IRAS* OBSERVATIONS OF THE INTERPLANETARY DUST EMISSION

M. G. Hauser
Goddard Space Flight Center
Greenbelt, Maryland 20771

T. N. Gautier and J. Good
Jet Propulsion Laboratory
Pasadena, California 91011

F. J. Low
University of Arizona
Tucson, Arizona 85721

ABSTRACT. The Infrared Astronomical Satellite (IRAS) has completed a sensitive, highly redundant survey of the full sky in four broad photometric bands at 12, 25, 60, and 100 micrometers wavelength. The survey measured interplanetary dust emission over elongation angles ranging from 60 to 120 degrees. Bright emission from the main cloud is consistent with optically thin blackbody emission. The grains are evidently quite black, with an "apparent albedo" of about 0.07. The data show clear evidence for deviation of the dust symmetry surface from the ecliptic plane. Surprising bands of emission were discovered near the ecliptic plane and about ten degrees on either side of it. The heliocentric distance of this material, suggested to be asteroidal in origin, is inferred to be about 2.5 AU from both color temperature and parallax measurements.

1. MISSION DESCRIPTION

The IRAS satellite was launched on Jan. 26, 1983, and operated successfully until depletion of its stored superfluid helium on Nov. 22, 1983 (Neugebauer et al. 1984a). The primary purpose of the mission was to conduct an unbiased survey of the full celestial sphere in four broad photometric bands at 12, 25, 60, and 100 micrometers wavelength. Approximately 60 percent of the mission life was devoted to the survey, giving redundant coverage of 98% of the celestial sphere. The satellite

*The Infrared Astronomical Satellite (IRAS) was developed and operated by the Netherlands Agency for Aerospace Programs (NIVR), the United States National Aeronautics and Space Administration (NASA), and the United Kingdom Science and Engineering Research Council (SERC).

R. H. Giese and P. Lamy (eds.), Properties and Interactions of Interplanetary Dust, 43–48.

was placed in a 900 km altitude, circular orbit at 99 deg inclination with a twilight nodal crossing. This is a Sun-synchronous orbit: precession of the orbital plane keeps the Sun-Earth line roughly normal to the orbital plane. The survey strategy was to scan the sky at approximately the orbital pitch rate at a fixed solar elongation, completing all or part of a small or great semi-circle scan (depending on elongation) on each side of the Earth.

The survey instrument contained a linear-staggered array of photoconductive detectors mounted at the focal plane of a 57-cm diameter Cassegrain telescope (Neugebauer et al. 1984a). The detectors in each wavelength band were arranged in two independent modules separated in the in-scan direction so that two independent measurements were obtained on each sky region in an interval of several seconds as the telescope scanned the sky. The full focal plane assembly viewed a 1/2-deg wide region in the cross-scan direction. The scan track was offset cross-scan by 1/4 degree on successive orbits, assuring that each sky region was seen on consecutive orbits to confirm the reality of the measurements. During the first half year of the survey, each sky position was scanned on a second pair of orbits about a week after the initial pair to permit discrimination of solar system objects.

For studies of the interplanetary dust emission (hereafter, zodiacal emission or ZE), data from all detectors in a given wavelength band for a given sky position were averaged together and then averaged over 1/2 deg in the in-scan direction to provide low resolution samples of high signal-to-noise ratio. The detector signals were dc-coupled, providing intensity measurements on all spatial scales larger than the instantaneous field of view. The electronic baselines were found to be very stable on time scales of hours, as evidenced by the reproducibility of the data on successive orbits. Calibration of the zero point and scale factor was accomplished using procedures briefly discussed by Neugebauer et al. (1984a) and Hauser et al. (1984).

In terms of Sun-referenced coordinates, each survey scan provided data at a fixed elongation with inclination varying uniformly with time. During the first half year of the survey (Feb. 9 to Aug. 26), all ecliptic longitudes were redundantly observed at elongation angles varying between about 80 and 100 degrees. A 70% complete second survey was achieved between Aug. 26 and Nov. 22 including elongation angles from 60 to 120 degrees. The net result is an extensive self-confirming data set containing roughly 8000 partial-circle scans, most crossing the ecliptic plane, and many extending from one ecliptic pole to the other.

