Asteroidal Dust

Stanley F. Dermott
University of Florida

Daniel D. Durda
Southwest Research Institute

Keith Grogan
NASA Goddard Space Flight Center

Thomas J. J. Kehoe
University of Florida

There is good evidence that the high-speed, porous, anhydrous chondritic interplanetary dust particles (IDPs) collected in Earth's stratosphere originated from short-period comets. However, by considering the structure of the solar-system dust bands discovered by IRAS, we are able to show that asteroidal collisions are probably the dominant source of particles in the zodiacal cloud. It follows that a significant and probably the dominant fraction of the IDPs collected in Earth's stratosphere also originated from asteroids. IDPs are the most primitive particles in the inner solar system and represent a class of material quite different from that in our meteorite collections. The structure, mineralogy, and high C content of IDPs dictate that they cannot have originated from the grinding down of known meteorite types. We argue that the asteroidal IDPs were probably formed as a result of prolonged mechanical mixing in the deep regoliths of asteroidal rubble piles in the outer main belt.

1. INTRODUCTION

In our collections on Earth, we have an abundance of meteorite samples from three major sources of extraterrestrial material: the asteroid belt, the Moon, and Mars. Some of the source bodies of these meteorites have experienced major physical, chemical, and mineralogical changes since the time of their formation; hence the resulting meteorites, while providing vital information on the origin and evolution of the parent bodies, give limited information on the nature of the primordial particles out of which these bodies accreted. However, this broad statement does not apply to unequilibriated ordinary chondrites. These primitive meteorites are composed almost entirely of particles that were freely orbiting in the solar nebula and although they show some signs of thermal metamorphism (*McSween et al.,* 1988) and aqueous alteration (*Zolensky and McSween,* 1988), they do provide information on initial conditions.

A fourth class of extraterrestrial material consists of particles recently accreted by Earth from the zodiacal cloud. These are the small, mostly 5–25-μm diameter, interplanetary dust particles (IDPs) collected, gently and mostly unaltered, in Earth's stratosphere and the larger micrometeorites (MMs) and cosmic spherules collected from polar ices and deep-sea floors (*Brownlee,* 1985; *Jessberger et al.,* 2001). Some of the IDPs appear to be the most primitive material in the solar system and, at present, provide our best source of information on the nature of the particles in the preplanetary solar nebula (*Bradley,* 1999). Observations of microcraters on the Long Duration Exposure Facility (LDEF) confirmed that each year Earth accretes 3×10^7 kg of dust particles, a mass influx ~100× greater than the influx associated with the much larger meteorites that have masses between 100 g and 1000 kg. The action of sunlight on these small interplanetary particles causes their orbits to decay into the Sun on timescales of less than 10 m.y. Thus, the dust is not original but must be continuously replenished. The emphasis of this chapter is on the origin of these IDPs and MMs and whether they are asteroidal or cometary. There is now good evidence that interstellar dust particles also penetrate the inner solar system (*Grün et al.,* 1993) and may provide a significant contribution to the dust flux at 1 AU (*Grün et al.,* 1997). In addition, small dust particles that originate in the Kuiper Belt may be transported to the inner solar system (*Flynn,* 1996; *Liou et al.,* 1996). However, the larger Kuiper Belt particles, which have long orbital-decay periods, are likely to be destroyed by collisions or removed by the giant planets before reaching Earth.

In section 2, we give a brief description of our current understanding of the nature of IDPs, emphasizing those features that may separate the putative cometary particles from those that are asteroidal. Despite the enormous advances that have been made in recent years in our understanding of these highly interesting particles, the question of their provenance, whether they are predominantly asteroidal, predominantly cometary, or a useful mixture of both, remains controversial. In section 3, we attempt to answer this key question by looking beyond the particles themselves to the zodiacal cloud as a whole.

Observations by the Infrared Astronomical Satellite (IRAS) in 1983 revealed that the zodiacal cloud is not devoid of large-scale structure (*Low et al.,* 1984). We now know that the Sun is not at the center of symmetry of the cloud (*Kelsall et al.,* 1998; *Dermott et al.,* 1999), that the plane of symmetry is warped (*Dermott et al.,* 2001), and that clouds of dust trail Earth in its orbit that are associated with a circumsolar ring of dust particles in resonant lock with the planet (*Dermott et al.,* 1994a; *Reach et al.,* 1995). Ultimately, after more analysis, these features should contribute significant information on the origin and evolution of the cloud (*Dermott et al.,* 2001). However, for the purposes of this chapter, it is clear that the most direct and important source of information on the origin of the particles in the zodiacal cloud is provided by the solar-system dust bands. Remarkably, these dust bands have now been observed from the ground, without the aid of a telescope, simply by using a wide-angle lens attached to a cooled CCD camera (*Ishiguro et al.,* 1999). In section 3, we show that these dust bands must originate from the disintegration of asteroids (*Low et al.,* 1984; *Dermott et al.,* 1984; *Sykes and Greenberg,* 1986; *Grogan et al.,* 2001), and we use the IRAS observations to estimate, with comparative confidence, the total asteroidal contribution to the zodiacal cloud.

In section 4, we discuss the collisional evolution of the asteroid belt. Earlier discussions on the sources of the particles in the cloud were based on estimates of the dust production rates from comets (*Whipple,* 1967; *Delsemme,* 1976) and asteroids (*Dohnanyi,* 1976). In the case of comets, these calculations may have been strengthened by the discovery of cometary trails (*Sykes and Walker,* 1992), and the analysis of these trails may lead to more accurate estimates of the average cometary input to the cloud (*Lisse et al.,* 1998; *Lisse,* 2001). However, we consider that the uncertainties in these types of calculation, both for the asteroidal and the cometary sources, are still too large to provide definitive results. We support this statement in section 5 by a discussion of the current uncertainties in the asteroidal dust production rate.

2. INTERPLANETARY DUST PARTICLES

Important reviews of the nature of IDPs and MMs have been given by *Brownlee* (1985), *Bradley et al.* (1988), and *Rietmeijer* (1988) and are to be found in the conference proceedings edited by *Zolensky et al.* (1994) and *Gustafson and Hanner* (1996). The most recent summaries, on which the comments in this chapter are largely based, have been given by *Bradley* (1999) and *Jessberger et al.* (2001).

The extraterrestrial origin of IDPs has been confirmed by the presence of solar-wind noble gases (*Rajan et al.,* 1997), solar-flare tracks, and solar-wind-irradiated rims (*Bradley et al.,* 1984). In addition, the nonsolar isotopic abundances of D, H, and N (*Messenger and Walker,* 1996) of some of these particles prove not only that they are extraterrestrial but also that some of these particles existed in the presolar nebula out of which the planets formed. Roughly 15% of the particles are essentially single-mineral grains or a few-mineral grains. However, the most common IDPs (75%) are unequilibriated, fine-grained mixtures of thousands to millions of mineral grains and amorphous components. Their composition is chondritic and similar, within a factor of 2, to the most primitive, C-rich, CI carbonaceous chondrites (*Schramm et al.,* 1989; *Thomas et al.,* 1996). *Jessberger et al.* (2001) have noted that the fact that the composition of these tiny particles is chondritic is remarkable "because most chondritic meteorites do not typically have chondritic elemental composition at the 10-micron size scale. Most meteorites are coarser grained and common 15-micron volumes are single mineral grains." It follows that most IDPs cannot be formed from the simple grinding down of known meteorites, but must result "from the mechanical mixing of large numbers of randomly selected tiny grains." The compositions of MMs are similar to CM- and CR-type carbonaceous chondrites. However, there are some very important differences between carbonaceous chondrites and both MMs (*Maurette et al.,* 1996) and IDPs. In particular, both MMs and IDPs are markedly C-rich. In fact, some IDPs have C contents about 2–3× higher than the most primitive, C-rich, carbonaceous chondrites (*Thomas et al.,* 1994). Moderately volatile elements such as Zn and Ga also show systematic enrichments in IDPs by a factor of 2–4 above CI chondrites (*Flynn et al.,* 1996).

On the basis of mineralogy, as revealed by transmission electron microscopy (TEM), infrared (IR) spectroscopy, and X-ray diffraction analyses, IDPs can be divided into two major groups: chondritic and nonchondritic (*Klöck and Stadermann,* 1994). The nonchondritic group is poorly studied, with only a few very refractory IDPs having received thorough mineralogic and isotopic characterization (*Zolensky,* 1987; *McKeegan,* 1987). The chondritic group is well studied and has been further subdivided into hydrous and anhydrous subgroups. The hydrous chondritic IDPs have been extensively altered by liquid water inside a parent body (*Zolensky and McSween,* 1988; *Zolensky and Barrett,* 1994), and this fact suggests that they are asteroidal. The anhydrous chondritic IDPs have, in general, higher porosities (*Corrigan et al.,* 1997) and consist mainly of olivine and/or pyroxene. In particular, the pyroxene-rich particles are physically, chemically, and isotopically more primitive than any other materials available for laboratory study. Most of these particles are complex admixtures of 0.1–5-μm-diameter single-mineral grains (most commonly enstatite and Fe-Ni sulfides), amorphous material, carbonaceous material, and GEMS [submicrometer spheroidal grains of silicate glass with embedded metal and sulfides (*Bradley,* 1999)]. Some anhydrous chondritic IDPs contain enstatite whisker crystals (*Fraundorf,* 1981) believed to be early nebular condensates. Other chondritic IDPs have very large D/H and

^{15}N-isotopic anomalies (*Messenger and Walker,* 1996), and these provide evidence for the survival of presolar interstellar components. It has even been suggested that these IDPs could actually contain a large quantity of well-preserved aggregates of circumstellar and/or interstellar materials (*Bradley,* 1999).

Reflectance spectra of chondritic IDPs in the visible wavelength range show that whereas most hydrous IDPs have spectra similar to carbonaceous chondrites and C-type asteroids, many of the most porous anhydrous chondritic IDPs have spectra similar to outer-belt P- and D-type asteroids (*Bradley et al.,* 1996). It has therefore been suggested that the highly primitive and porous anhydrous chondritic IDPs probably originate from comets and/or outer-belt (P- and D-type) asteroids. However, a recently fallen unique carbonaceous chondrite (Tagish Lake) with a hydrous mineral assemblage shows an IR reflectance spectra identical to D-class asteroids, which might therefore preclude these asteroids from being the parents of the anhydrous IDPs (*Hiroi et al.,* 2001). The mineralogy of the hydrous chondritic IDPs is roughly similar (but not identical) to that of the CI, CM, and CR carbonaceous chondrites, and these are thus believed to derive from asteroids (*Bradley,* 1999). We note that *Keller et al.* (1993) argue that these well-mixed aggregates could be agglutinates from asteroidal regoliths. *Klöck and Stadermann* (1994) have argued that anhydrous chondritic IDPs, although mineralogically unlike known meteorites, contain forsterite with a unique chemical signature that is also present in primitive chondrites, establishing a possible link between these IDPs and meteorites. Thus, there is some evidence that both hydrated and anhydrous chondritic IDPs could come from asteroids.

We should note that there may be very little difference between an outer-belt P- or D-type asteroid and a cometary nucleus (*Brownlee,* 1996). Nevertheless, the question of the origin of the anhydrous chondritic IDPs is of outstanding importance. We need to know if we already have samples of comets originating in the Kuiper Belt in our collections or whether, in order to analyze a real cometary particle, we must have a sample-return mission. To try to settle this question, *Brownlee et al.* (1995) have used the thermally stepped He-release method developed by *Nier and Schlutter* (1993) to determine the atmospheric entry speed of IDPs. *Jackson and Zook* (1992) claim that there is little overlap between the geocentric encounter velocities of asteroidal and cometary particles and thus that the high-speed, strongly heated particles must be cometary, whereas the low-speed, unheated particles are probably asteroidal. The validity of this entry-speed criterion is discussed in section 5. *Brownlee et al.* (1995) analyzed a set of IDPs with computed entry velocities of 20 km s^{-1}, which they consider to be almost certainly cometary, and found that these particles are all porous anhydrous chondritic IDPs dominated by GEMS. This would appear to be conclusive evidence that the porous anhydrous chondritic IDPs are cometary. However, while accepting the conclusion of Brownlee et al., we argue here that the dominant source of the particles in the zodiacal cloud is probably asteroidal. The cometary particles are certainly of particular interest, because comets may preserve unprocessed material from the presolar molecular cloud that gave birth to our solar system. However, the asteroidal IDPs are equally interesting, partly for the same reason, but also because they appear to be samples of asteroids, probably the more friable and more distant asteroids, that are not well represented in our meteorite collections.

