THE INFRARED ZODIACAL LIGHT

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ABSTRACT. Thermal emission from interplanetary dust is the main source of diffuse radiation at λ 5-50 μm. Analysis of infrared sky maps from IRAS and ZIP lead to the result that the average optical properties of the dust change with heliocentric distance. The present uncertainties in calibration should be resolved by COBE. Existence of a dust sublimation zone at 4 solar radii awaits confirmation at the next solar eclipse.

1. Introduction

Recent surveys of the background sky at infrared wavelengths have enabled us to take a new look at the average optical properties and spatial distribution of the interplanetary dust. In fact, thermal emission from interplanetary dust is the strongest source of diffuse radiation at wavelengths 5-50 μm. Measurements at several wavelengths yield the average temperature and albedo of the grains and, by applying appropriate inversion techniques, the heliocentric gradients of these quantities. The IRAS sky survey detected structure in the zodiacal cloud--dust bands and comet trails--giving us, for the first time, an observational link to the sources of the interplanetary dust cloud (see review by Sykes, this volume).

This paper will describe the infrared observational database, discuss the dust properties derived from the infrared data, and make some recommendations for future observations and analysis.

2. Infrared Observations

Absolute calibration and separation from other diffuse radiation sources are the two major difficulties in obtaining reliable measurements of the infrared zodiacal light. Emission from the earth's atmosphere and thermal radiation from the instrument complicate the problem.

Infrared observations of point sources normally screen out foreground and background radiation by chopping--i.e., by rapidly comparing the signal from the object + background with the signal from the background alone a small angular distance away. Such a technique is inappropriate for obtaining absolute measurements of the spatially extended zodiacal dust emission. To circumvent the high foreground emission, the zodiacal emission has to be observed from high altitude (balloon, rocket) or from space, with Helium-cooled sensors. Ideally the instrument should chop against an accurately calibrated internal reference source.

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Early measurements from sounding rockets at large solar elongation angles were carried out by Soifer et al (1971) and Briotta (1976). Briotta obtained an 8-13 μm spectrum which showed a silicate emission feature. If confirmed, this implies that sub-μm or μm-sized silicate grains are abundant. Salama et al (1987) obtained balloon measurements of the spectral energy distribution at λ11, 19, 50, 108, 225 μm and the brightness gradient at ecliptic longitudes 10-90 deg. Because the signal was chopped against a sky position several degrees away, the measured intensities are differential.

Zodiacal emission maps at λ 11 and 20 μm and solar elongation angles $30 < \varepsilon < 75$ deg were made on a July, 1974 rocket flight by Price et al (1980). The intensity at ecliptic latitude $\beta > 30$ deg was taken as the background level; this procedure will underestimate the true brightness. The absolute calibration was revised by Price et al (1982); the zodiacal light intensities in the 1980 paper should be decreased by a factor of 2.

Much more extensive maps at 15 wavelengths between 2 and 30 μm were obtained by Murdock and Price (1985) during two rocket flights in July 1980 and August 1981--the so-called ZIP experiment. The cooled radiometer included an internal absolute reference source. Pre- and post-flight calibration agreed to 5%; the absolute calibration accuracy is estimated to be 20%. Scans covered solar elongation angles $22 < \varepsilon < 180$ deg and ecliptic latitudes $-60 < \beta < 90$ deg. Data within 3 deg of the galactic plane were eliminated, but otherwise no attempt at separating the zodiacal and galactic components was made. The sky coverage allowed the authors to determine a 3-dimensional model for the dust spatial distribution. The dust bands at $\beta \sim 10$ deg are evident in their plots at $\varepsilon = 60$ and 90 deg. Although the authors state that no spectral features were detected, it appears from their plots that a 10 μm silicate feature can not be ruled out.

Murdock and Price compared their values with previous data. The ZIP intensities are 35% higher than the (corrected) July 1974 intensities and 40% lower than Soifer et al (1971) and Briotta (1976) at $\varepsilon = 103$ deg . More important for modeling the dust properties, the ZIP intensities are a factor of two lower than the IRAS intensities in Hauser et al (1984) at 12 and 25 μm. The final IRAS calibration reduced the discrepancy to a factor of ~1.5 (Good 1988).

