IRAS DUST BANDS AND THE ORIGIN OF THE ZODIACAL CLOUD

S. F. DERMOTT and P. D. NICHOLSON
Center for Radiophysics and Space Research
Cornell University
Ithaca, NY 14853
USA

ABSTRACT. Previous discussions of the origin of the zodiacal cloud have attempted to distinguish between an asteroidal and a cometary source on the basis of collisional dynamics, that is, by calculating the rates of production and destruction of particles from the two possible sources. The uncertainties in these calculations are too large to permit a useful conclusion. The recognition that the solar system dust bands discovered by IRAS are probably produced by the gradual comminution of the asteroids in the major Hirayama asteroid families may allow us to estimate, with *comparative* confidence, the contribution to the zodiacal cloud of the asteroid belt as whole.

1. Introduction

Prior to the analysis of the data returned by IRAS, the origin of the particles that make up the zodiacal cloud was not known. While it was accepted that the source is either asteroidal or cometary, it was not possible to determine which of these two possible sources, if any, is dominant. While many attempts have been made to calculate the rate of production and destruction of asteroidal and cometary particles, the sources of uncertainty in these calculations are both large and numerous (see section 3). Two recent developments have provided important inputs to this problem.

Recent microscopic analysis of 200 interplanetary dust particles reported by Brownlee at this meeting (Schramm et al., 1988) have shown that while 45% of the particles (those classified as chondritic porous) are probably cometary, 37% of the particles (those classified as chondritic smooth) have characteristics (chemical alteration by liquid water) that suggest an asteroidal origin.

During its all-sky survey, IRAS discovered three prominent bands of warm (165 – 200 K) emission circling the sky at geocentric ecliptic latitudes of −10, 0 and +10 degrees (Low et al, 1984; Neugebauer et al., 1984). Low et al. (1984) suggested that the bands may be associated with dust derived from asteroidal collisions, while Sykes and Greenberg (1986) argued that random distintegrations of single asteroids in the 15 km diameter range are frequent enough to account for the IRAS observations. While these suggestions are important, neither does much to advance the debate. The fact that IRAS observed dust in the asteroid belt does not necessarily imply that the dust is asteroidal in origin. Numerous short-period comets have inclinations similar to those of the IRAS dust bands; the peak in the distribution of the observed inclinations is actually close to 10 degrees. Many of the observed short-period comets also have pericenters between 2 and 4 AU and, because of selection effects, we cannot rule out the possibility that a large number of short-period

D. McNally (ed.), Highlights of Astronomy, Vol. 8, 259–266.

comets with pericenters in the asteroid belt remain undetected. Furthermore, those comets that remain undetected because of low vaporization rates are the objects that are most likely to generate long-lived dust belts that extend around the sky.