3. SOLAR SYSTEM DUST BANDS

Observations made by IRAS were the first to reveal fine structure in the zodiacal cloud. Figure 1 shows a Fourier-filtered IRAS observation of the zodiacal cloud in the 25-μm infrared wave band, illustrating the smooth low-frequency background cloud and the high-frequency residual structure that we associate with the solar-system dust bands (*Grogan et al.,* 2001). It is important to note here that because the low-frequency component of the dust bands is indistinguishable from the low-frequency background zodiacal cloud, the high-frequency residuals resulting from the

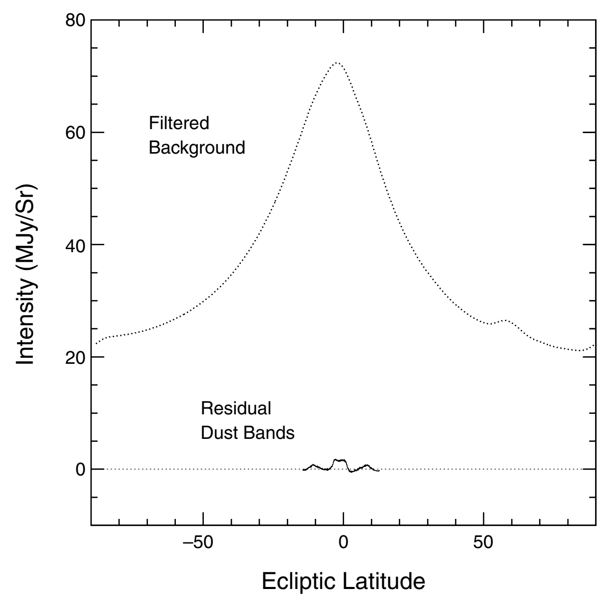


Fig. 1. Fourier-filtered IRAS observation of the zodiacal cloud in the 25-μm infrared wave band, showing the smooth low-frequency background cloud (upper curve) and the high-frequency residual structure (lower curve). This pole-to-pole observation was made at 90° solar elongation (the angle between the telescope pointing direction and the Earth-Sun line) in the direction leading Earth in its orbit when the planet was at an ecliptic longitude of 293°. The high-frequency residuals, which we associate with the solar-system dust bands, can be seen as projecting "shoulders" in the unfiltered IRAS observation near latitudes of ±10° and a central "cap" near 0°. The filtered dust-band profile above merely represents the "tip of the iceberg" in terms of the dust-band material in the zodiacal cloud (*Dermott et al.,* 1994b). The structure around 60° latitude (upper curve) is due to dust in the plane of the galaxy (adapted from *Grogan et al.,* 2001).

filtering process will merely represent the "tip of the iceberg" in terms of the total contribution of dust-band material to the zodiacal cloud (*Dermott et al.,* 1994b). In the unfiltered IRAS observations, the dust bands appear as projecting "shoulders" near latitudes of ±10° and a central "cap" near 0°. We argue that these dust bands are associated with the collisional debris of the *Hirayama* (1918) asteroid families (*Dermott et al.,* 1984; *Sykes and Greenberg,* 1986; *Grogan et al.,* 1997; *Reach et al.,* 1997), the near-ecliptic dust bands with the Themis and Koronis families, and the 10° band with the Eos family; as such they represent a unique observational constraint on the contribution of asteroidal material to the zodiacal cloud.

Our approach to generating a physical model for the various components of the zodiacal cloud, including the dust bands, is essentially a two-step process: (1) Given a postulated source of dust particles, we numerically investigate the orbital evolution of the particles due to Poynting Robertson (P-R) light drag and solar-wind drag (*Burns et al.,* 1979), using equations of motion that also include the effects of radiation pressure and planetary gravitational perturbations (*Dermott et al.,* 1992). (2) Once these dust-particle orbits have been computed for a range of particle sizes, their distribution is visualized in three dimensions via the FORTRAN code SIMUL (*Dermott et al.,* 1988; *Grogan et al.,* 1997), taking into account the thermal and optical properties of the particles and their variation with particle size. Using this tool, the viewing geometry of any telescope can be reproduced exactly, allowing IRAS-type brightness profiles to be created and compared with the observed profiles.

A dust band is a toroidal distribution of asteroidal dust particles with common proper inclinations, common forced inclinations, and common forced longitudes of ascending node (*Dermott et al.,* 1984). The particles' common proper inclination (representing their "intrinsic" inclination) derives from their common source in a given asteroid family, and their common forced inclinations and longitudes of ascending node [reflecting the effect of secular planetary perturbations; for further explanation see, for example, *Murray and Dermott* (1999)] result from the dominant perturbing force of Jupiter on particles located in the outer part of the main asteroid belt. Figure 2 shows some results from our numerical simulations, illustrating the variation of the forced inclination and the forced longitude of ascending node with semimajor axis at the present epoch (Julian Date 2450700.5) for asteroid-family dust particles with diameters of 10, 100, and 200 μm (*Dermott et al.,* 2001). The forced inclination and the forced longitude of ascending node of the asteroid-family particles define the orientation of the mean plane of the dust band associated with the family and are a function of semimajor axis, time, and particle size. The low dispersion of the forced inclinations and longitudes of ascending node of these asteroidal particles in the region of the main asteroid belt (≥2.5 AU), regardless of particle size, is the fundamental reason why dust bands are observed. However, the effects of secular perturbations on particles in highly eccentric orbits, typical of particles that are cometary in origin, prevent such well-defined dust bands from being formed (*Liou et al.,* 1995).

As large dust particles (≥100 μm in diameter) encounter the ν_{16} secular resonance at the inner edge of the asteroid belt (at ~2 AU), the effect of the resonance acts to disperse their forced inclinations and forced longitudes of ascending node. The ν_6 secular resonance (also at ~2 AU) produces analogous behavior in the forced eccentricities and forced longitudes of pericenter of the dust particles. The effects of passage through these secular resonances are far more pronounced on the waves of large (~100-μm-diameter) dust particles compared to the waves of small (~10-μm-diameter) dust particles due to the weaker effects of P-R and solar-wind drag on the large particles (*Wyatt and Whipple,* 1950) and their consequently slower inward evolution toward the Sun. The large particles are thus acted on by the resonances for longer periods of time. The orbital-element distributions of the large asteroidal dust particles therefore lose their characteristic family signatures in the inner region of the main belt and diffuse into the (low-frequency) zodiacal background cloud. We continue to investigate the dynamics of even-larger particles, up to and beyond 500 μm.

In this new large particle regime, we will need to incorporate the effects of particle-particle collisions into our simulations, as the timescales for the particles' orbits to decay into the Sun due to P-R and solar-wind drag become comparable with the particles' collisional lifetimes (*Grün et al.,* 1985; *Wyatt et al.,* 1999). Some particles may therefore not penetrate far into the inner solar system. The nature of the size-frequency distribution of the particles will be a complex function of dust production rates, P-R and solar-wind drag rates, collisional lifetimes and the nature of particle-particle collisions, and will, presumably, vary with heliocentric distance. The situation is further complicated by the fact that even if the size distribution of the debris resulting from an asteroidal collision could be described by a power law (*Dohnanyi,* 1969), the size-frequency power-law index, q, will reflect the characteristics of the parent. The equilibrium size distribution of the collisional cascade originating from a single asteroid has been shown to be a function of the impact strength of that asteroid (*Durda and Dermott,* 1997). Thus, it is possible for the value of q associated with a given family to be different from that of other families and different from the value for the background cloud. In the case of a "rubble pile" (*Davis et al.,* 1989), the value of q associated with the initial disruption may be significantly higher than that associated with the disruption of a solid, coherent asteroid. This provides us with further motivation to relate the dust bands to given parent bodies in the main belt. However, as a first step in answering the fundamental question of the extent to which large and small particles contribute to the dust-band emission, we model the size-frequency distribution as a single power law. We will refine this assumption in the future when we have a better understanding of the role of the complicating factors outlined above.

The forced elements of dust particles obtained from numerical simulations, combined with the proper elements of

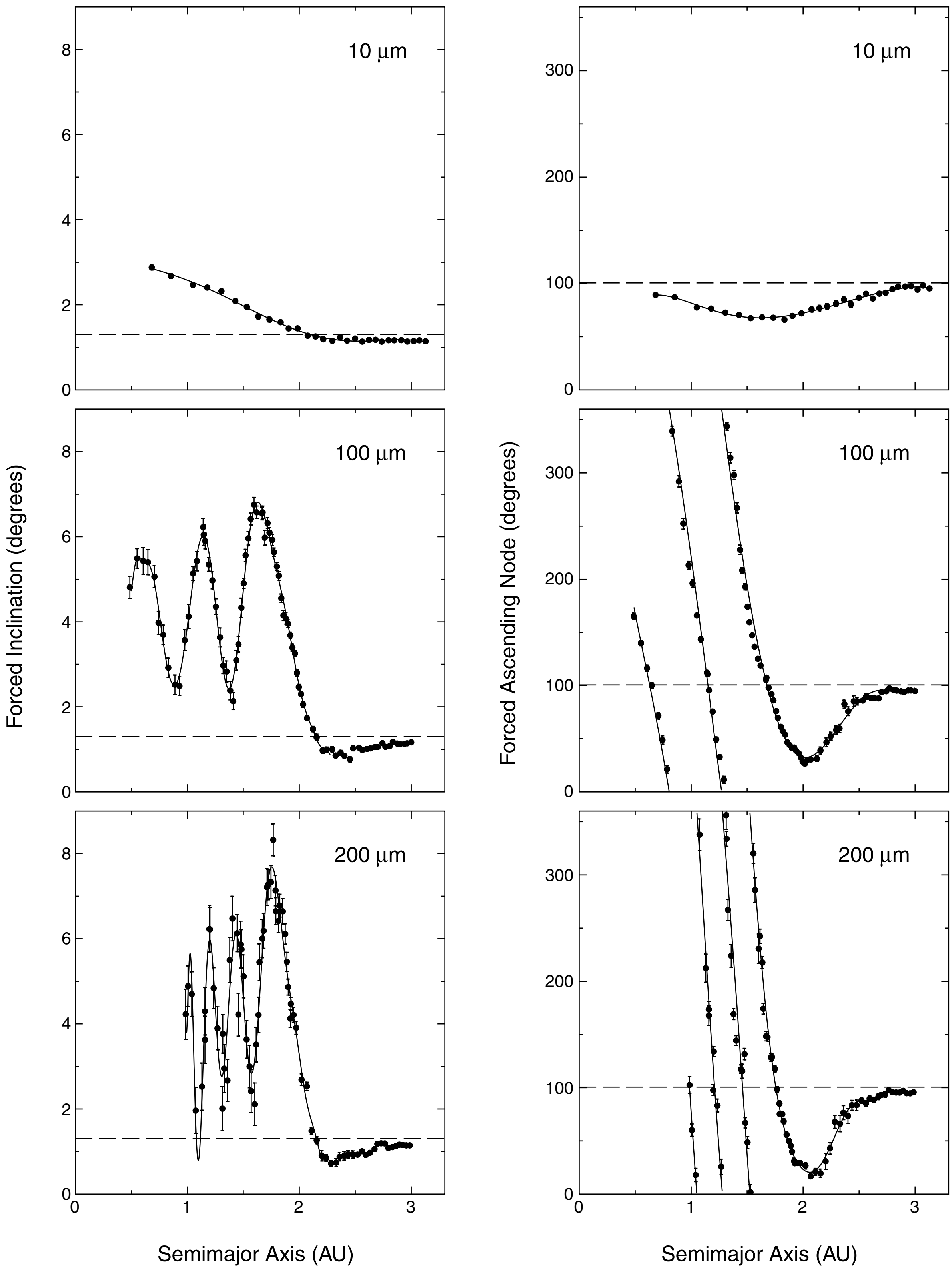


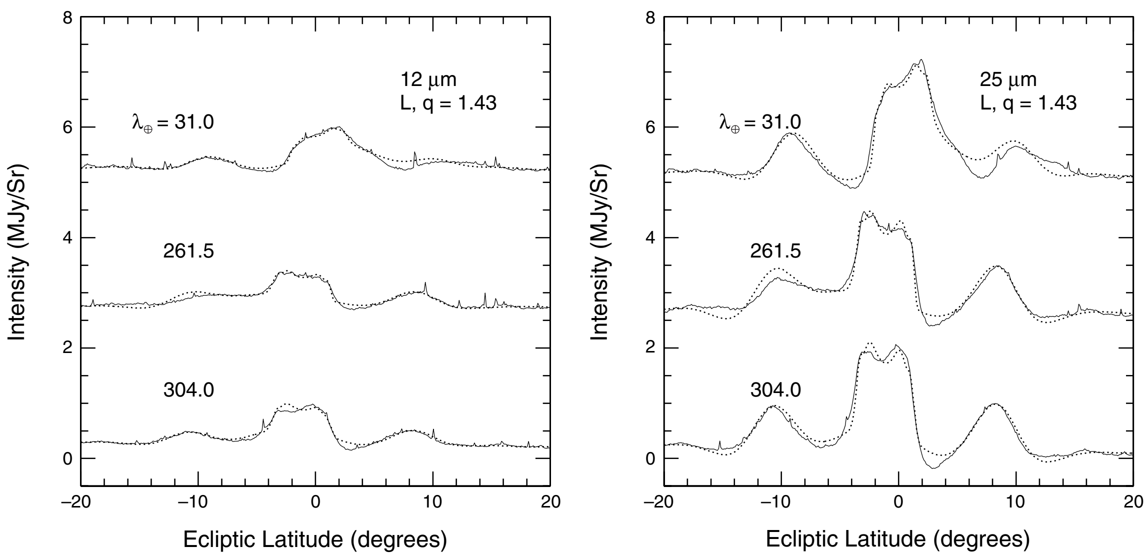
Fig. 2. Variation of the forced inclination (left) and the forced longitude of ascending node (right) with semimajor axis at the present epoch (Julian Date 2450700.5) for asteroidal dust particles composed of astronomical silicate (*Draine and Lee,* 1994) of density 2500 kg m^{-3} with diameters 10, 100, and 200 μm. The dashed lines show the present osculating inclination (left) and osculating longitude of ascending node (right) for Jupiter (*Dermott et al.,* 2001).

the source bodies (see Table 1), are provided as input data to the SIMUL algorithm. For a given range of particle sizes and a given size-frequency power-law index q, the total surface area of material associated with the model bands is adjusted until the amplitudes of the 25-μm model dust bands matches the 25-μm observations; q can then be varied until a single model provides a match in amplitude to the 12-, 25-, and 60-μm observations simultaneously. An estimate for the low-frequency component of the dust bands is obtained by employing the same filter in the modeling process that we use to define the observed dust bands and iterating. Figure 3 shows the best results of our modeling,

TABLE 1. Dust band model parameters: proper element distributions (semimajor axis, a, eccentricity, e, and inclination, I) of the source bodies (mean, σ) and cross-sectional area of material required.