Launched in January 1983, the IRAS satellite carried out a 10 month sky survey in 4 broad spectral bandpasses centered at 12, 25, 60, and 100 μm (Neugebauer et al 1984). While the primary objective was to survey point sources and small extended objects, the diffuse sky backgound was measured as well. The focal plane array consisted of 62 detectors, arranged so that each point in the sky scanned across two detectors in each bandpass (Beichman et al 1988). The spacecraft was placed in a sun-synchronous 900 km polar orbit, with the orbit plane approximately perpendicular to the sun-earth line. The usual observing pattern was to scan at a fixed solar elongation angle during one orbit, then offset by 1/4 deg (half of the focal plane field of view) on each successive orbit. Scans during the first 6 months were restricted to $80 < \varepsilon < 100$ deg; in the last 3 months the region $60 < \varepsilon < 120$ deg was surveyed. A field near the north ecliptic pole was measured regularly to monitor the electronic baseline stability; baseline drift was < 5% per day at 12, 25 μm and < 20% per day at 60 and 100 μm. Absolute calibration of the extended emission was based on the point source absolute calibration (Beichman et al 1988).

The IRAS project prepared a zodiacal observation history file, a time-ordered listing of the background flux in each bandpass, averaged into 0.5 x 0.5 deg bins. This file contains approximately 8000 scans for studying the large- scale structure of the zodiacal emission and annual variations. No synopsis of this database has ever been published in tabular or graphical form.

Before one can study the zodiacal emission, separation of the galactic background emission has to be made. Table 1, from Boulanger and Perault (1988) compares the zodiacal and galactic emission in the 4 bandpasses. The zodiacal emission dominates at 12 and 25 μm; the galactic component can be fairly readily separated by assuming symmetry with respect to the galactic plane and the zodiacal dust symmetry plane. Separation is more difficult at 60 and 100 μm. Boulanger and Perault used the correlation between the infrared emission and the H I gas

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emission to identify the galactic component. They find a residual isotropic emission of ~1.2 MJy/sr at 100 μm, which could be of either solar system or galactic origin. With the present calibration uncertainties, however, it is premature to attach significance to this result.

TABLE 1. Comparison of Galactic and Zodiacal emission in the IRAS database (MJy/sr)*

	Zodiacal Emission $\varepsilon = 90°$		Galactic Emission	
λ	β=0°	β=90°	$\lvert b\rvert < 2°$	$b = 90°$
12 μm	40	14	6	0.05
25	85	28	10	0.08
60	38	7	30	0.2
100	10	2	130	1.0

*Boulanger and Perault (1988)

COBE, the Cosmic Background Explorer, has just completed a 10-month survey of the diffuse background sky, from an orbit similar to that of the IRAS satellite. In contrast to IRAS, which was optimized for the survey of point sources, the COBE instruments were designed to make extremely accurate measurements of the diffuse radiation, as the microwave spectrum of the 2.735 K cosmic background so eloquently demonstrates (Mather et al 1990a). The diffuse infrared background experiment (DIRBE) maps the sky simultaneously in ten bandpasses from 1-300 μm, including the four IRAS bandpasses (Gulkis et al 1990; Mather et al 1990b). Linear polarization is measured in the three short wavelength channels J(1.2 μm), K(2.2 μm), L (3.5 μm). The field of view is 0.7 x 0.7 deg and the signal is chopped between the sky and a zero-flux internal reference. The instrument views at an angle of 30 deg to the spacecraft spin axis, sampling elongations $64 < \varepsilon < 124$ deg on every spin and covering half the sky every day. The complete database should allow unambiguous separation of the zodiacal and galactic emission.

A very preliminary comparison of the DIRBE fluxes with those of IRAS indicates zero-point differences of a few MJy/sr in all four bandpasses and an overestimate of the IRAS DC gain at 60 and 100 μm. The combined errors are largest at 100 μm toward faint sky regions, amounting to a factor of 3 (IRAS higher) at the ecliptic pole (Mather et al 1990b). We eagerly await the results from this experiment!

