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COBE Observations of Zodiacal Emission

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Abstract. The *COBE* Diffuse Infrared Background Experiment has obtained some of the most extensive observations of the interplanetary dust (IPD) cloud ever assembled. For the 10 months of cryogenic operation, the brightness of the entire celestial sphere was mapped with an 0.7° × 0.7° field of view at wavelengths of 1.25, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140, and 240 μm, and the linear polarization was mapped at 1.25, 2.2, and 3.5 μm. Observations with reduced sensitivity continued at all wavelengths short of 12 μm for over 3 years after cryogen expiration. Throughout these observations, nearly 1/2 of the sky was mapped every day at elongation angles ranging from 64° to 124°. I describe the DIRBE and the general character of the infrared sky, outline the DIRBE team's approach to isolating the IPD signal, and review results of our initial studies of the zodiacal dust bands, the circumsolar dust ring, and the character of IPD cloud particles.

1. Introduction

The interplanetary dust (IPD) cloud has been studied for many years to understand its nature, origin, and relationship to other solar system components. As a distributed medium in which the Earth moves, it has also been studied as an important contributor to the sky brightness. Most of the study of the cloud has been at optical wavelengths, where one measures the zodiacal light arising from scattering of Sunlight by IPD particles. However, in recent times the zodiacal emission from IPD particles has been mapped at infrared wavelengths by space instruments such as the Zodiacal Infrared Project (Murdock & Price 1985) and the *Infrared Astronomical Satellite* (*IRAS*). Measurement of zodiacal emission adds much insight into both IPD cloud geometry and particle characteristics, in part because it is not necessary to know the scattering phase function in order to interpret the observations.

The Diffuse Infrared Background Experiment (DIRBE) on NASA's Cosmic Background Explorer (*COBE*) satellite has provided extensive high quality observations of both scattering and emission by the IPD particles. These new measurements greatly improve upon and expand the available data, providing accurate absolute brightness measurements over a broader infrared wavelength range than previously studied, providing all-sky linear polarization measure-

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ments, providing dense sampling over time in all directions within elongation angles of 64° to 124°, and providing by far the longest time base for such observations (about 3-1/2 years). The first ten months of these observations, as I will describe, have already provided new insight into the character of the cloud. When the full data set is reduced, it will also allow a search for temporal variation in cloud properties.

2. Overview of the DIRBE

The *COBE* mission has been described by Boggess et al.(1992), and the DIRBE instrument has been described by Silverberg et al. (1993). The *COBE* spacecraft was launched into a 900-km altitude, 99°-inclination, orbit with ascending node near the terminator. This Sun-synchronous orbit maintained an orbital plane roughly orthogonal to the Earth-Sun line throughout the mission, allowing the instruments to scan the sky at large offset angles from the Earth and Sun at all times. The DIRBE observational approach was to obtain absolute brightness maps of the full sky in 10 photometric bands at 1.25, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140, and 240 μm. In order to aid discrimination of the IPD signal, linear polarization was also measured at 1.25, 2.2, and 3.5 μm. Because of the Earth's motion within the IPD cloud, the diffuse infrared brightness of the entire sky varies over the course of a year. To monitor this variation, the DIRBE 0.7° × 0.7° field of view was offset 30° from the *COBE* spacecraft spin axis, which was maintained at a solar elongation angle of 94°. This produced a helical scan of the sky. All spectral bands viewed the same instantaneous field of view, and the helical scan allowed the DIRBE to map 50% of the celestial sphere each day. Over the course of six months this yielded observations of each celestial direction hundreds of times at all accessible solar elongation angles (depending upon ecliptic latitude) in the range 64° to 124°. Hence, the DIRBE data provide a detailed 'light curve' for every direction during its periods of visibility, a powerful aid to extraction of the IPD contribution to the total sky brightness.