Asteroid Family	$\bar{a}$, σ_a (AU)	$\bar{e}$, σ_e	$\bar{I}$, σ_I (°)	Area (10^9 km^2)
Eos	3.015, 0.012	0.076, 0.009	9.35, 1.5	4.0
Themis	3.148, 0.035	0.155, 0.013	1.43, 0.32	0.35
Koronis	2.876, 0.026	0.047, 0.006	2.11, 0.09	0.35

Dust particles originating from each family are distributed into the inner solar system as far as 2 AU according to a 1/r Poynting-Robertson drag distribution, where r specifies the radial distance from the Sun (*Grogan et al.,* 2001).



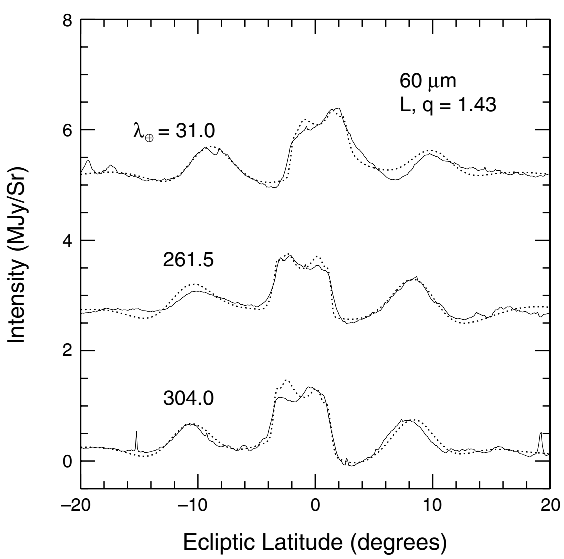


Fig. 3. Filtered IRAS dust band profiles (solid lines) in the 12-, 25-, and 60-μm wave bands are compared with models (dotted lines) having a size-frequency distribution with power-law index q = 1.43, at three different ecliptic longitudes of Earth ($\lambda_\oplus$). All profiles were made at 90° solar-elongation angle in the leading (L) direction of Earth in its orbit. The model dust bands were constructed using particles from the Themis and Koronis families for the central band pair and from the Eos family for the 10° band pair. A dispersion of 1.5° was imposed on the proper inclination of the Eos material in this model and all the material was confined to the asteroid belt (2.0 AU < r < 3.1 AU, where r specifies the radial distance from the Sun). The low value of q (<1.66) implies that large particles (diameters ~10^2 μm) dominate the surface area distribution (adapted from *Grogan et al.,* 2001).

comparing the dust band observations (solid curves) to the dust-band models (dotted curves) in the 12-, 25-, and 60-μm wave bands (*Grogan et al.,* 2001). The model includes particles with diameters in the range 1–100 μm and has a size-frequency power-law index q equal to 1.43. As q < 5/3, large particles dominate the total surface area of this distribution (*Dohnanyi,* 1969). The amplitudes in all wave bands are well matched, and the shapes of the dust-band profiles describe the variation in shape of the observations around the sky very well.

A clear result from our modeling is that a high size-frequency power-law index q, in which small particles dominate (*Dohnanyi,* 1969), fails to account for the observations of the solar-system dust bands. This index has to be reduced to the point where large particles dominate the size distribution, and we place an upper limit of q ≃ 1.4. This is consistent with the cratering record on the LDEF satellite (*Love and Brownlee,* 1993), which suggests a value for q of ~1.15 at Earth and a peak in the particle diameter at ~100–200 μm. Since the Fourier filter preferentially isolates material exterior to the 2 AU secular resonance (in the inner solar system the dust-band material is dispersed into the low-frequency background cloud due to the action of secular resonances), our results are more indicative of the size-frequency index of dust particles in the main asteroid belt.

We also find that models confining the dust-band material to the main asteroid belt (exterior to 2 AU) better match the IRAS observations, as the integrity of the dust bands is lost interior to 2 AU due to the action of secular resonances. In the future, we will incorporate the results from our simulations of large particle dynamics into our models and will populate the inner solar system as well as the main-belt region, allowing the dust bands to disperse naturally into the background cloud. However, we can obtain an estimate for the dust-band contribution to the zodiacal cloud as a whole by simply extending our best fit dust-band models to populate the inner solar system artificially. The distribution of orbits obtained in this manner will not be exactly correct, due to our insufficient treatment of the secular resonances and the effects of jovian mean-motion resonances and gravitational scattering by the terrestrial planets, but it will still be reasonably accurate in terms of the total surface area associated with the dust bands. Figure 4 compares the thermal emission obtained from this raw dust-band model to the corresponding unfiltered profile in the IRAS 25-μm wave band (*Grogan et al.,* 2001). The result is shown for inner solar-system distributions of material corresponding to $1/r^{\gamma}$, where r is the radial distance from the Sun and $\gamma = 1.0$, as expected for a system evolved by P-R drag, or $\gamma = 1.3$, as observed by the *Helios* and *Pioneer 10/11* space probes (*Leinert et al.,* 1983) and predicted in parametric models of the zodiacal cloud, most recently by *Kelsall et al.* (1998). We expect the radial distribution of material in the zodiacal cloud to be a function of the particles' eccentricities (*Dermott et al.,* 1999) and note that the orbital eccentricities of large asteroidal particles are strongly influenced by resonances and gravitational scattering as they evolve into the inner solar system. The effects of particle collisions will also influence the radial distribution, as some collisional debris will be deposited into the cloud, whereas a fraction will be blown out by radiation pressure. The net effect of all these processes has yet to be calculated. For the values of γ assumed above, the dust bands appear to contribute approximately 30% to the total thermal emission. Also shown is the amplitude of the emission from dust-band material confined to the main asteroid belt (exterior to 2 AU). This indicates that ~4% of the in-ecliptic IR emission from the zodiacal cloud is produced by dust-band particles that orbit exterior to 2 AU and also clearly demonstrates the extent to which the dust band contribution is underestimated if it is assumed that the filtered dust-band observations represent the entirety of the dust-band component of the cloud.

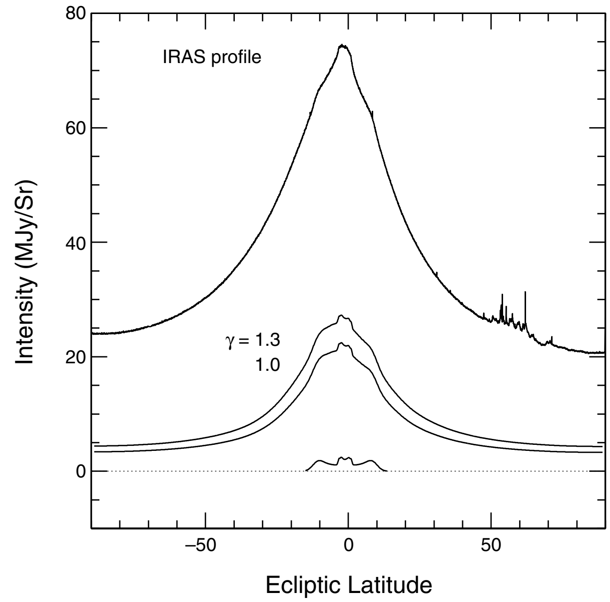


Fig. 4. Contribution of dust-band material to the zodiacal cloud. This figure shows a comparison of the thermal emission obtained from the raw best fit dust-band model to the corresponding unfiltered IRAS profile in the 25-μm wave band. The result is shown for inner-solar-system distributions of material corresponding to $1/r^{\gamma}$, where r is the radial distance from the Sun and $\gamma = 1.0$, as expected for a system evolved by Poynting-Robertson drag, or $\gamma = 1.3$, as observed by the *Helios* and *Pioneer 10/11* space probes (*Leinert et al.,* 1983) and predicted in parametric models of the zodiacal cloud, most recently by *Kelsall et al.* (1998). The dust bands appear to contribute approximately 30% to the total thermal emission. Also shown (bottom profile) is the amplitude of the dust-band material if confined to the main asteroid belt [exterior to 2 AU (*Grogan et al.,* 2001)].

Figure 5 shows the ratio of the area of collisionally evolved material associated with the entire main-belt asteroid population to that associated with all the asteroid families combined, for asteroid diameters greater than 1 km (*Grogan et al.,* 2001). The best-fit lines have a slope corresponding to a size-frequency power-law index q = 1.795 (*Durda and Dermott,* 1997), slightly less than the *Dohnanyi*

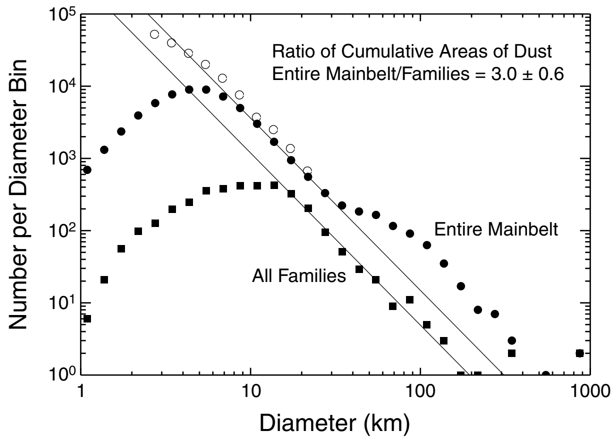


Fig. 5. Diameter-frequency diagram for the main-belt asteroid population, obtained by combining data from the catalogued population and McDonald/Palomar-Leiden surveys (MDS/PLS). Open points represent counts for which the PLS data had to be corrected for incompleteness. These were not included in the least-squares fits to the linear portion of the distribution. The ratio of the area of dust associated with the entire main-belt asteroid population to that of the combined asteroid families alone was calculated to be 3.0 ± 0.6 [*Grogan et al.* (2001); updated from *Durda and Dermott* (1997)].

(1969) value of q = 1.83, which is only expected if the breakup criterion for an asteroid is independent of its size. This diagram can be used to make a rough estimate of the total contribution of main-belt asteroid collisions to the dust in the zodiacal cloud, by extrapolating the observed size distributions of larger asteroids in both populations assuming a collisional equilibrium power-law size-frequency distribution. The result is that the main-belt asteroid population contributes approximately 3× the dust area of the Hirayama families alone, and therefore the total asteroidal contribution to the zodiacal cloud could account for almost the entirety (~90%) of the interplanetary dust complex (*Grogan et al.,* 2001). However, as noted above, employing the same single power-law size-frequency distribution to characterize both the main-belt and family asteroid populations is probably an oversimplification, and while this implies some uncertainty in the precise contribution of asteroidal material to the zodiacal cloud, the asteroidal contribution must still be significant and is probably dominant.

4. COLLISIONAL CASCADE

The size distribution of the collisionally evolved asteroids is given by

$$N(D) = \frac{1}{3(q-1)}\left(\frac{D_0}{D}\right)^{3(q-1)} \qquad (1)$$

where N(D) is the number of asteroids with diameter >D, D_0 is a constant, and q is the power-law index (*Dohnanyi,* 1969). If 5/3 < q < 2, then the total area in the cascade population is dominated by contributions from the smallest particles of diameter ~D_{min}, where D_{min} is the lower cutoff of the size distribution, whereas the total volume, and hence also the total mass, of the source population is dominated by the contributions from the larger fragments. If D_{vol} denotes the diameter of the sphere that would contain the total volume of the source material, then observations of the Hirayama families show that $D_0 \simeq 0.83D_{vol}$ (*Dermott et al.,* 1984).

The importance of collisions in determining a particle's evolution depends on its collisional lifetime. For the particles of diameter D_{typ} that constitute most of the zodiacal cloud's cross-sectional area (that is, those particles that are expected to characterize its mid-IR emission), this lifetime can be approximated (in years) by

$$t_{coll}(D_{typ}, r) \simeq \frac{t_{per}}{4\pi\tau_{eff}(r)} \qquad (2)$$

where r is the heliocentric radial distance and $\tau_{eff}(r)$ is the zodiacal cloud's effective face-on optical depth, which would be equal to the zodiacal cloud's true face-on optical depth if its particles had unity extinction efficiency (*Artymowicz,* 1997; *Wyatt et al.,* 1999). The orbital period of the particle in years is given by $t_{per} \simeq \sqrt{(a/a_\oplus)^3}$, where a is the semimajor axis of the particle in AU and $a_\oplus$ = 1 AU is the semimajor axis of Earth's orbit.