3. Models of the Zodiacal Emission

Whether viewed in visible or infrared light, the observed zodiacal light is an integral over the line of sight. The spatial distribution and the scattering or emitting properties of the dust are convolved together in this integration. At visual wavelengths, the angular scattering function of the dust is one of the unknowns complicating the line-of-sight integration. In the infrared, we may make the simplifying assumption that the thermal emission from the dust is isotropic. Instead, the temperature of the dust grains, and the variation of the temperature with heliocentric distance, have to be known or assumed. Based on the size distribution of the dust measured from space probes near 1 AU, particles 10-100 μm in size should make the major contribution to the zodiacal emission as viewed from earth (Grün et al 1985).

Two approaches have been applied to modeling the zodiacal light, in order to extract physical information about the dust. In the first approach, global models are constructed, assuming some

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parameters and varying others, and predictions of the integrated zodiacal light are computed for comparison with the observations. While this approach does not necessarily lead to a unique answer, one can distinguish the types of models and parameter ranges that are consistent with the data.

Over the years, numerous models for the spatial distribution of the interplanetary dust cloud have been published, based on the optical zodiacal light isophotes. A good summary is given by Giese et al (1986). The various models have been compared with the ZIP and IRAS data by Giese and Kneissel (1989) (see also Kneissel and Mann, this volume). Spatial distributions can be formulated which are compatible with both optical and infrared observations at $\varepsilon \geq 60$ deg. But models which are similar at $60 < \varepsilon < 120$ deg (the range covered by IRAS and DIRBE) can deviate markedly at small elongations, predicting either a minimum or a maximum dust density at small heliocentric distances. The optical data imply a maximum, while ZIP data apparently imply a minimum, although even the line of sight at $\varepsilon = 22°$ samples no closer to the sun than $r =$ 0.34 AU. Yet zodiacal light observations from the Helios probe at 0.3 AU show no sign of a decrease in dust density at $r \geq 0.1$ AU (Leinert et al 1981). The dust distribution is surely more complex than an idealized mathematical model, and probably consists of two or more components with different orbital distributions, size distributions, and optical properties (e.g., Kneissel and Mann, this volume; Levasseur-Regourd et al. this volume). Infrared data at small ε are clearly important; the answer is not so simple as to assign one dust component to explain the infrared observations and another to account for the optical scattering!

The annual variation of the ecliptic pole brightness in the IRAS database can be used to define the dust symmetry plane relative to the ecliptic near 1 AU. The inclination is found to be ~1.6 deg and the longitude of the ascending node $\Omega = 43\text{-}77$ deg (Hauser 1987). The symmetry plane derived from earth-based optical zodiacal light data is $i = 1.5 \pm 0.4$ deg and $\Omega = 96 \pm 15$ deg. (Dumont and Levasseur-Regourd 1978). In contrast, the symmetry plane measured from the Helios probe at $r < 1$ AU has $i = 3.0 \pm 0.3$ deg and $\Omega = 87 \pm 4$ deg, (Leinert et al 1980), closer to that of Venus' orbit and supporting the concept of a warped symmetry surface for the dust distribution.

The IRAS survey has revived interest in modeling the zodiacal emission (see Hauser 1987 for a review). Some models, such as that of Boulanger and Perault (1988), are strictly empirical fits to the survey scans, with the goal of accurately subtracting the "foreground" zodiacal emission from the galactic emission. Other models have been global, specifying the 3-D spatial distribution, dust temperature, and emissivity. However, the large number of parameters and the differing assumptions about grain properties make the results less than unique. Take, for example, the temperature distribution, $T(r) \propto r^{-\delta}$. Deul & Wolstencroft (1988), Rowan-Robinson et al. (1990), and Hong and Um (1987) assume $\delta = 0.5$ (blackbody), while Good (1988, 1990) solves for it, finding $\delta = 0.36$. Röser and Staude (1978), Reach (1988), and Temi et al (1989) compute $T(r)$ from Mie theory. Dirty silicate spheres or large absorbing spheres will have temperatures close to a blackbody, while small absorbing grains are considerably hotter and have a smaller radial gradient. Collected interplanetary dust particles (IDPs) have irregular structure and heterogenous composition, and their optical properties surely differ from those of homogeneous spheres. Giese et al (1978) proposed large fluffy absorbing particles to explain the observed zodiacal light polarization. Very irregular particles, even large ones (size 10-100 μm), may have wavelength-dependent cross-sections, and thus temperatures which differ from the blackbody approximation. The temperature gradient retrieved from inversion of the zodiacal emission integral yields $\delta =$ 0.33, significantly less steep than that of a blackbody, as described below. Of course, the assumed temperature gradient affects the spatial distribution derived from the model.