2. RESULTS AND INTERPRETATION

The data from single scans clearly show smoothly varying emission peaking near the ecliptic plane in all bands; this emission is the dominant large-scale feature at 12 and 25 μm (Hauser et al. 1984). This large-scale emission shows a number of interesting features, including high brightness at all wavelengths, irregularity of the profiles near the ecliptic plane, differences in brightness between the ecliptic poles, and displacement of the symmetry axis of the profile from the

https://doi.org/10.1017/S0252921100084311 Published online by Cambridge University Press

ecliptic plane. Some implications of these features are discussed below. It should first be emphasized that there is no clear evidence of significant large-scale galactic emission more than 20 degrees or so from the galactic plane except at 100 μm. A procedure for estimating the ZE component of the 100 μm emission is given by Hauser et al. (1984): in what follows, we deal only with the ZE component at all wavelengths.

2.1 Brightness and Spectrum of ZE: Grain Albedo and Size

The ZE brightness at 12 and 25 μm exceeds that of previously published rocket data at comparable wavelengths by amounts varying from 50% to a factor of 3-4 (Briotta 1976; Price, Murdock, and Marcotte 1980). An immediate implication is low dust albedo. Comparing the spectrally integrated emission in the ecliptic plane at elongation 90 deg with the integrated scattered intensity in the same direction, based upon a visual brightness of 200 $S_{10}(V)$ (Levasseur-Regourd and Dumont 1980), shows the emission to be about a factor of 13 brighter. The "apparent albedo" is thus $\sim$0.07. Adopting an anisotropic scattering function implies a larger albedo, but the particles are evidently quite black.

The spectrum of the ZE is, within the IRAS calibration uncertainties, consistent with optically thin blackbody emission, though a grain radiative efficiency proportional to frequency cannot be ruled out. The implication is a significant population of grains with radii $a > 16$ μm. The blackbody grain temperature toward the ecliptic pole, 275±57 K, is at or slightly below the greybody temperature at 1 AU of 298 K.

2.2 Angular Distribution of the ZE: Dust Spatial Distribution

No attempt has yet been made to invert the brightness distribution to obtain the spatial distribution of the dust. However, the brightness profiles in the ecliptic plane from elongation 68 to 103 deg and in the plane at elongation 90 deg have been compared with the emission model tabulated by Frazier (1977) based on a dust density distribution determined from visual observations of zodiacal light:

$$n(r,z) \sim (1/r) \exp[-2.6 \, (z/r)^{1.3}],$$

where z is distance normal to the symmetry plane and r is the radial distance from the Sun in that plane. A tentative conclusion is that the infrared observations are generally consistent with dust radial and z distributions determined from previous studies.

An important characteristic of the dust distribution is its symmetry plane, which can provide clues to the dynamics and perhaps origin of the dust. Two characteristics of the IRAS data relate fairly directly to the symmetry plane: the difference in brightness at the ecliptic poles at any given time, and the ecliptic latitude about which the scan profiles are symmetric. Both of these quantities show an annual variation as a result of the Earth's motion with respect to the symmetry plane.

The difference in brightness between the ecliptic poles can be determined from single half-orbit IRAS scans extending from one ecliptic pole to the other at 90 deg elongation. For small inclination of the symmetry plane, the annual variation of this difference is expected to be sinusoidal. The data show the expected sinusoidal variation clearly in all bands except 100 μm, where galactic sources make the measurement of the difference more difficult. The ecliptic longitude of the ascending node of the symmetry plane is about 78 deg (Hauser and Gautier 1984), slightly smaller than the 87 deg value reported by Leinert et al. (1980) from the Helios measurements. The fractional difference in polar brightness varies annually by 40% peak-to-peak. This variation implies an inclination of the symmetry plane with respect to the ecliptic plane of about 2.5 degrees.

The time variation of the apparent ecliptic latitude of the symmetry axis of each scan across the ecliptic plane has been examined in a preliminary fashion. Comparison of the data obtained at elongation angles between 80 and 100 deg with expectations for a model in which the dust is concentrated in a Sun-centered circle in the symmetry plane, and for models with more realistic dust spatial distributions, yields symmetry plane parameters of about 1.5 deg inclination, 55 deg ascending node (Hauser and Gautier 1984). Comparing these results with those of ground and space-based visible zodiacal light studies lends support to the suggestion that the symmetry "plane" is really a more complicated surface (Misconi 1980), with parameters resembling those of the Venus orbit in the region interior to 1 AU observed by Helios, and parameters more nearly those of the Martian orbit exterior to 1 AU.