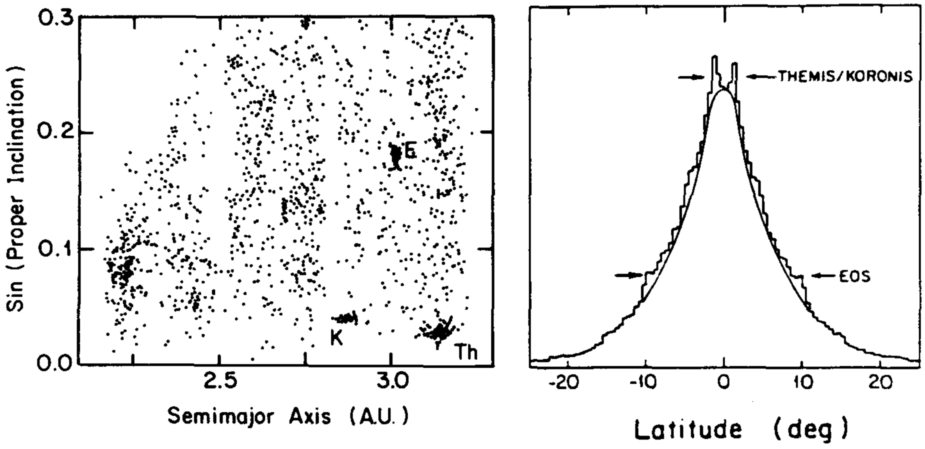

Figure 1. The proper inclination and semimajor axis of all asteroids listed in the TRIAD file are shown on the left. The clusters of asteroids at the points marked K, E, and Th are the Koronis, Eos and Themis asteroid families. The figure on the right shows a simulation of the latitudinal distribution of dust particles associated with the ~ 2000 asteroids in the TRIAD file. The peaks marked Themis/Koronis and Eos arise from the clustering of inclinations associated with the three major families.

Dermott et al. (1984) pointed out (a) that the latitudes of the bands appear to coincide with the known latitudes of the three most prominent Hirayama asteroid families, that is, the Eos, Themis, and Koronis families (Fig. 1), and (b) that the expected *equilibrium* number density of particles in the 10 to 100μm size range associated with the families could be large enough to account for the IRAS observations. Dohnanyi (1969) has shown that despite the uncertainties in the physics of individual collisions, the *equilibrium* particle size-frequency distribution can be described with comparative confidence. In a series of papers, Dermott et al., (1984, 1985, 1986, 1988a) gave a detailed description of the expected geometry of the bands and described stringent tests of the asteroidal family hypothesis. The beauty of the asteroidal family model is that it is highly specific and clearly testable, although conclusive tests are far from simple. If the geometry of the bands could be related to the orbital elements of the families, then, since the particle production rate of the family members is proportionately no different from that of the rest of the asteroid belt, we would have conclusive evidence that asteroids are a significant source of the particles in the zodiacal cloud. Further outstanding problems that would then have to be addressed are the transport of particles from the asteroid belt to the Earth and the orbital eccentricities of the particles on arrival at the Earth. (Dermott and Gomes, 1988c).

2. Modelling the IRAS solar system dust bands

The data returned by IRAS showed, for the first time, that the structure of the zodiacal cloud is not entirely smooth. Some of the raw data used in our analysis of the newly discovered structure are shown in Figs. 2 and 3. The dust bands evident in these figures extend round the sky in unbroken bands that are approximately parallel to the ecliptic. A simplified view of the cross-section of a dust band is shown in Fig. 4. As a result of their vertical and radial harmonic oscillations, the particles spend more time near the outer edges of the boxes marked AABB than in their interiors, with the result that there are concentrations of particles in the corners of the boxes. Measurement of the apparent variations of the geometry of the bands, as seen from the Earth, with the time of the year and the elongation angle, ϵ, can be used to determine the orbital elements of the dust particle orbits.

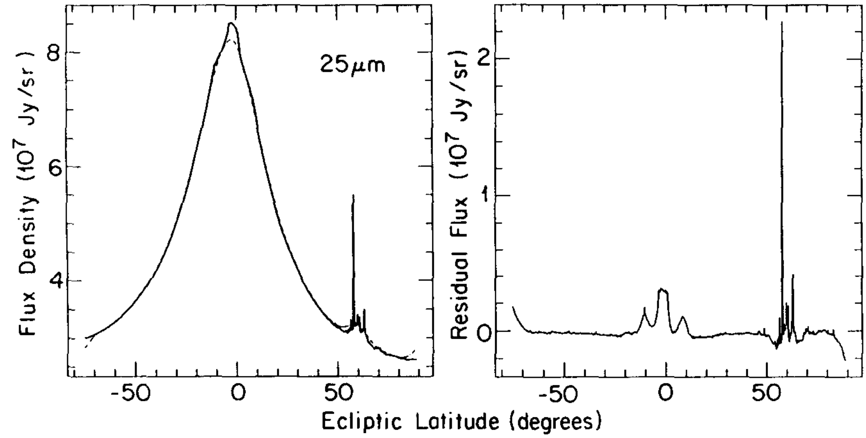

Figure 2. Fourier methods were used to separate the smooth, large-scale structure of the zodiacal background, shown on the left, from the narrower dust bands shown on the right. The short-scale structure evident at high latitudes is due to the galaxy.