The second approach to modeling is to make use of inversion techniques. Hong and Um (1987) developed an inversion method to recover the heliocentric gradient of the volumetric cross section, the product of the spatial density $n(r)$ and the average absorption cross section $\sigma(r, \lambda)$. Applying their method to ZIP data at several elongations, they concluded that $n(r)\,\sigma(r, \lambda)$ can not be represented by a single radial gradient in all directions, that the gradient is less steep than that derived from scattered light observations, and that the infrared σ (r, λ) varies with r in a manner requiring more than one dust component.

Dumont and Levasseur-Regourd (1988) have applied their "nodes of lesser uncertainty" method to IRAS and ZIP data in order to retrieve the dust temperature and albedo and their radial gradients near 1 AU. Using the 12 and 25 μm values from Hauser (1984), based on the preliminary IRAS calibration, they derive a color temperature at 1 AU, T_o = 257 K, and $T(r) = 257\ r^{-0.33}$. The revised IRAS calibration would raise T_o without altering the gradient. This result is very similar to Good's (1988) global model, $T(r) = 266r^{-0.36}$. The 11 and 21 μm ZIP data yield a similar gradient but higher T_o; $T(r) = 298r^{-0.32}$.

When the method is applied to the optical data as well, the albedo at 90 deg phase angle can be retrieved; Levasseur-Regourd et al. (1990b) find A = 0.08 (IRAS) and A = 0.15 (ZIP), with $A(r) \propto r^{-0.3\pm0.1}$ near 1 AU. Levasseur-Regourd et al (1990) have shown that the polarization also depends upon distance in and perpendicular to the ecliptic plane (see Levasseur-Regourd et al., this volume, for more detailed discussion).

In summary, the most important conclusion from the modeling to date is that the optical properties of the dust (specifically the wavelength-dependent absorption cross-section and the scattering function) must change with position in the solar system. Consequently, the heliocentric gradient of the spatial density derived on the assumption of constant optical properties has to be questioned.

The revised absolute calibration and improved spectral coverage from the DIRBE experiment will make more detailed modeling possible. We have other means of analyzing the dust at 1 AU, but analyses of the dust scattering and emission remain the best means of determining average dust properties away from 1 AU.

4. Circumsolar Dust

Detecting the thermal emission from dust particles near the sun is an important means of probing their physical properties. Whereas the visible integral over the line of sight at small elongation angles is weighted towards particles near 1 AU seen in forward scattering, the thermal emission integral is weighted towards the hottest grains closest to the sun. Peterson (1963) stimulated interest in such observations when he predicted that a brightness maximum should be detectable at the edge of the sublimation zone at wavelengths of ~ 2 μm, near the peak in the Planck function for grain temperatures > 1000 K.

A distinct emission peak at 4 solar radii was recorded in coronal scans at 2.2 μm during the 1966 eclipse by both Peterson (1969) and MacQueen (1968), as well as a broad shallow feature at 3.5 R_o. The 4 R_o peak was seen even more clearly during a 5-hour balloon flight with an infrared coronograph two months later; total radiance at 4 R_o was a factor of 2 above the continuum (MacQueen 1968). These data have the advantage of much slower scan rate across the corona. Smaller peaks at 8.7 and 9.2 R_o were also detected. However, balloon observations during the 1983 eclipse show only a slight inflection near 4 R_o at 2.2 μm, although a broad peak centered at 3.8 R_o is present at 1.65 μm (Mizutani et al 1984). Perhaps the amount of dust near the sun does vary with time; sun-grazing comets may play a role.

If silicates are a component of the circumsolar dust, then strong thermal emission is expected in the reststrahlen bands near 10 μm. Mankin et al (1974) and Lena et al (1974) detected 8-13 μm emission near the ecliptic during eclipse. A possible peak near 4 R_o is comparable to the sky noise (Mankin et al) or to the differences between scans (Lena et al).

Since 1983, there have been great advances in infrared detectors. The coronal emission is a problem well-suited for modern, sensitive two-dimensional arrays. Experiments using such arrays are planned for the July 1991 solar eclipse at Mauna Kea (D. Hall, private communication).