The combined effect of P-R light drag and solar-wind drag acting on micrometer-sized dust particles results in an evolutionary decrease in both the osculating semimajor axis, a, and eccentricity, e, of the particles' orbits, given by (*Wyatt and Whipple,* 1950)

$$\dot{a}_{PR} = -(\alpha/a)(2 + 3e^2)/(1 - e^2)^{3/2} \qquad (3)$$

$$\dot{e}_{PR} = -5(\alpha/a^2)e/2(1 - e^2)^{1/2} \qquad (4)$$

where $\alpha = 6.24 \times 10^{-4}\beta(1 + sw)$ AU^2 yr^{-1} and β is the ratio of radiation pressure to the gravitational attraction of the Sun on a particle. The effect of solar-wind drag on a particle is usually approximated as being 30% of the effect of P-R drag (*Gustafson,* 1994); that is, sw is set to an average value of 0.3. The effects of P-R and solar-wind drag therefore cause the orbit of a particle to spiral in toward the Sun. However, it does not affect the orientation of the particle's longitude of pericenter, $\dot{\varpi}_{PR} = 0$. Nor does it change the orientation of the plane of the particle's orbit, $\dot{I}_{PR} = \dot{\Omega}_{PR} = 0$, where I and Ω are the inclination and longitude of ascending node of the orbit respectively. The constant β depends upon the size and other physical properties of a particle: a useful approximation, valid for particles composed of astronomical silicate with diameters D ≳ 1 μm, is given by

$$\beta(D) \simeq 1150/\rho D \qquad (5)$$

where ρ is the particle's density measured in units of kg m^{-3} and D is measured in μm.

For a particle with zero eccentricity, equation (3) can be solved trivially to find the time it takes for the particle to spiral in from a heliocentric radial distance r_0 to r_f

$$t_{PR} \simeq 400\left[(r_0/a_\oplus)^2 - (r_f/a_\oplus)^2\right]/\beta(1 + sw) \qquad (6)$$

where r_0 and r_f are specified in AU, and t_{PR} is given in years. For eccentric orbits, equation (4) can be solved in conjunction with equation (3) to find the time taken for the particle's orbital eccentricity to decay from an initial value e_0 to a final value e_f

$$t_{PR} = \frac{2C^2}{5\alpha}\int_{e_f}^{e_0} \frac{e^{3/5}}{(1 - e^2)^{3/2}} de \qquad (7)$$

where the constant $C = a_0(1 - e_0^2)/e_0^{4/5}$, with a_0 specified in units of AU and α is defined as above to again obtain t_{PR} in years.

Now consider the fragments created in the breakup of an asteroid at a heliocentric radial distance r. The largest fragments, with $D > D_{crit}$, are broken up by collisions before their orbits have suffered any significant P-R drag evolution, while the smaller fragments, with $D < D_{crit}$, for which the P-R drag evolution is faster, can reach the Sun without a catastrophic collision. By equating the collisional and P-R drag lifetimes, *Wyatt et al.* (1999) estimate that

$$D_{crit} \simeq \frac{0.23}{\rho\tau_{eff}(r)}\sqrt{\frac{a_\oplus}{r}} \qquad (8)$$

where r is measured in units of AU, ρ in kg m^{-3}, and D_{crit} in µm. It is interesting to note here that if the effective normal optical depth, τ_{eff}, were to increase, as expected following the collisional disruption of a large rubble-pile asteroid (see the discussion in section 5), then the value for D_{crit} would be proportionately lower.

The daughter fragments created in the breakup of an "endless" supply of asteroids on orbits with semimajor axis a_s flow toward the Sun due to the effects of P-R and solar wind drag. If we ignore any further disintegrations of the particles that are involved in the flow, then the orbits of all the particles in a given size range will be distributed between the source and the Sun according to (e.g., see *Gor'kavyi et al.,* 1997)

$$N(a) \propto 1/\dot{a}_{PR} \propto a \qquad (9)$$

where N(a)da is the number of orbits with semimajor axes in the range a to a + da and $\dot{a}_{PR}$ is the rate of change of a particle's semimajor axis due to P-R and solar-wind drag given by equation (3). Thus, the spacing of the orbits increases as the particles approach the Sun, and this fact tends to decrease the number density of the particles, defined as the number of particles per unit volume. But given that both the circumferences of the orbits and the vertical extent of the particle distributions also decrease proportionally with decreasing a, it follows that, for particles in near-circular orbits, the number density of these particles, regardless of their size, will increase inversely with heliocentric distance.

However, because the flow rate of a particle is inversely proportional to its diameter, that is, because $\dot{a}_{PR} \propto 1/D$ (equations (3) and (5)), it follows that the size distribution of the particles in the flow region interior to the asteroid belt, must be quite different from that in the source region.

If the collisional processes leading to the size distribution of the large parent bodies, $N_s(D)$, still hold for the production of the P-R drag-affected particles, then the size distribution in the flow region is given by

$$N(D) \propto N_s(D)/\dot{a}_{PR} \propto N_s(D)D \qquad (10)$$

Thus, if $N_s(D)$ is given by equation (1) with q = 1.83 [as expected for a collisionally evolved system that has reached an equilibrium state (*Dohnanyi,* 1969)], then the cross-sectional area of the zodiacal cloud's smaller, P-R drag-affected particles is concentrated in the largest of these small particles, while the cross-sectional area of the particles that are large enough to be unaffected by P-R drag ($D > D_{crit}$) is concentrated in the smallest of these larger particles. The result is that most of the zodiacal cloud's cross-sectional area is expected to be concentrated in particles with $D_{typ} \approx D_{crit}$, justifying the use of equation (2) for the collisional lifetime of these particles.

Observations of the mean polar brightness of the zodiacal cloud at 1 AU can be used to estimate (the results are somewhat model-dependent) that, near Earth, the effective normal optical depth $\tau_{eff} \sim 4 \times 10^{-8}$ (see also equation (11)). If, as we believe, these zodiacal particles originated in the asteroid belt and migrated to 1 AU due to P-R drag, then the zodiacal cloud's volume density should vary ~1/r and, as its column height scales as r, the zodiacal cloud's effective normal optical depth in the asteroid belt should be similar to that at 1 AU. Assuming the zodiacal cloud particles to have a density 2500 kg m^{-3}, the cross-sectional area of material in the asteroid belt should be concentrated in particles with $D_{typ} \sim 10^3$ µm (equation (8)), for which the collisional lifetime and the P-R drag lifetime are both $\sim 10^7$ yr (equations (5) and (6)).

However, because their collisional and P-R drag lifetimes are similar, we must expect many of these large particles to be broken up by collisions before they reach the inner solar system, in which case we must expect the cross-sectional area of material at 1 AU to be concentrated in particles smaller than that in the asteroid belt. This is in agreement with the LDEF cratering record that shows the cross-sectional area distribution at 1-AU peaks for particles with D ~ 140 µm (*Love and Brownlee,* 1993) and other evidence (see the review by *Grün et al.,* 1985).

We have shown (see Table 1) that the total cross-sectional area of dust associated with the three major Hirayama families that we need to model the dust bands is 4.7×10^9 km^2, and that 85% of this dust is associated with the Eos family alone. However, the dust in these models is constrained between approximately 2 and 3 AU, whereas the actual dust associated with the Hirayama families must migrate to the inner solar system due to the effects of P-R and solar-wind drag. We therefore estimate that, as $N(a) \propto a$ (equation (9)), the total area of dust associated with these families in the zodiacal cloud is a factor of 9/5 greater. However, we also estimate that the area of dust needed to account for the whole of the zodiacal cloud must be 3× greater than the total contribution from the Hirayama families alone, that is, $A_{cloud} \sim 2.5 \times 10^{10}$ km^2. Note that if this dust is distributed between the Sun and r = 3 AU, then it follows that the effective face-on optical depth

$$\tau_{eff} \simeq A_{cloud}/\pi r^2 \sim 4 \times 10^{-8} \quad (11)$$

in agreement with the observations discussed above.

If A_{cloud} is characterized by N particles with diameter D_{typ}, then

$$A_{cloud} \simeq (\pi/4)ND_{typ}^2 \quad (12)$$

and it follows that the total mass of the cloud, M_{cloud}, is given by

$$M_{cloud} \simeq (2/3)A_{cloud}\rho D_{typ} \quad (13)$$

At 1 AU, $D_{typ} \sim 140$ μm and hence $M_{cloud} \sim 6 \times 10^{15}$ kg. However, in the asteroid belt, D_{typ} is probably closer to 500 μm, and it follows that the total mass of the cloud must be between 6×10^{15} kg and 2×10^{16} kg. This is roughly a factor of 2 less than the estimate made by *Whipple* (1967) of a zodiacal cloud mass between 1.1×10^{16} kg and 4.5×10^{16} kg.

It is worth noting that if all this dust were gathered together into one object with a diameter of D_{equiv}, then

$$D_{equiv} \simeq (4A_{cloud}D_{typ}/\pi)^{1/3} \quad (14)$$

giving $D_{equiv} \sim 25$ km, assuming $D_{typ} \sim 500$ μm. Neglecting the effects of collisions, this dust will reside in the cloud for a period of about 3.0×10^6 yr, the time taken for the orbit of a 500-μm-diameter dust particle composed of astronomical silicate with density 2500 kg m^{-3} to decay into the Sun under the effects of P-R and solar-wind drag from 3 AU (equations (5) and (6)). Any calculation of the dust production rate must therefore be averaged over this period of time.

Alternatively, we may consider the average mass loss rate from the zodiacal cloud due to infall under the effects of P-R and solar-wind drag, which can be expressed as

$$\dot{M}_{cloud} \simeq M_{cloud}/t_{PR} \quad (15)$$

where, in this case, $t_{PR} \sim 3.0 \times 10^6$ yr for $D_{typ} \sim 500$ μm, giving $\dot{M}_{cloud} \sim 6.7 \times 10^9$ kg yr^{-1}. This value compares favorably with the estimated $\sim 8.2 \times 10^9$ kg yr^{-1} total Poynting-Robertson mass loss rate inside 1 AU (*Grün et al.,* 1985).

The value determined above for $\dot{M}_{cloud}$ must also be equivalent to the average rate at which material from the zodiacal cloud flows past Earth. According to the results from LDEF (*Love and Brownlee,* 1993), Earth accretes mass from the cloud at the rate of $\dot{M}_{accrete} \sim 3 \times 10^7$ kg yr^{-1}. If $P_{capture}$ is the total probability of Earth capturing a particle from the zodiacal cloud then Earth's mass accretion rate can be expressed as

$$\dot{M}_{accrete} = \dot{M}_{cloud}P_{capture} \quad (16)$$

Rearranging this equation allows $P_{capture}$ to be written directly in terms of the observable quantities $\dot{M}_{accrete}$ and A_{cloud}, giving

$$P_{capture} = 3.6\dot{M}_{accrete}/A_{cloud} \sim 4.3 \times 10^{-3} \quad (17)$$

or roughly 0.4%, where $\dot{M}_{accrete}$ is specified in units of kg yr^{-1} and A_{cloud} in km^2. It is interesting to note that this estimate of $P_{capture}$ does not explicitly depend upon the assumed value of ρD_{typ}.

The total probability of Earth capturing a particle from the zodiacal cloud may also be written as

$$P_{capture} = \dot{P}_{capture}t_{accrete} \quad (18)$$

where $\dot{P}_{capture}$ is Earth's annual rate of capture of particles and $t_{accrete}$ is the timescale, in years, over which these particles are accreted. Particles in the zodiacal cloud are distributed on tori of width 2ae (*Dermott et al.,* 1985; *Wyatt et al.,* 1999) and so this timescale is given by the time taken for a torus of particles to flow past Earth under the effects of P-R and solar-wind drag. The first particles to be accreted by Earth from such a torus will be those that initially have pericenters, $q_0 = a_0(1 - e_0)$ at 1 AU, while the last particles to be accreted will be those that have final apocenters, $Q_f = a_f(1 + e_f)$, at 1 AU. Both the semimajor axis and eccentricity of the particles in this torus will decrease with time due to the effects of P-R and solar-wind drag, and so $t_{accrete}$ is given by equation (7) with e_0 specified such that $q_0 = 1$ AU; e_f is determined such that $Q_f = 1$ AU, consistent with decaying from its initial value, e_0, due to P-R and solar-wind drag; and $C = q_0(1 + e_0)/e_0^{4/5}$. As both $\dot{P}_{capture}$ and $t_{accrete}$ depend on the orbital-element distributions of the particles in each torus, which in turn are determined by the orbital elements of the source body of the particles, this calculation needs to be performed separately for each class of orbit. Results from LDEF (*Love and Brownlee,* 1993) indicate that the mass distribution of particles accreted by Earth reaches a peak for particles near 200-μm diameter (see also *Grün et al.,* 1985), thus this is the value we adopt here for D_{typ} in order to determine a β value for these particles (equation (5)), which we assume to have a density of 2500 kg m^{-3} irrespective of source.