There are two major considerations. (1) The latitudinal separation of the bands as seen from the Earth, β, varies with elongation angle, ϵ, and measurement of these variations leads to a determination of the inclination of the dust particle orbits and the heliocentric distances of the inner edges of the bands (the points marked P in Fig. 4). (2) The variation of the mean latitude of the bands with ecliptic longitude, or time of the year, due to the gravitational perturbation of the dust particle orbits by the planets leads to a determination of the forced inclinations and nodes and this also leads to a determination of the heliocentric distances of the bands (Fig 5).

The chief difficulties in interpreting the geometry of the bands are (1) the geocentric viewpoint of the IRAS telescope and (2) the large range of elongation angles sampled by IRAS. These difficulties cannot be completely removed by a simple coordinate transformation. Our geocentric viewpoint gives rise to small systematic displacements in the apparent locations of the bands which would not arise if the bands were viewed from the Sun. To overcome these and other difficulties we have constructed a three-dimensional numerical model that permits the calculation of the distribution of night sky brightness that would be produced by any particular distribution of dust particle orbits. This model includes the effects of planetary perturbations on the dust particle orbits, reproduces the exact viewing geometry of the IRAS telescope, and allows for the eccentricity of the Earth's orbit. The result is a model for the variation with ecliptic latitude of the brightness observed in a given waveband as the line of sight of the telescope sweeps through the model dust band at a constant elongation angle.

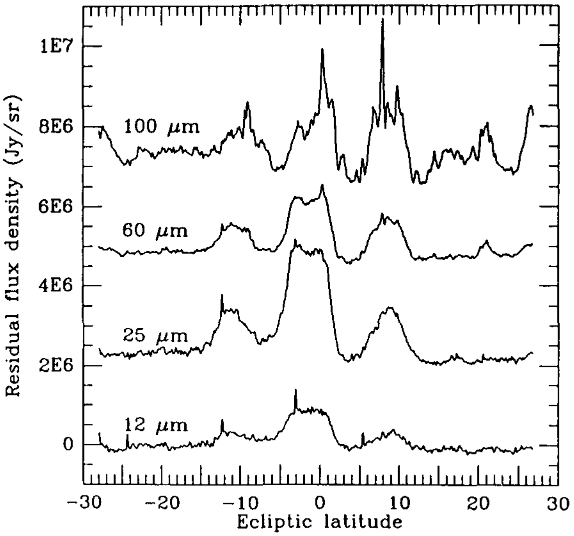

Figure 3. The dustbands seen in the four IRAS wavebands. The structure seen in the 100 μm waveband, although very similar to the structures seen in the other wavebands, is actually due to a region of star formation in the galaxy (Rowan-Robinson, private comm.) Some of the latter structure is also seen in the 60 μm waveband.

Some of our results are shown in Figs. 4 and 5. The parallax observations (Fig. 4) show that the inner edge of the "ten-degree" bands is close to 2.44 AU, while the inclination of the points P as seen from the Sun is 8.4 degrees. This is in *apparent* conflict with the asteroidal family model since the pericenter distance of the Eos band is to 2.8 AU while the mean inclination of the Eos family members is 10.2 deg.

In Fig. 5 an observed dust band profile is compared with the predicted profile for the Eos and Themis asteroid families. Several important comments can be made about this comparison (which is typical of the numerous other comparisons that we have made). (1) The observed latitudes of the peaks that we associate with the Themis family are in excellent agreement with the predictions based on secular perturbation theory. (2) The observed latitudes of the peaks that we associate with the Eos family are less than those predicted by one or two degrees (in good agreement with the discrepancy found from the parallax measurements). (3) The observed profiles are much broader and more rounded than the model profiles.