2.3 The Interplanetary Dust Bands

The most surprising feature in the ZE data noticed thus far is structure in the latitude profiles near the ecliptic. Though this structure is a small perturbation on the main shape of the profiles, it has been found to be very reproducible from scan to scan. The structure generally takes the form of shoulders about 10 deg on either side of the ecliptic plane and a flattened top at the ecliptic plane. In order to enhance the visibility of these features, the scan data were filtered so as to suppress the very large scale gradients. When presented as a contour plot, the data then clearly show ridges at the ecliptic and about 10 deg on either side (Neugebauer et al. 1984b). These features represent about 5% of the total emission intensity near the ecliptic. Similar filtering of the data from the entire survey shows the ridges to persist all around the sky, leading to their description as "bands" of zodiacal dust about the ecliptic (Low et al. 1984). From the relative intensities of these bands, Low et al. inferred color temperatures in the range 165 - 200 K, implying heliocentric distances (for grey particles) in the range 2.2 - 3.2 AU. Examination of the apparent separation of the outer bands in the data from the second half year clearly shows systematic variation as elongation changes from 60 to 120 deg, as expected from parallax considerations for material at a few AU. Initial analysis of these data yield an inclination for the orbits of the outer band material with respect to their symmetry plane of about 8.1 deg,

https://doi.org/10.1017/S0252921100084311 Published online by Cambridge University Press

with a heliocentric distance of 2.5 AU, quite consistent with the color temperature determination (Gautier, Hauser, and Low 1984).

These bands of emission are interpreted as arising from dust in inclined orbits in the vicinity of the main asteroid belts. If, for example, orbital inclinations of about 10 deg are preferentially populated, then the fact that particles spend more time near the points of extreme displacement from the symmetry plane than close to it will cause enhancements in the observed emission near 10 degrees. The bands are particularly intriguing because they may represent a clear example of an asteroidal, as opposed to cometary, origin for at least part of the interplanetary dust. Dermott et al. (1984) have proposed a detailed model for the bands based upon the orbital properties of Hirayama's asteroid families, which do include groupings near 10 deg and 0 deg inclination. This model includes specific predictions for additional consequences, e.g., variations in brightness and band separation with longitude, which will have to be compared closely with the data.

3. CONCLUSION

The IRAS survey has yielded an extensive new set of observations of the interplanetary dust. The results discussed here are based upon preliminary examination of a small fraction of the available data. Final data reduction with a consistent calibration scheme is still in progress. Detailed analysis of the IRAS data along with previous observations should contribute substantially to our understanding of the nature of the interplanetary dust, its distribution, and its origins.

ACKNOWLEDGMENTS

We thank our many colleagues whose labors contributed to the IRAS mission, and particularly the dedicated staff of the IRAS Scientific Data Analysis System at the Jet Propulsion Laboratory for rendering the data into forms needed for this investigation. We are grateful to J. Weinberg for presenting this paper at the Colloquium. T. N. Gautier was supported by an NRC Resident Research Associateship.

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RESPONSE TO QUESTIONS SUBMITTED FOLLOWING PAPER DELIVERED FOR THE AUTHORS BY J. WEINBERG

LAMY: The method of residues used by J. Maucherat for analyzing the D2B ZL data (i.e., comparing the same field of view at 6 months interval) turned out very powerful. Could it be used to analyze the IRAS data or part of the data?

AUTHORS: The IRAS extended emission data are being reduced separately for each sky coverage so that such comparisons can be carried out.

LEVASSEUR-REGOURD: Would the 20% variation in intensity between the first and the second semester observations mainly be due to the position of the symmetry plane--better, the surface of maximum brightness--with respect to the ecliptic plane?

AUTHORS: The inclination of the symmetry surface with respect to the ecliptic plane is evidently the main cause of the effect. Another potential contributor, which would not show up in the polar differences, is the eccentricity of the Earth's orbit. Search for evidence of this contribution awaits complete reduction of the data with a consistent baseline calibration.

FECHTIG: A possible interpretation for low albedo is the following: as the beer can experiment on Pioneer 10/11 has shown, the dust particles at $r > 5$ AU are moving eccentrically ($e \sim 0.99$) and/or have random inclinations. Therefore, the particles are on typical cometary orbits, and are hence young (time since release from comet nucleus). Young cometary particles have organic mantles (Greenberg) which turn black when irradiated in space (Lanzerotti et al.). Therefore, particles in the outer solar system have extremely low albedos.

GRÜN: With what radial and z dependence of the dust density distribution are the IRAS data compatible? What particle size distribution is implied by the IRAS data?

AUTHORS: The brightness distributions for a small sample of the IRAS data are roughly compatible with the spatial distributions inferred from visible light studies, as indicated above. Further modelling is in progress to determine whether the spatial distributions can be more tightly constrained. Implications for the particle size distribution have not yet been investigated.

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