The average values of $\dot{P}_{capture}$ and e_0 determined numerically (*Kortenkamp and Dermott,* 1998a) for 10-μm-diameter dust particles from three different sources are shown in Fig. 6 and listed in Table 2, along with corresponding values for the typical accretion timescale, $t_{accrete}$. Using these values, we calculate that $P_{capture}$ for particles in the zodiacal cloud with typical asteroidal orbits is 4.6×10^{-3}, con-

TABLE 2. Estimates of the total capture probability, $P_{capture}$, and mass accretion rate, $\dot{M}_{accrete}$, by Earth for dust particles derived from three different sources: asteroidal particles, cometary particles previously trapped in jovian mean-motion resonances, and cometary particles not previously trapped in resonance.

Particle Source	$\dot{P}_{capture}$ (10^{-9} yr^{-1})	e_0 (q_0 = 1 AU)	$t_{accrete}$ (10^3 yr)	$P_{capture}$ ($\times 10^3$)	$\dot{M}_{accrete}$ (10^6 kg yr^{-1})
Asteroidal	180	0.05	25	4.6	31
Resonant cometary	34	0.2	96	3.3	22
Nonresonant cometary	4.6	0.6	380	1.7	11

The typical accretion timescales, $t_{accrete}$, were calculated by assuming that the first particles to be accreted from each source had initial pericenters q_0 at 1 AU with eccentricities e_0, and the last particles to be accreted had final apocenters Q_f at 1 AU, while allowing the particles' orbits to decay under the effects of Poynting-Robertson and solar-wind drag. Values for the annual capture rate, $\dot{P}_{capture}$, were obtained from the results of numerical simulations [source data from *Kortenkamp and Dermott* (1998a)].

sistent with the value derived above (equation (17)) from observable quantities. This value for $P_{capture}$ in turn implies a mass-accretion rate by Earth of 3.1×10^7 kg yr^{-1}, in close agreement with the value determined from the LDEF cratering record. Particles released from comets and then trapped into a mean-motion resonance with Jupiter, which then acts to reduce the orbital eccentricities of the particles to near-asteroidal values (*Liou and Zook,* 1996), could also account for the observations. Note that the values shown for the mass-accretion rate, $\dot{M}_{accrete}$, in Table 2 were calculated in each case by making the simplifying assumption that all particles in the zodiacal cloud were produced by the single particle source in question. In reality, dust particles from the three sources shown in Table 2, plus a variety of others, all contribute to the zodiacal cloud in differing proportions.

It is worth noting here that the calculated value of $P_{capture}$ for cometary particles not previously trapped in jovian mean-motion resonances is only a factor of a few less than the observed value. While this implies a mass-accretion rate by Earth that is still probably too small to account for the observed value, even assuming that such cometary particles do comprise the entire zodiacal cloud, previous studies of the capture of dust particles by Earth have suggested a much stronger bias towards accreting asteroidal over cometary dust particles. *Flynn* (1990), for example, came to this conclusion based upon the lower geocentric-encounter velocities, and hence greater effective capture cross-section of Earth due to gravitational focusing, of particles on near-circular, near-ecliptic orbits. *Kortenkamp and Dermott* (1998a), however, did appreciate that the lower geocentric-encounter velocities of particles on these "asteroidal-type" orbits also impinged negatively upon the effective volume swept out by Earth per unit time (see Fig. 6), but were still led to conclude that Earth would have a strong preference for accreting asteroidal rather than cometary particles. We now realize that the latter conclusion may be misleading. It is important here to distinguish between the annual rate of capture of particles from a given torus, while Earth is inside that torus, $\dot{P}_{capture}$, and the total probability of a particle being accreted

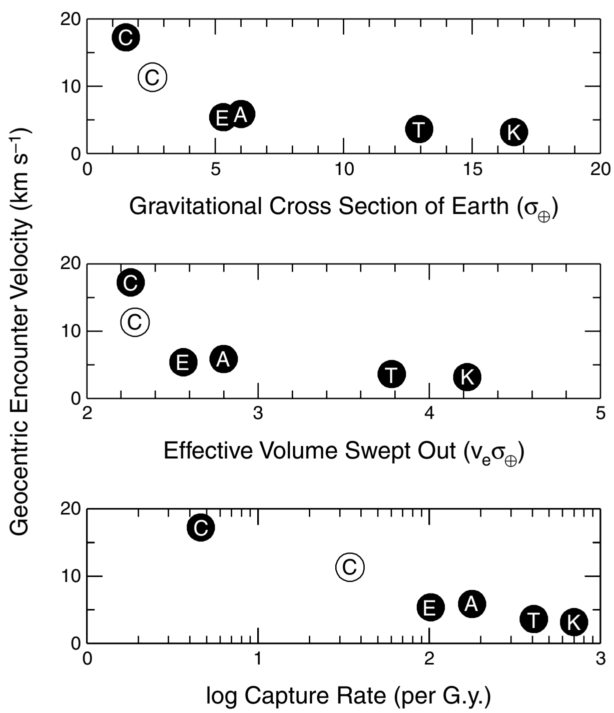


Fig. 6. Mean geocentric encounter velocities (prior to acceleration by Earth) for 10-μm-diameter dust particles from several different source populations are plotted against the mean gravitational capture cross-section of Earth (measured in units of the geometric cross-section of Earth at 100 km altitude, $\sigma_\oplus = 1.32 \times 10^8$ km^2; top), the mean effective volume of each population swept up by Earth (measured in units of $v_e\sigma_\oplus$, where v_e = 11.1 km s^{-1} is the escape velocity of Earth at 100 km altitude; middle), and the log of the mean capture rate (bottom). E, K, and T labels indicate particles from the Eos, Koronis and Themis asteroid families respectively, while A indicates other nonfamily asteroidal particles. Open points labeled C indicate cometary particles that were previously trapped in jovian mean-motion resonances. Solid points labeled C indicate cometary particles that were not previously trapped in jovian mean-motion resonances. Reprinted from *Kortenkamp et al.* (2001) with kind permission from Kluwer Academic/Plenum Publishers.

by Earth, $P_{capture}$. While a bias toward preferentially accreting asteroidal particles certainly exists in the annual capture rates shown in Table 2, and this bias must be included when calculating $P_{capture}$ and hence the average rate of capture of particles from the asteroidal and cometary sources, this asteroidal bias in the annual rates is almost entirely compensated for by the much longer timescale ($t_{accrete}$) over which cometary particles, with their wider tori, are accreted by Earth. Note that there are still significant uncertainties in the values for $P_{capture}$, mainly because the values for $\dot{P}_{capture}$ and e_0 were determined from numerical simulations of 10-μm-diameter dust particles only. These particles are much smaller than those indicated by the peak in the LDEF mass distribution. The orbits of the 10-μm-diameter particles evolve more rapidly under the effects of P-R and solar-wind drag than the orbits of larger particles, and are therefore less prone to the effects of secular resonances, trapping into mean-motion resonances, or gravitational scattering by the terrestrial planets. Larger particles will therefore typically arrive at 1 AU with higher orbital eccentricities and inclinations than the 10-μm-diameter particles and will suffer lower annual rates of capture by Earth (*Kortenkamp and Dermott,* 1998a). These numerical simulations therefore need to be extended to much larger particle sizes.

5. DISCUSSION

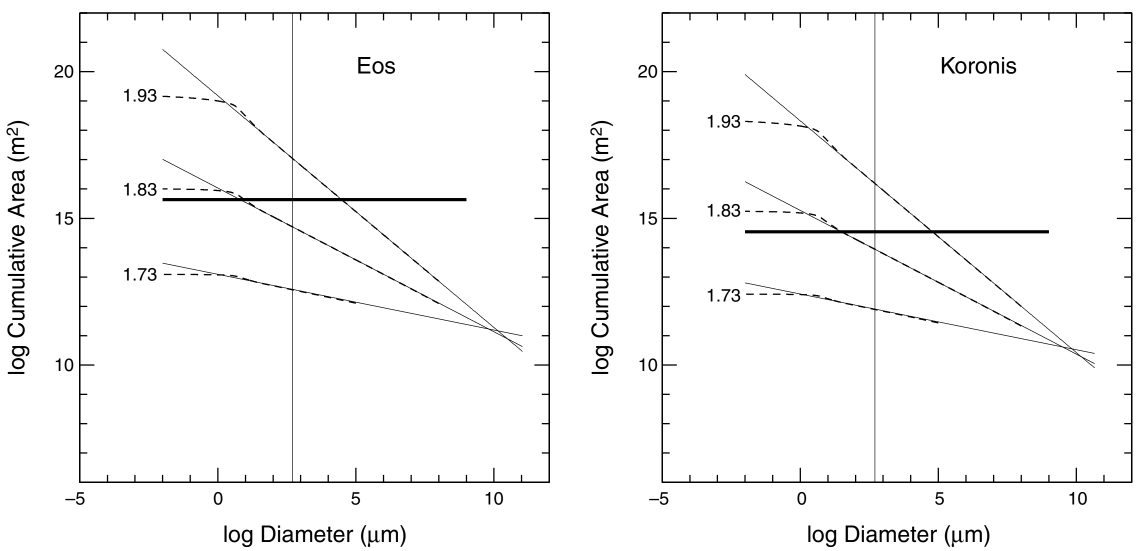
Our modeling and analysis of the solar system dust bands indicate that large particles with diameters between 10^2 and 10^3 μm dominate the dust-band structures (*Grogan et al.,* 2001). Numerical investigation of the dynamical behavior of these large particles demonstrates that the action of secular resonances at the inner edge of the main asteroid belt disperses the inclinations and nodes of the particles into the broad-scale zodiacal background cloud, accounting for the natural inner edge of the dust bands just exterior to 2 AU. This leads us to estimate that ~4% of the in-ecliptic infrared emission from the zodiacal cloud is produced by dust-band particles that orbit exterior to 2 AU. However, some of these asteroidal dust particles must migrate to the inner solar system under the effects of P-R light drag and solar-wind drag (*Wyatt and Whipple,* 1950), where they are both warmer and closer to Earth. We therefore conclude that IR emission from the asteroidal dust particles associated with the dust bands alone is likely to be much greater than 4% of the total emission. If these asteroidal particles migrate to the inner solar system without further breakup, we calculate that the contribution is 30%. If the particles are broken up and blown out of the solar system before reaching the inner solar system, then our estimate would, of course, remain closer to 4%. However, it is certainly possible, and perhaps even more likely, that particle breakup leads to an increase in the effective area of the dust, in which case our estimate would be greater than 30%. Whether the effective area of the dust actually increases or decreases is not known and thus 30% is, at present, our best estimate of the contribution of asteroidal dust, from the dust-band particles alone, to the zodiacal cloud. But 30% must be an underestimate of the total asteroidal contribution. From a separate discussion of the ratio of the average rate of dust production in the asteroid belt as a whole to that due to those asteroids in the Eos, Koronis, and Themis families alone, which we estimate to be 3:1, we are led to conclude that asteroidal dust may effectively constitute the entirety of the zodiacal cloud, with a quarter (85% of 30%) of the whole cloud originating from the Eos family alone.

This conclusion is, however, contrary to the long-held belief that comets are the dominant source of particles in the zodiacal cloud (e.g., see *Whipple,* 1967), and is still a matter of considerable debate. *Zook* (2001), for example, estimates that the cometary contribution to the near-Earth flux of particles is ~75%, based on cratering rates from an ensemble of Earth- and lunar-orbiting satellites, in complete contrast to our result. In the argument above we have assumed that the dust production rate in asteroid families is similar to that in the nonfamily asteroidal population. If, however, the dust production rate in asteroid families is significantly greater than that in the nonfamily asteroidal population, as suggested by *Dell'Oro et al.* (2001), then the total asteroid-to-family asteroid dust ratio would be less than 3:1 and our estimate of total asteroidal contribution to the zodiacal cloud would be correspondingly lower.

Weak support for a dominant asteroidal component to the zodiacal cloud is provided by our analysis linking the total cross-sectional area of the cloud needed to account for the observed IR flux, A_{cloud}, to the observed value of the annual mass-accretion rate of particles from the zodiacal cloud by Earth, $\dot{M}_{accrete}$, as measured by LDEF. Particles at 1 AU in near-circular asteroidal orbits (note that this includes particles originating from comets that have had their orbits circularized by resonance with Jupiter) can account for the observed accretion rate, whereas particles originating from comets that have not been affected by resonances give an accretion rate that is probably too small. However, some caution needs to be exercised here as the numerical simulations from which these results were obtained (*Kortenkamp and Dermott,* 1998a) need to be extended to determine the effect of particle size on average rates of capture. There is also roughly a factor of 2 uncertainty in the mass-accretion rates estimated from the LDEF cratering record (*Love and Brownlee,* 1993). In fact, on the basis of elemental abundances in stratospheric aerosols, *Murphy* (2001) argues for an extraterrestrial mass-accretion rate in the lower range of that indicated by LDEF (see also *Cziczo et al.,* 2001), in agreement with previous estimates of the mass-accretion rate obtained by *Hughes* (1978) (using both visual and radio meteor observations and also satellite data) and *Grün et al.* (1985) (based upon *in situ* spacecraft measurements and the lunar microcratering record) that are indeed closer to half the value determined from LDEF. Until the actual mass flux to Earth of extraterrestrial material is more tightly constrained, the predicted fluxes from the various dust sources cannot be usefully employed as a discriminant of the actual source.