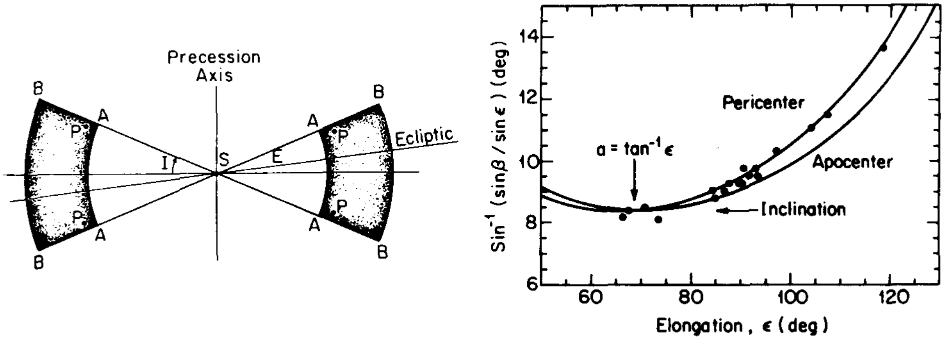

Figure 4. (Left): Cross-sectional view of a dustband. Particles are concentrated along the surfaces A (pericenter bands) and B (apocenter bands). The points P represent the positions of the apparent peaks in the latitudinal brightness variation as seen from the Earth. (Right): Variation of the geocentric ecliptic latitude β of the "ten-degree" dust bands with elongation angle, ϵ, as measured from IRAS HCON3 data. The curves P and A mark the bounds on β for a band with an inclination of 8.4 degrees, distance 2.44 AU, forced eccentricity 0.107 and forced pericenter of 32 degrees.

We have recently shown (Dermott et al., 1988b) that these discrepancies probably do not detract from the asteroidal family model. On the contrary, they may be evidence that particles formed in the asteroid belt spiral in towards the Earth. The model profile shown in Fig. 5 allows only for the dispersion in orbital elements displayed by the known family members. However, the thermal flux from the dust bands is due principally to those particles in the 10 to 100 μm size range and it is possible that the orbits of these particles decay due to Poynting-Robertson light drag before the particles are lost from the system (Dermott et al., 1986). If this is the case, then the particles in the dust bands will have significant dispersions in both their proper and their forced orbital elements. Our numerical model shows that dispersion of the orbital elements acts both to broaden a band and reduce its apparent inclination and we have suggested that the dispersion of the forced orbital elements due to the secular resonances at the inner edge of the asteroid belt may act to define the observed inner edges of the dust bands. Thus, by postulating that particles are transported out of the asteroid belt by P-R light drag we may be able to account for both the observed broadness of the dust band profiles and the apparent reduction in the inclination of the "ten-degree" bands that we associate with the Eos family.

3. The size of the source

Our numerical model also permits an accurate modelling of the total cross-sectional area of the particles associated with a given band. The observed areas are $\approx 2 \times 10^{19}$ cm^2. Since the orbits of the asteroids intersect, it is certain that they occasionally suffer high-velocity collisions and it is equally certain that the major asteroidal families, the Eos, Themis, and Koronis families, are the results of such collisions. However, the amount of dust that the disintegration of a single collision generates is highly uncertain. Consider the following, over-simplified, description of this type of calculation. If the size-frequency distribution of the particles in a given population is described by a power law of the form

