApJ, 451, 188, "Far-Infrared Spectral Observations of the Galaxy by COBE"), for example, report evidence for a ubiquitous cold (~5 K) dust component.