More importantly, perhaps, our calculation of the area of dust in the dust bands associated with the three most prominent Hirayama families is consistent with the collisional cascade model of *Dohnanyi* (1969). Figure 7 links the cumulative surface areas associated with the Eos, Koronis, and Themis asteroid families to the observed volumes of the source material in these families for a range of values of the size-frequency power-law index q (*Dermott et al.,* 1984; *Grogan et al.,* 2001). In each case, we see that the area of dust in each family with $D > D_{crit} \sim 500$ μm (the particles largely unaffected by P-R drag) needed to satisfy the dust-band observations can be accounted for if q is close to 1.83, the value predicted by *Dohnanyi* (1969). This is a comparatively robust conclusion, although more work is needed on calculating the area of dust in the transition region between collisional evolution and P-R drag evolution. However, even though we know the orbits of the asteroids in the collisional cascade, and we have an accurate measure of their total volume, we do not know how the strength of these bodies varies over the size range from micrometers to kilometers. Furthermore, we are not entirely confident that a simple power law is an adequate description of the size-frequency distribution. Hence, we do not claim that Dohnanyi-type supply arguments can be employed to predict, with useful precision, the observed quantity of dust from first principles, without the crucial input of the IR dust-band observations. Only consider, for example, that an error in the assumed average value of q of 0.1 would result in an error in the cumulative area of material of $\sim 10^3$ (see Fig. 7). This leads us to state that in the case of comets these supply-type arguments are also not good enough to be decisive, largely because of our ignorance of the numbers and sizes of the comets that may have contributed to the zodiacal cloud over the past 10^7 yr.

There are some outstanding problems with linking the dust bands with the prominent Hirayama families. Firstly, there is a discrepancy between the mean proper inclination of the 10° dust-band model (9.35°; see Table 1) and the



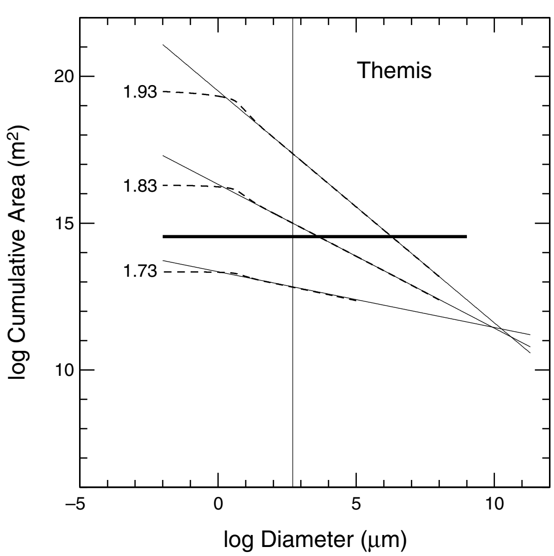


Fig. 7. Cumulative area of dust associated with the Eos, Koronis, and Themis asteroid families [as defined by *Zappalà et al.* (1995)] assuming three different size-frequency distributions for each with power-law indexes q = 1.73, 1.83, and 1.93. The solid lines represent the geometrical area, while the broken lines are the cross-sectional area of emission calculated for spheres of astronomical silicate of density 2500 kg m^{-3}, using Mie theory. In each panel, the cumulative area of dust from each family (Table 1) needed to model the IRAS observations of the dust bands is represented by a heavy, horizontal line. A vertical line corresponding to a diameter of 500 μm is shown for reference. In order to account for the amplitude of the dust bands associated with the three prominent Hirayama families, the average size-frequency power-law index q in each case has to be close to the value of 1.83 predicted by *Dohnanyi* (1969). Adapted from *Grogan et al.* (2001).

mean proper inclination of the Eos asteroid family (10.08°). This suggests that the 10° dust-band material does not trace the orbital-element distribution of the Eos family as a whole, as would be expected from the equilibrium model (*Dermott et al.,* 1984) in which the dust bands represent the continual grinding down of family asteroids. There are two possible explanations for this discrepancy. Forces may have acted on the dust particles in this band, or on the small bodies in the collisional cascade that produced these particles, to reduce their inclinations. The Yarkovsky effect, which preferentially acts upon meter- to kilometer-sized bodies, may be responsible for the migration of the dust particle parent bodies in orbital-element space (see *Bottke et al.,* 2001, 2002). Recent work by *Vokrouhlický* (2001), for example, speculates about the possibility of a jet of small asteroids from the Eos family streaming along the $z_1 = g + s - g_6 - s_6$ secular resonance to lower-inclination orbits due to the dynamic mobility induced by the Yarkovsky effect. This interesting possibility needs to be investigated more fully. More prosaically, we could simply be observing the latest disintegration of a small member of the Eos family, or even an unrelated background asteroid with the appropriate proper inclination. The origin of the large dispersion in proper inclination (1.5°) required to successfully model the 10° dust band (see Table 1), in rough agreement with the 1.4° found by *Sykes* (1990) and the 2° found by *Reach et al.* (1997), remains unclear, although the most likely source of the dispersion is simply the action of the ν_{16} secular resonance near 2 AU. However, this leaves open the question of why a large dispersion is required to model the 10° band, and only the small dispersion of the Koronis and Themis families is required to successfully reproduce the central band observations. One answer may be that the emission associated with the central band is due to relatively recent collisions within these families.

We recognize, of course, that the asteroid belt will contribute dust to the zodiacal cloud one asteroid at a time. Figure 8 shows a simulation of the variation with time of the total cross-sectional area of dust associated with the main belt (*Grogan et al.,* 2001) and describes both the steady decline in the total area of the dust and the inevitable stochastic variations. This numerical approach to describing the collisional evolution of the asteroid belt is detailed by *Durda and Dermott* (1997). The initial main-belt mass is taken to be approximately 3× greater than the present mass (*Durda et al.,* 1998); this population evolves after 4.5 b.y. to resemble the current main belt. The calculation is performed for particles from 100 μm to the largest asteroidal sizes, with an arbitrary fragmentation power-law index q = 1.9. The "spikes" in dust production are due to the breakup of small- to intermediate- (diameter ~40 km) sized asteroids. Therefore, while the volume of the source material in the zodiacal cloud may decay at a fairly constant and well-defined rate, the total area of dust associated with the cloud during that time, given a breakup value of q = 1.9, may fluctuate by an order of magnitude or more. On the surface this appears to be evidence for a catastrophic (non-

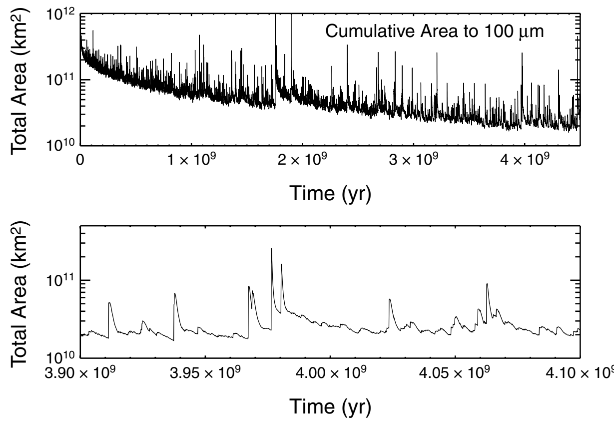


Fig. 8. Variation with time of the total cross-sectional area of dust associated with the breakup of an asteroid that was big enough to supply all the observed collision products of the main belt. This simulation modeled the stochastic breakup of asteroidal fragments down to a diameter of 100 μm. A size-frequency distribution with power-law index q = 1.9 was assumed for the initial breakup of each asteroid and this accounts for the heights of the "spikes" in the plots. The upper panel shows the evolution over the age of the solar system, while the lower panel shows in more detail a 200-m.y. period of evolution centered on 4 b.y. following the start of the simulation [*Grogan et al.* (2001); adapted from *Durda and Dermott* (1997)].

equilibrium) origin for the dust bands (*Sykes and Greenberg,* 1986), in which the dust bands are produced by the disruption of random main-belt asteroids. However, we note that the grinding down of an asteroid family is also a stochastic process. Spikes in the dust-production rate correspond to the breakup of individual asteroids and can therefore originate from any asteroid within the family. The dust band associated with the family, produced by the fresh injection of material from the most recent fragmentation, may therefore shift in latitude over time.

Dust particles generated by the collisional evolution of the asteroid belt eventually spiral into the inner solar system under the effects of P-R light drag and solar-wind drag. Variations in the production rate of these particles, as suggested by the results of the modeling shown in Fig. 8, should therefore result in a variation in the rate of accretion of dust particles by Earth. With certain caveats, it is possible to determine this variation by measuring the concentration of ^{3}He contained in sedimentary layers in Earth's crust, with the ^{3}He acting as a proxy for dust particles of extraterrestrial origin (*Farley,* 2001). Important information on the dust flux at 1 AU should therefore be contained in the geologic record. In fact, exciting data on the variation of the extraterrestrial dust accretion rate over a period of tens of millions of years has recently been published by *Mukhopadhyay et al.* (2001).

Interplanetary dust particles acquire He from the implantation of solar-wind or flare particles in space, and its concentration is therefore strongly surface-correlated. LDEF results (*Love and Brownlee,* 1993) indicate that the cross-sectional area distribution of these particles at 1 AU peaks for those with diameters of ~140 μm. However, *Farley et al.* (1997) calculate that due to the effect of heating during atmospheric entry, volatile components are stripped from large dust particles, and most of the extraterrestrial He (>70%) reaching the sedimentary layers is carried into Earth's atmosphere by particles between about 3 and 35 μm in diameter, with the dominant peak occurring at ~7 μm. The size distribution and total mass of He-bearing particles on the seafloor is therefore distinct from the size distribution and total mass of the parental dust-particle population. *Farley et al.* (1997) estimate that only ~4% of the total surface area and ~0.5% of the total mass of accreted dust particles are delivered to the surface of Earth at temperatures below which He is released (~600°C). Platinum-group elements, on the other hand, have proven to be the most sensitive nonvolatile tracers of extraterrestrial matter in marine sediments (*Peucker-Ehrenbrink,* 2001). Iridium and Os, specifically, can therefore be employed as a proxy for the flux of dust particles across the entire size spectrum and in particular for the large particle population not registered by the He proxy. Furthermore, differences in the dust particle flux estimates based upon these different proxies may indicate variations in the size-frequency distribution of extraterrestrial material accreted by Earth over geologic time (B. Peucker-Ehrenbrink, personal communication, 2001). However, as pointed out by *Farley et al.* (1997), mass-correlated nonvolatile tracers such as Ir are subject to extreme undersampling that may require the use of extraordinarily large sediment samples (many kilograms) in order to accurately infer the dust-particle flux. A comprehensive suite of papers reviewing many aspects of the accretion of extraterrestrial material by Earth has recently been compiled by *Peucker-Ehrenbrink and Schmitz* (2001).

The resolution of the debate between a collisional equilibrium or catastrophic model for the origin of the dust bands depends on whether the disruption of a single asteroid can liberate a large enough cross-sectional area of dust to account for the total emission from any given dust band. In this connection, we note that there is now substantial evidence for the existence of a large population of rubble-pile asteroids in the main belt. For example, asteroids with diameters between about 0.2 and 10 km show a cut-off in rotation period of ~2 h, indicating that they lack tensile strength and are probably "loosely bound, gravity-dominated aggregates" (*Pravec and Harris,* 2000). Larger asteroids (>10 km) may also be rubble piles, but the rotational statistics are insufficient to confirm this possibility (*Pravec and Harris,* 2001). Asteroids smaller than a few hundred meters in diameter typically have spin rates faster than the rotational breakup limit for rubble-pile asteroids, implying that they must have some tensile strength and may possibly be monolithic bodies. It has been argued that these bodies are the collisional fragments of larger rubble-pile asteroids and that the sharp division between the rotational periods of these small bodies and the rubble-pile asteroids indicates that the characteristic size of the largest rubble-pile fragments must be ~0.2 km (refer to *Pravec et al.,* 2002). Recent spacecraft missions and telescopic observations of asteroids have also provided measurements of a number of surprisingly low bulk densities in the 1300 kg m^{-3} range (see *Hilton,* 2002; *Britt et al.,* 2002), indicating bulk porosities of ~50% (*Britt and Consolmagno,* 2001; *Britt et al.,* 2002). This has led some authors to conclude that such asteroids are loosely bound rubble piles containing large voids (e.g., see *Britt et al.,* 2002). The increasing body of evidence suggesting the existence of gravitational aggregates is discussed in more detail in *Richardson et al.* (2002).