$$\frac{dN(r)}{dln(r)} = \left(\frac{r}{r_o}\right)^{-3(q-1)}$$

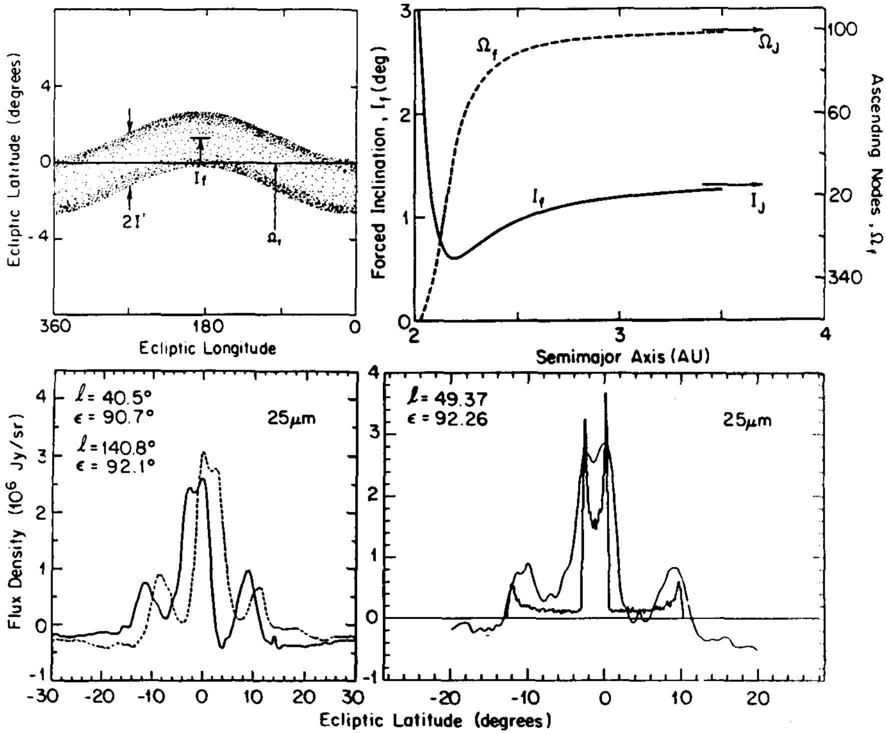

Figure 5. (Top left): Variation of the ecliptic latitude of a dust band with ecliptic longitude, as measured in a sun-centered coordinate system. The latitudinal width of the band at all longitudes is $2I'$, twice the proper inclination of the dust particle orbits. The amplitude of the the apparent sinusoidal variation in latitude is determined by the forced inclination, I_f. (Top right): Variation of the forced inclination I_f and the corresponding longitude of the ascending node Ω_f with distance from the Sun. (Bottom left): Two observations of the dust bands at different geocentric ecliptic longitudes showing the large variation in ecliptic latitude predicted by Dermott et al. (1984). (Bottom right): An observed dust band profile is compared with the prediction based on the distribution of orbits in the Eos and Themis families.

then four parameters are needed to specify the distribution. These are the scale factor r_o, the coefficient q, and the maximum and minimum particle radii, r_{max} and r_{min}. We can relate the surface area, A, of the dust to its total volume by calculating the equivalent radius, R_e, of that volume and by allowing that r_{max} is some fraction γ of R_e. The observed sizes of the asteroids in the major families suggest that $\gamma \approx 0.64$. The variation of A with q for various values of r_{min} is shown in Fig. 6.

If $q = 2$, then the disintegration of a single asteroid of diameter 15 km would provide the requisite area of dust (Sykes and Greeberg, 1986). However, since we have no way of knowing the appropriate value of q, and since varying q over a range as narrow as 1.8 to 2.2 produces a factor of 10^4 variation in A, we have little confidence that this type of prediction is useful. However, some semblance of confidence is restored if we consider the *equilibrium* size-frequency distribution. Dohnanyi (1969) has shown that despite the vagaries associated with the individual distintegrations the *equilibrium* size-frequency distribution is well-described by a power law with $q = 1.837$. If the Hirayama families represent equilibrium distributions down to some size as small as $\sim 100\mu m$, which we admit is debatable, then the equivalent radii needed to satisfy the observations are closely similar to the observed equivalent radii of the major families (Dermott et al., 1984).