The fate of dust particles near the sun is a complex function of their optical properties (Mukai and Mukai 1973, Mukai et al 1974, Lamy 1974, Schwehm & Rohde 1977, Mukai and Yamamoto 1979). Because of their low absorption at visible wavelengths, pure silicate grains can reach ~ 2 R_O before reaching sublimation temperatures. The ratio of the repulsive force of radiation pressure to the force of gravity (β) is always < 1 for all grain sizes, and the grains remain near the sun until they sublimate completely.

Absorbing grains, on the other hand, heat to sublimation temperatures at somewhat larger solar distances. Mukai et al (1974) computed that graphite grains will concentrate in a sublimation zone near 4 R_O, creating a dust ring. As the grains sublimate and their radii shrink, β will increase and the remnant grain will be accelerated outward. Small grains from the solar direction, with speeds > 50 km/s, have been detected from space probes (Berg and Grun 1973, Zook and Berg 1975). Mukai and Yamamoto (1979) proposed a two-component model to fit both the 1-2 μm and the 10 μm observations. They compute that both graphite and p-obsidian grains will form a dust ring at 4-5 R_O, where both components sublimate rapidly. At T ~2100 K, the graphite grains produce the observed 1.6-2.2 μm peaks, while the silicate grains generate the high 10 μm flux.

Given what we have learned about the dust composition from Comet Halley and from studies of interplanetary dust, the next step towards a model for real grains near the sun should consider the progressive physical changes to the carbonaceous organic-rich grain material upon heating, and whether a high-temperature graphitic material will form, which would follow the evolutionary path described here. Moreover, the role of collisions has been neglected in this picture. Yet, Grun et al (1985) have concluded that collisions play the dominant role in the evolution of the interplanetary dust at small heliocentric distances.

5. Science Questions for the Future

This section briefly summarizes the current status and lists some of the science questions to be answered by future work.

A. *Zodiacal emission*

The zodiacal emission has now been well-observed over the year at 60 < ε < 120 deg from IRAS and COBE. It is important that the absolute calibration be resolved, so that an accurate spectral energy distribution can be defined. These results should then be published in tables or plots, so that those without large computers can have access to them. Future observations should concentrate on ε < 60 deg and ε > 120 deg and on improved 5-25 μm spectral resolution, to answer the following questions:

What is the infrared emission as f(ε, β, λ) at 2 < ε < 60 deg and what does this tell us about the spatial distribution and thermal propertiues of the dust at small r?

What is the spectral energy distribution as f(ε, β) from λ 5-25 μm? Is it consistent with our expectations based on IDP composition?

Is 10 μm emission from small silicate grains present?

What is the intensity of the dust emission at 50 < λ < 150 μm? Is there a cold, outer solar system component?

ISO and SIRTF can play an important role in answering these questions.

B. *Dust near the sun*

We can anticipate important new results with modern, sensitive array detectors during the July 1991 solar eclipse. These observations will help answer the following questions.

What is the distribution of dust near the sun? Does it form a spherical halo or is it concentrated towards a plane? (which plane?)
At what temperature(s) do grains sublimate? Is there a well-defined sublimation zone?
Is the amount of dust time-variable? Do sun-grazing comets make a significant contribution?
Is a 10 μm emission feature visible that pinpoints the location of small silicate grains?

A dust detector on a solar probe could measure the dust flux and orbital distribution and the size distribution, to help determine the relative role of collisions and sublimation in the destruction of grains near the sun (Tsurutani and Randolph, this volume).

C. *Modeling the dust emission*

Models have given us a general picture of the dust spatial distribution and optical properties. Inversion methods are a useful tool and should be applied to the DIRBE data. To progress, however, future models have to wrestle with the properties of real grains and should not ignore what has been learned about the dust from other sources. The following questions are relevant:

What physical changes to the grains can cause the albedo variation with r?
What optical/infrared properties of real grains are consistent with $T(r) \propto r^{-0.33}$?
What are the scattering and emitting properties of the mixed silicate + carbonaceous IDPs? Are they consistent with the zodiacal emission?
How will the heterogeneous IDP particles evolve when strongly heated near the sun?

Ultimately, dynamical models -- sources, sinks, orbital evolution - have to be linked to the "static" zodiacal light models.

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