If all the dust in the zodiacal cloud is released from the final catastrophic disruption of a single rubble pile of diameter D_{rubble}, then the equivalent depth of the regolith layer, $d_{regolith}$, needed to account for the present observed cross-sectional area is given by

$$d_{regolith} \simeq \frac{2A_{cloud}D_{typ}}{3\pi D_{rubble}^2} \qquad (19)$$

where we have assumed that the regolith forms a uniform, shallow layer on a deep rubble pile. In the case of a 200-km-diameter rubble pile, similar in size to the precursor of the Eos family, the whole of the zodiacal cloud with A_{cloud} ~ 2.5 × 10^{10} km^2 could have been released from a regolith of depth $d_{regolith}$ ~ 70 m, if we assume that D_{typ} ~ 500 μm. However, in the case of a rubble pile, D_{typ} is not determined by considerations of the balance between the collisional and P-R drag timescales and D_{typ} could be very much smaller than 500 μm, perhaps by a factor of 10–10^2. The depth of the regolith on an ancient rubble pile is also likely to be very much greater than 70 m, perhaps by a factor as large as 10^2. These considerations suggest that the disruption of those large asteroids that were the precursors of the major asteroid families (*Hirayama,* 1918; *Zappalà and Cellino,* 1993), if these precursor bodies were rubble piles (*Michel et al.,* 2001, *Richardson et al.,* 2002), could have resulted in an increase in the mass of dust in the zodiacal cloud by a factor of 10^2 (equation (13)) and an increase in the cross-sectional area of dust in the zodiacal cloud by a factor of 10^3–10^4 (equation (19)).

If the final stage of dust production is indeed the release of particles from both small and large rubble-pile asteroids, we would expect there to be variations in the dust-production rate in the past, and consequently, variations in Earth's accretion rate of dust particles (*Kortenkamp and Dermott,* 1998b). According to our calculations above, following the collisional disruption of a large rubble pile, Earth's mass-accretion rate of dust particles could have been enhanced by 2 orders of magnitude over the current estimated mass flux of particles measured by LDEF (*Love and Brownlee,* 1993), resulting in mass-accretion rates that may have been as high as several million tonnes per year. The potential effects of such enhanced dust loading of the atmosphere from extraterrestrial sources has previously been considered by, among others, *Muller and MacDonald* (1997), who suggest a possible causal link with glacial cycles. The consequences of a large influx of cometary debris onto Earth is discussed by *Napier* (2001).

The magnitude of any climatic effects caused by atmospheric dust loading depends mostly on the quantity of submicrometer particles deposited above the tropopause (*Toon et al.,* 1994), where they have a residence time on the order of a year (*Murphy,* 2001). Results obtained by LDEF, however, indicate that the mass flux of dust particles accreted by Earth peaks for particles of ~200 μm in diameter (*Love and Brownlee,* 1993), and so the proportion of incoming particles in the submicrometer size range may be relatively small unless the size distribution of particles released from rubble-pile asteroids differs significantly from the usual background flux of particles, as noted above. Nevertheless, particles in the correct size range can also be produced as a result of ablation and fragmentation of incoming dust particles during atmospheric entry (e.g., see *Hunten et al.,* 1980; *Love and Brownlee,* 1991). At present, the fraction of particles in the submicrometer size range resulting from this incoming extraterrestrial dust flux that is retained in the upper atmosphere is not precisely known, although some constraints are provided by measurements of elemental abundances in stratospheric aerosols (e.g., see *Cziczo et al.,* 2001; *Murphy,* 2001). Consequently, there must be a large uncertainty in the magnitude of the climatic effects produced by this enhanced extraterrestrial dust loading. Further, more detailed, modeling of this problem will need to be performed to accurately quantify the anticipated accretion rates of submicrometer particles by Earth during such periods of enhanced dust flux and to ascertain any potential climatic consequences this may have.

To place this atmospheric dust loading in the wider context, *Toon et al.* (1994) estimate that the impact of a large extraterrestrial body can pulverize and hurl into the atmosphere an amount of material equal to roughly $10^2\times$ the mass of the impacting bolide, of which 0.1% will be lofted into the stratosphere as submicrometer-sized particles. The impact event postulated by *Alvarez et al.* (1980) to have occurred at the time of the Cretaceous-Tertiary (K-T) boundary, for example, is estimated to have been caused by a bolide with the equivalent impact energy of 10^8 Mt of TNT and an entry velocity of ~25 km s^{-1}, implying that on the order of 10^{14} kg of submicrometer particles could have been lofted into the stratosphere by this single event alone. The resulting "impact winter" scenario would have been truly devastating for life on Earth and likely played an important role in the K-T mass extinction, although this is a matter of ongoing debate.

Considered as an abbreviated event, the atmospheric loading due to the enhanced accretion of asteroidal dust particles clearly pales in comparison to an event on the scale of the K-T impact. In this regard, the climatic consequences of volcanic eruptions may well serve as a more commensurate parallel for the effects of such dust loading of the atmosphere (e.g., see *Robock,* 2000). In the case of volcanic eruptions, any long-term global effect on climate is largely determined by the quantity of sulfur volatiles injected into the stratosphere where they are converted into sulfuric acid aerosols that have optical properties similar to fine dust particles (*Toon et al.,* 1994) and an e-folding residence time of ~1 yr (*Robock,* 2000). Large volcanic eruptions in recent history are typically estimated to have injected tens of millions of tonnes of chemically and microphysically active aerosol particles into the stratosphere (*Robock,* 2000), although eruptions in the more distant past may have been far more productive in this respect (*Rampino et al.,* 1988). Indeed, examples exist in the geologic record of massive flood basalt eruptions (*Hooper,* 2000) that may have been capable of sustaining, or episodically exceeding, this level of atmospheric aerosol loading over million-year timescales. As a wave of dust released by the destruction of a large rubble pile would take between approximately 10^4 and 10^7 yr to drift inward past Earth under the effect of P-R and solar-wind drag, the cumulative effects of such an eruption perhaps serves as a more appropriate analog for the climatic effects caused by the atmospheric loading of these asteroidal dust particles. It is interesting to note in this context that two of the largest known flood basalt eruptions, the Siberian Traps and the Deccan Traps, appear to coincide with the Permian-Triassic and the K-T mass extinctions, respectively, although no definite causal link has yet been established (*Stothers,* 1993).

Potential impactors large enough to produce globally catastrophic effects on Earth are likely to originate from the complete collisional disruption of one of the larger asteroids and possibly a precursor of one of the major asteroidal families (*Zappalà et al.,* 1998). As discussed above, such a massive collisional event would have certainly also generated an enormous quantity of dust. It follows from this argument that a large impact event on Earth would have also been associated with the influx of a large wave of dust, although the two events may well have been widely separated in time due to the different dynamical mechanisms and timescales involved in their delivery, with a wave of dust associated with the smallest dust particles probably arriving before the impactor. In this scenario, the extinction of life on Earth may have occurred not necessarily because of the effects of the giant impact, although this could have provided the *coup de grâce* (*Hallam,* 2001), but because the production of potential large impactors in the asteroid belt generates a wave of dust that Earth cannot avoid. Most, and in some cases all, of the potential impactors produced by the catastrophic disruption of a large asteroid may have missed Earth, but interaction with the concomitant wave of dust is unavoidable. In this regard, we should not ignore the fact that large increases in the area of dust in the zodiacal cloud between Earth and the Sun could also affect Earth's level of insolation.

We have strong, quantitative evidence that asteroidal dust is a significant component of the zodiacal cloud. The final question is whether this preponderance of asteroidal particles is reflected in our collections of IDPs, MMs, and cosmic spherules that provide a sample of the zodiacal cloud particles at 1 AU. As discussed in section 2, hydrous chondritic IDPs are generally believed to be derived from asteroids because of their chondritic nature, their similarity to C-type asteroids, and the evidence of their aqueous alteration. Their remarkable fine-grained nature at the submicrometer scale, which is more chondritic than the chondritic meteorites (*Jessberger et al.,* 2001), requires that they had to be formed in environments where substantial mechanical mixing occurred. Natural locations for such processes are found in the solar nebula itself or in asteroidal regoliths (*Keller et al.,* 1993), in particular, the surface layer of rubble piles (*Britt and Consolmagno,* 2001; *Britt et al.,* 2002). On the other hand, it has been suggested that the highly porous and primitive composition of anhydrous chondritic IDPs is indicative of a cometary origin.

One of the most promising methods of discriminating between asteroidal and cometary IDPs on dynamical grounds is to determine their precapture orbits from their thermal histories. However, there are some problems with this method of classification. The distinction between the orbital elements of cometary and asteroidal dust particles may not be as sharp as that displayed by the orbits of their parent bodies. Cometary particles that are trapped in mean-motion resonance with Jupiter can have their orbital eccentricities decreased to asteroidal values (*Liou and Zook,* 1996). On the other hand, large asteroidal particles, with diameters in the range ~100–500 μm, move slowly through the inner solar system toward the Sun under the effects of P-R and solar-wind drag and can have their orbital elements increased to the low end of the cometary range due to the action of mean-motion and secular resonances, as well as gravitational scattering by the terrestrial planets. Caution may therefore be in order when classifying particles as either asteroidal or cometary without an appreciation of their orbital histories.

This argument does not apply to those smaller dust particles (with diameters in the range ~5–25 μm) generated directly by interasteroidal collisions in the main belt. These particles traverse the inner solar system more rapidly and arrive at 1 AU in near-circular, near-ecliptic orbits. Thus, the result of *Brownlee et al.* (1995) that the very-high-speed IDPs are dominated by porous anhydrous chondritic IDPs could be strong evidence that these particles are cometary. However, we believe that the other dust particles accreted by Earth must be predominantly asteroidal in origin. Given that these particles are quite different from known meteorites, it follows that the composition of the asteroid belt is largely unexplored and may consist largely of more friable material not well represented by the strong meteorites in our collections. However, it is interesting to note that because 85% of the dust-band material is associated with a single family, Eos, it follows from our calculations that 25% (85% of 30%) of all accreted dust particles could, in fact, be samples of a single K-type asteroid.

Acknowledgments. It is a pleasure to thank M. Zolensky and D. Brownlee for their valuable contributions and also J. Burns for his careful review. This research was supported by NASA ADP Grant NAG5-9280 and NASA PGG Grant NAG5-4531.

REFERENCES

Alvarez L. W., Alvarez W., Asaro F., and Michel H. V. (1980) Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science, 208,* 1095–1108.

Artymowicz P. (1997) Beta Pictoris: An early solar system? *Annu. Rev. Earth Planet. Sci., 25,* 175–219.

Bottke W. F. Jr., Vokrouhlický D., Brož M., Nesvorný D., and Morbidelli A. (2001) Dynamical spreading of asteroid families by the Yarkovsky effect. *Science, 294,* 1693–1696.

Bottke W. F. Jr., Vokrouhlický D., Rubincam D. P., and Brož M. (2002) The effect of Yarkovsky thermal forces on the dynamical evolution of asteroids and meteoroids. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Bradley J. P. (1999) Interstellar dust — evidence from interplanetary dust particles. In *Formation and Evolution of Solids in Space* (J. M. Greenberg and A. Li, eds.), pp. 485–503. Kluwer, Dordrecht.

Bradley J. P., Brownlee D. E., and Fraundorf P. (1984) Discovery of nuclear tracks in interplanetary dust. *Science, 226,* 1432–1434.

Bradley J. P., Sandford S. A., and Walker R. M. (1988) Interplanetary dust particles. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, eds.), pp. 861–898. Univ. of Arizona, Tucson.

Bradley J. P., Keller L. P., Brownlee D. E., and Thomas K. L. (1996) Reflectance spectroscopy of interplanetary dust particles. *Meteoritics & Planet. Sci., 31,* 394–402.

Britt D. T. and Consolmagno G. J. (2001) Modeling the structure of high porosity asteroids. *Icarus, 152,* 134–139.

Britt D. T., Yeomans D., Housen K., and Consolmagno G. (2002) Asteroid density, porosity, and structure. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Brownlee D. E. (1985) Cosmic dust: Collection and research. *Annu. Rev. Earth Planet. Sci., 13,* 147–173.

Brownlee D. E. (1996) The elemental composition of interplanetary dust. In *Physics, Chemistry, and Dynamics of Interplanetary Dust* (B. Å. S. Gustafson and M. S. Hanner, eds.), pp. 261–264. ASP Conference Series 104.

Brownlee D. E., Joswiak D. J., Schlutter D. J., Pepin R. O., Bradley J. P., and Love S. G. (1995) Identification of individual cometary IDP's by thermally stepped He release (abstract). In *Lunar and Planetary Science XVI,* pp. 183–184. Lunar and Planetary Institute, Houston.

Burns J. A., Lamy P. L., and Soter S. (1979) Radiation forces on small particles in the solar system. *Icarus, 40,* 1–48.

Corrigan C. M., Zolensky M. E., Dahl J., Long M., Weir J., Sapp C., Burkett P. J. (1997) The porosity and permeability of chondritic meteorites and interplanetary dust particles. *Meteoritics & Planet. Sci., 32,* 509–515.

Cziczo D. J., Thomson D. S., and Murphy D. M. (2001) Ablation, flux, and atmospheric implications of meteors inferred from stratospheric aerosol. *Science, 291,* 1772–1775.

Davis D. R., Weidenschilling S. J., Farinella P., Paolicchi P., and Binzel R. P. (1989) Asteroid collisional history: Effects on sizes and spins. In *Asteroids II* (R. P. Binzel et al., eds.), pp. 805–826. Univ. of Arizona, Tucson.

Dell'Oro A., Paolicchi P., Cellino A., Zappalà V., Tanga P., and Michel P. (2001) The role of families in determining collision probability in the asteroid main belt. *Icarus, 153,* 52–60.

Delsemme A. H. (1976) The production rate of dust by comets. In *Interplanetary Dust and Zodiacal Light* (H. Elsässer and H.