The DIRBE instrument was an absolute radiometer, utilizing an off-axis folded Gregorian telescope with a 19-cm diameter primary mirror. The optical configuration (Magner 1987) was carefully designed for strong rejection of stray light from the Sun, Earth limb, Moon or other off-axis celestial radiation, or parts of the *COBE* payload (Evans 1983). The instrument, which was maintained at a temperature below 2 K within the *COBE* superfluid helium dewar during the first ten months of the mission, measured absolute brightness by chopping between the sky signal and a zero-flux internal reference at 32 Hz. Instrumental offsets were measured about five times per orbit by closing a cold shutter located at the prime focus. The offset signal was removed in the ground data processing. Internal radiative reference sources were used to stimulate all detectors when the shutter was closed to monitor the stability and linearity of the instrument response. The highly redundant sky sampling and frequent response checks provided precise photometric closure over the sky and reproducible photometry to $\sim$ 1% or better for the duration of the mission. Calibration of the DIRBE photometric scale was obtained from observations of known, isolated bright celestial sources.

The prime part of the DIRBE mission lasted from 11 Dec 1989 until 21 Sept 1990, when the liquid helium in the dewar was depleted. Following helium depletion, operation of the DIRBE detectors from 1.25–4.9 μm continued at reduced sensitivity until the end of *COBE* operations in December, 1993. Results discussed here are based upon data acquired in the prime mission; reduction of the full 'warm-era' data set is in progress.

3. The Character of the Infrared Sky

The DIRBE sky brightness maps show the dominant anticipated features of Galactic starlight and zodiacal light at short wavelengths, emission from the IPD dominating at 12 and 25 μm, and emission from the interstellar medium dominating at longer wavelengths (Hauser 1993; DIRBE Sky Maps at Elongation 90°, available from the National Space Science Data Center (NSSDC): Leisawitz 1995). The brightness of the sky in any fixed direction varies roughly sinusoidally over the year, though the detailed time dependence and amplitude of variation depends upon direction in the sky (Kelsall et al. 1993; Reach et al. 1995a), indicating rather complex features of the IPD cloud. The DIRBE polarization maps reveal the expected strong linear polarization arising from the zodiacal light (Berriman et al. 1994; DIRBE Weekly Sky Maps, NSSDC: Leisawitz 1995). The DIRBE data dramatically illustrate the presence of the IPD cloud: the diffuse infrared sky brightness has substantial gradients with ecliptic latitude; it is variable over the year in all directions; and it is strongly linearly polarized in the near-infrared.

4. The IPD Contribution to the Infrared Sky Brightness

Since the primary motivation for the DIRBE was to search for extragalactic infrared background radiation, much attention has been devoted to determining with precision the contribution to the sky brightness from the IPD and sources in the Galaxy. Identification of the IPD signal has been based primarily upon the apparent annual variation of brightness as the Earth orbits the Sun. The polarization measurements have not yet been used in the modeling. The method is to fit the temporal variation of some 1500 independent lines-of-sight with the brightness calculated using a parameterized three-dimensional physical model of the IPD cloud (Hauser 1995a; Hauser 1995b; Reach et al. 1995a; Franz et al. 1995). The cloud spatial density components include a smooth, large scale distribution, the IPD bands most apparent near 1.4° and 10° ecliptic latitude (see Section 5.1.), and a circumsolar dust ring near 1 A. U. with density enhancements leading and trailing the Earth (see Section 5.2.). The smooth cloud is assumed to be axisymmetric, though not necessarily centered on the Sun, with a plane of symmetry inclined with respect to the ecliptic plane. The annual time variation arises only from the motion of the Earth within the cloud, including the effect of the eccentricity of the Earth's orbit: the cloud is assumed to be intrinsically time-independent.

The model accuracy has been assessed in two basic ways: by the fidelity with which it reproduces the annual brightness variation, especially the time-independence of the residual sky maps (observed brightness minus IPD model brightness) made on a weekly basis during the mission; and by the presence of obvious spatial artifacts in the residual maps. In general, the evident artifacts do not exceed several percent of the sky brightness, so that this approach yields quite a good isolation of the IPD contribution to the infrared sky brightness. Some details of the model and results have been presented by Reach et al. (1995a) and Franz et al. (1995).