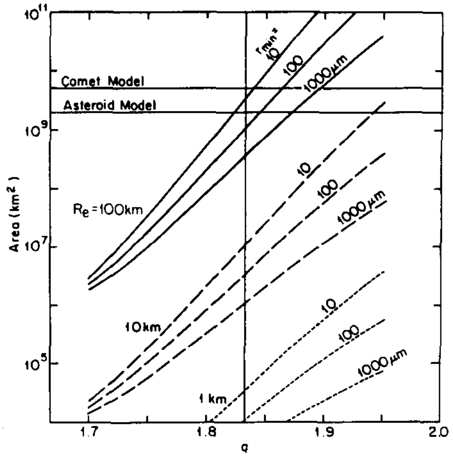

Figure 6. The total volume of material, as represented by the equivalent radius, R_e, needed to produce a given cross-sectional area in terms of the index of the power law distribution, q, and the lower cut-off in the particle size distribution, r_{min}. The vertical line refers to the equilibrium distribution, $q = 1.837$.

4. Conclusions

The arguments that we have presented for the asteroidal origin of a significant fraction of the particles in the zodiacal cloud are powerful since they are largely geometrical and depend only on physical processes, for example, secular perturbation theory, that are well understood. We have shown that the most prominent dust bands are probably derived from the major asteroidal families, that is, the Eos and Themis families, and Sykes (1988) reports that he has been able to detect a band that he associates with the Koronis family. However, to reconcile the observed shapes of the profiles, and the latitude of the "ten-degree" bands, with the predictions based on our accurate numerical models, we have to allow that the dispersions in the orbital elements of the very small dust particles ($r <$

$100\mu m$) are larger than those of the parent asteroids. We have argued that this could be evidence for orbital decay due to Poynting- Robertson light drag and that the asteroids could be the source of "chondritic smooth" particles detected by Brownlee. The analysis of the available IRAS data is far from complete and we must expect that these arguments will undergo considerable refinement. Of particular interest, although not addressed in this short review, are the numerous faint bands discovered by Sykes (1988) that do not appear to be related to any known asteroidal families.

5. References

Dermott, S. F., Nicholson, P. D., Burns, J. A., and Houck, J. R. (1984) "Origin of the solar system dust bands discovered by IRAS", *Nature*, **312**, 505-509.

Dermott, S. F., Nicholson, P. D., Burns, J. A., and Houck, J. R. (1985) 'An analysis of IRAS' solar system dust band data', In "*Properties and interaction of interplanetary dust*", eds. R. H. Giese and P. Lamy, Riedel, Dordrecht, 395-409.

Dermott, S. F., Nicholson, P. D., and Wolven, B. (1986) 'Preliminary analysis of the IRAS solar system dust data', In "*Asteroids, Comets and Meteors, II*", eds. C-I. Lagerkvist and H. Rickman, Uppsala, pp. 583-594.

Dermott, S. F., Nicholson, P. D., Kim, Y., and Wolven, B. (1988a) 'The impact of IRAS on asteroidal science', In "*Comets to Cosmology*", ed. A. Lawrence, Springer-Verlag, Berlin, pp. 3-18.

Dermott, S. F., Nicholson, P. D., Gomes, R., and Malhotra, R. (1988b). "Modelling the IRAS solar system dust bands", *Adv. Space Res.* (in press).

Dermott, S. F., and Gomes, R. (1988c). "Orbital decay of asteroidal dust particles due to Poynting-Robertson light drag and the origin of interplanetary dust particles" *Icarus* (submitted).

Dohnanyi, J. S. (1969) "Collisional model of asteroids and their debris", *J. Geophys. Res.*, **74**, 2531-2554.

Low, F. J. et al. (1984) "Infrared cirrus: new components of the extended infrared emission", *Astroph. J. (Letters)* **278**, L19.

Neugebauer, G. et al. (1984) "Early results from the infrared astronomical satellite", *Science*, **224**, 14-21.

Schramm. L. S., Brownlee, D., and Wheelock, M. M. (1988) "Major element composition of stratospheric micrometeorites", *Meteoritics* (in press).

Sykes, M. V. and Greenberg, R. J. (1986) "The formation and origin of the IRAS zodiacal dust bands as a consequence of single collisions between asteroids", *Icarus*, **65**, 51-69.

Sykes, M. V. "IRAS observations of extended zodiacal structures", *Astrophys. J. (Letters)*, **334**, (in press).