5. The Character of the IPD Cloud

The DIRBE team has carried out a number of investigations of the IPD cloud using the DIRBE data. These are briefly reviewed here.

5.1. Dust Bands

The *IRAS* survey revealed thermal emission from zodiacal dust bands (Low et al. 1984), interpreted to arise from dust produced by collisions in the asteroid belt (Dermott et al. 1984, Sykes 1990). The status of an investigation of the three-dimensional structure of these bands using DIRBE data is discussed by Reach et al. (1995b) at this meeting.

Confirmation of these bands and further information regarding the band particle location and radiative properties was obtained in a study by Spiesman et al. (1995). These authors showed that not only was band particle emission present in the DIRBE 12–100 μm maps, but that scattered light from the band particles is also discernible at near-infrared wavelengths. These results were obtained by suitable averaging and spatial filtering of the data to enhance small angular scale features, rather than by reliance on the model discussed in Section 4. Spiesman et al. showed that the band location inferred from DIRBE data was consistent with the *IRAS* results, and that the band particle albedo (0.22) is substantially higher than that of the comets studied with DIRBE (0.065–0.13; Lisse 1992; Lisse et al. 1994), further confirming that comets are not the sole source of IPD material.

5.2. Dust Ring

The *IRAS* data suggested that the sky is always slightly fainter when viewed in the direction of the Earth's orbital motion (leading direction) than in the direction trailing the Earth (Reach 1991), though it was not certain that this difference exceeded systematic calibration uncertainties. Recently Dermott et al. (1994) carried out detailed dynamical calculations of the behavior of asteroidal particles trapped in orbital resonances with the Earth as they spiral in towards the Sun due to drag forces. They showed that one would expect an asymmetric ring of such particles near 1 A. U., with a relatively large density enhancement trailing the Earth and a smaller enhancement leading the Earth, in accord with the character of the *IRAS* data. Reach et al. (1995c) have confirmed this result using DIRBE data, showing that at wavelengths of strong IPD emission (4.9, 12, and 25 μm), the peak brightness at 90° elongation is fainter in the leading direction than the trailing direction throughout the year. Furthermore, by fitting a version of the DIRBE empirical IPD model which did not contain the solar ring component (Section 4.) only to sky brightness measurements obtained in the leading direction and then subtracting this from the measurements in the trailing direction, they found the strong trailing density enhancement expected from the calculations of Dermott et al. (1994). The existence of this component of the IPD cloud is thus well established.

5.3. Zodiacal Light Polarization and Color

A preliminary study of the DIRBE polarization measurements has been carried out by Berriman et al. (1994). In the ecliptic plane, they found the linear polarization to decline from 12% at 1.25 μm to 8% at 3.5 μm, with the polarization vector perpendicular to the ecliptic plane as expected and near-infrared color redder than solar. Using data from a small sky region, they attempted to account for the observed polarization and color with spherical grains of various composition, size and structure. No such model was in agreement with the data, indicating that these extensive new DIRBE measurements will justify and constrain more realistic IPD grain models.

6. Conclusion and Future Work

The DIRBE has provided a wealth of new data for IPD studies, leading to new insights into the IPD cloud. Modeling of the IPD contribution to the infrared sky brightness has already yielded rather high fidelity results. However, because the search for the extragalactic infrared background radiation requires the highest possible precision in identifying and removing the bright foreground emissions, further efforts at IPD model improvement are planned. The data from the cryogenically-cooled part of the *COBE* mission are publicly available. Data from the remaining 3+ years of *COBE* operation are being reduced, and data products similar to those currently released are planned for release in 1996. Such data will be a further aid to IPD cloud studies, providing multi-year observations to test the present static cloud models and allowing tests for intrinsic time dependence of the cloud. The IPD cloud model of the DIRBE team, and sky maps with the modeled IPD contribution removed, will also be made publicly available.

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