Fechtig, eds.), pp. 314–318. Lecture Notes in Physics Vol. 48, Springer-Verlag, Berlin.

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 bands. In *Properties and Interactions of Interplanetary Dust* (R. H. Giese and P. Lamy, eds.), pp. 395–410. ASSL Proc. 199, Reidel, Dordrecht.

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

Dermott S. F., Gomes R. S., Durda D. D., Gustafson B. Å. S., Jayaraman S., Xu Y.-L., and Nicholson P. D. (1992) Dynamics of the zodiacal cloud. In *Chaos, Resonance and Collective Dynamical Phenomena in the Solar System* (S. Ferraz-Mello, ed.), pp. 333–347. Kluwer, Dordrecht.

Dermott S. F., Jayaraman S., Xu Y.-L., Gustafson B. Å. S., and Liou J.-C. (1994a) A circumsolar ring of asteroidal dust in resonant lock with the Earth. *Nature, 369,* 719–723.

Dermott S. F., Durda D. D., Gustafson B. Å. S., Jayaraman S., Liou J.-C., and Xu Y.-L. (1994b) Zodiacal dust bands. In *Asteroids, Comets, Meteors 1993* (A. Milani et al., eds.), pp. 127–142. Kluwer, Dordrecht.

Dermott S. F., Grogan K., Holmes E. K., and Kortenkamp S. J. (1999) Dynamical structure of the zodiacal cloud. In *Formation and Evolution of Solids in Space* (J. M. Greenberg and A. Li, eds.), pp. 565–582. Kluwer, Dordrecht.

Dermott S. F., Grogan K., Durda D. D., Jayaraman S., Kehoe T. J. J., Kortenkamp S. J., and Wyatt M. C. (2001) Orbital evolution of interplanetary dust. In *Interplanetary Dust* (E. Grün et al., eds.), pp. 569–639. Springer-Verlag, Berlin.

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

Dohnanyi J. S. (1976) Sources of interplanetary dust: Asteroids. In *Interplanetary Dust and Zodiacal Light* (H. Elsässer and H. Fechtig, eds.), pp. 187–205. Lecture Notes in Physics Vol. 48, Springer-Verlag, Berlin.

Draine B. T. and Lee H. M. (1984) Optical properties of interstellar graphite and silicate grains. *Astrophys. J., 285,* 89–108.

Durda D. D. and Dermott S. F. (1997) The collisional evolution of the asteroid belt and its contribution to the zodiacal cloud. *Icarus, 130,* 140–164.

Durda D. D., Greenberg R., and Jedicke R. (1998) Collisional models and scaling laws: A new interpretation of the shape of the main-belt asteroid size distribution. *Icarus, 135,* 431–440.

Farley K. A. (2001) Extraterrestrial helium in seafloor sediments: Identification, characteristics, and accretion rate over geologic time. In *Accretion of Extraterrestrial Matter Throughout Earth's History* (B. Peucker-Ehrenbrink and B. Schmitz, eds.), pp. 179–204. Kluwer, New York.

Farley K. A., Love S. G., and Patterson D. B. (1997) Atmospheric entry heating and helium retentivity of interplanetary dust particles. *Geochim. Cosmochim. Acta, 61,* 2309–2316.

Flynn G. J. (1990) The near-Earth enhancement of asteroidal over cometary dust. *Proc. Lunar Planet. Sci. Conf. 20th,* pp. 363–371.

Flynn G. J. (1996) Sources of 10 micron interplanetary dust: The contribution from the Kuiper belt. In *Physics, Chemistry, and Dynamics of Interplanetary Dust* (B. Å. S. Gustafson and M. S. Hanner, eds.), pp. 171–175. ASP Conference Series 104.

Flynn G. J., Bajt S., Sutton S. R., Zolensky M. E., Thomas K. L., and Keller L. P. (1996) The abundance pattern of elements having low nebular condensation temperatures in interplanetary dust particles: Evidence for a new chemical type of chondritic material. In *Physics, Chemistry, and Dynamics of Interplanetary Dust* (B. Å. S. Gustafson and M. S. Hanner, eds.), pp. 291–294. ASP Conference Series 104.

Fraundorf P. (1981) Interplanetary dust in the transmission electron microscope: Diverse materials from the early solar system. *Geochim. Cosmochim. Acta, 45,* 915–943.

Gor'kavyi N. N., Ozernoy L. M., Mather J. C., and Taidakova T. (1997) Quasi-stationary states of dust flows under Poynting-Robertson drag: New analytical and numerical solutions. *Astrophys. J., 488,* 268–276.

Grogan K., Dermott S. F., Jayaraman S., and Xu Y.-L. (1997) Origin of the ten degree dust bands. *Planet. Space Sci., 45,* 1657–1665.

Grogan K., Dermott S. F., and Durda D. D. (2001) The size-frequency distribution of the zodiacal cloud: Evidence from the solar system dust bands. *Icarus, 152,* 251–267.

Grün E., Zook H. A., Fechtig H., and Giese R. H. (1985) Collisional balance of the meteoritic complex. *Icarus, 62,* 244–272.

Grün E., Zook H. A., Baguhl M., Balogh A., Bame S. J., Fechtig H., Forsyth R., Hanner M. S., Horanyi M., Kissel J., Lindblad B.-A., Linkert D., Linkert G., Mann I., McDonnell J. A. M., Morfill G. E., Phillips J. L., Polanskey C., Schwehm G., Siddique N., Staubach P., Svestka J., and Taylor A. (1993) Discovery of jovian dust streams and interstellar grains by the ULYSSES spacecraft. *Nature, 362,* 428–430.

Grün E., Staubach P., Baguhl M., Hamilton D. P., Zook H. A., Dermott S. F., Gustafson B. Å. S., Fechtig H., Kissel J., Linkert D., Linkert G., Srama R., Hanner M. S., Polanskey C., Horanyi M., Lindblad B.-A., Mann I., McDonnell J. A. M., Morfill G. E., and Schwehm G. (1997) South-North and radial traverses through the interplanetary dust cloud. *Icarus, 129,* 270–288.

Gustafson B. Å. S. (1994) Physics of zodiacal dust. *Annu. Rev. Earth Planet. Sci., 22,* 553–595.

Gustafson B. Å. S. and Hanner M. S., eds. (1996) *Physics, Chemistry, and Dynamics of Interplanetary Dust.* ASP Conference Series 104. 568 pp.

Hallam A. (2001) Mass extinctions in Phanerozoic time. In *Meteorites: Flux with Time and Impact Effects* (M. M. Grady et al., eds.), pp. 259–274. Geological Society of London Special Publication 140.

Hilton J. L. (2002) Asteroid masses and densities. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Hirayama K. (1918) Groups of asteroids probably of common origin. *Astron. J., 31,* 185–188.

Hiroi T., Zolensky M. E., and Pieters C. M. (2001) The Tagish Lake meteorite: A possible sample from a D-type asteroid. *Science, 293,* 2234–2236.

Hooper P. J. (2000) Flood basalt provinces. In *Encyclopedia of Volcanoes* (H. Sigurdsson et al., eds.), pp. 345–359. Academic, San Diego.

Hughes D. W. (1978) Meteors. In *Cosmic Dust* (J. A. M. McDonnell, ed.), pp. 123–185. Wiley, Chichester.

Hunten D. M., Turco R. P., and Toon O. B. (1980) Smoke and dust particles of meteoric origin in the mesosphere and stratosphere. *J. Atmos. Sci., 37,* 1342–1357.

Ishiguro M., Nakamura R., Fujii Y., Morishige K., Yano H., Yasuda

H., Yokogawa S., and Mukai T. (1999) First detection of visible zodiacal dust bands from ground-based observations. *Astrophys. J., 511,* 432–435.

Jackson A. A. and Zook H. A. (1992) Orbital evolution of dust particles from comets and asteroids. *Icarus, 97,* 70–84.

Jessberger E. K., Stephan T., Rost D., Arndt P., Maetz M., Stadermann F. J., Brownlee D. E., Bradley J. P., and Kurat G. (2001) Properties of interplanetary dust: Information from collected samples. In *Interplanetary Dust* (E. Grün et al., eds.), pp. 253–294. Springer-Verlag, Berlin.

Keller L. P., Thomas K. L., and McKay D. S. (1993) Asteroidal agglutinate particles as a component of anhydrous interplanetary dust. *Meteoritics, 28,* 378–379.

Kelsall T., Weiland J. L., Franz B. A., Reach W. T., Arendt R. G., Dwek E., Freudenreich H. T., Hauser M. G., Moseley S. H., Odegard N. P., Silverberg R. F., and Wright E. L. (1998) The COBE diffuse infrared background experiment search for the cosmic infrared background. II. Model of the interplanetary dust cloud. *Astrophys. J., 508,* 44–73.

Klöck W. and Stadermann F. J. (1994) Mineralogical and chemical relationships of interplanetary dust particles, micrometeorites and meteorites. In *Analysis of Interplanetary Dust* (M. E. Zolensky et al., eds.), pp. 51–87. AIP Conference Proceedings 310.

Kortenkamp S. J. and Dermott S. F. (1998a) Accretion of interplanetary dust particles by the Earth. *Icarus, 135,* 469–495.

Kortenkamp S. J. and Dermott S. F. (1998b) A 100,000-year periodicity in the accretion rate of interplanetary dust. *Science, 280,* 874–876.

Kortenkamp S. J., Dermott S. F., Fogle D., and Grogan K. (2001) Sources and orbital evolution of interplanetary dust accreted by Earth. In *Accretion of Extraterrestrial Matter Throughout Earth's History* (B. Peucker-Ehrenbrink and B. Schmitz, eds.), pp. 13–30. Kluwer, New York.

Leinert C., Röser S., and Buitrago J. (1983) How to maintain the spatial distribution of interplanetary dust. *Astron. Astrophys., 118,* 345–357.

Liou J.-C. and Zook H. A. (1996) Comets as a source of low eccentricity and low inclination interplanetary dust particles. *Icarus, 123,* 491–502.

Liou J.-C., Dermott S. F., and Xu Y.-L. (1995) The contribution of cometary dust to the zodiacal cloud. *Planet. Space Sci., 43,* 717–722.

Liou J.-C., Zook H. A., and Dermott S. F (1996) Kuiper belt dust grains as a source of interplanetary dust particles. *Icarus, 124,* 429–440.

Lisse C. M., A'Hearn M. F., Hauser M. G., Kelsall T., Lien D. J., Moseley S. H., Reach W. T., and Silverberg R. F. (1998) Infrared observations of comets by COBE. *Astrophys. J., 496,* 971–991.

Lisse C. M. (2001) The death of short period comets (abstract). *Bull. Am. Astron. Soc., 33,* 1093.

Love S. G. and Brownlee D. E. (1991) Heating and thermal transformation of micrometeoroids entering the Earth's atmosphere. *Icarus, 89,* 26–43.

Love S. G. and Brownlee D. E. (1993) A direct measurement of the terrestrial mass accretion rate of cosmic dust. *Science, 262,* 550–553.

Low F. J., Beintema D. A., Gautier T. N., Gillet F. C., Beichmann C. A., Neugebauer G., Young E., Aumann H. H., Boggess N., Emerson J. P., Habing H. J., Hauser M. G., Houck J. R., Rowan-Robinson M., Soifer B. T., Walker R. G., and Wesselius P. R. (1984) Infrared cirrus: New components of the extended infrared emission. *Astrophys. J. Lett., 278,* L19–L22.

Maurette M., Engrand C., and Kurat G. (1996) Collection and microanalysis of Antarctic micrometeorites. In *Physics, Chemistry, and Dynamics of Interplanetary Dust* (B. Å. S. Gustafson and M. S. Hanner, eds.), pp. 265–273. ASP Conference Series 104.

McKeegan K. D. (1987) Oxygen isotopes in refractory stratospheric dust particles: Proof of extraterrestrial origin. *Science, 237,* 1468–1471.

McSween H. Y. Jr., Sears D. W. G., and Dodd R. T. (1988) Thermal metamorphism. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, eds.), pp. 102–113. Univ. of Arizona, Tucson.

Messenger S. and Walker R. M. (1996) Isotopic anomalies in interplanetary dust particles. In *Physics, Chemistry, and Dynamics of Interplanetary Dust* (B. Å. S. Gustafson and M. S. Hanner, eds.), pp. 287–290. ASP Conference Series 104.

Michel P., Benz W., Tanga P., and Richardson D. C. (2001) Collisions and gravitational reaccumulation: Forming asteroid families and satellites. *Science, 294,* 1696–1700.

Mukhopadhyay S., Farley K. A., and Montanari A. (2001) A 35 m.y. record of helium in pelagic limestones from Italy: Implications for interplanetary dust accretion from the early Maastrichtian to the middle Eocene. *Geochim. Cosmochim. Acta., 65,* 653–669.

Muller R. A. and MacDonald G. J. (1997) Glacial cycles and astronomical forcing. *Science, 277,* 215–218.

Murphy D. M. (2001) Extraterrestrial material and stratospheric aerosols. In *Accretion of Extraterrestrial Matter Throughout Earth's History* (B. Peucker-Ehrenbrink and B. Schmitz, eds.), pp. 129–142. Kluwer, New York.

Murray C. D. and Dermott S. F. (1999) *Solar System Dynamics*. Cambridge Univ., Cambridge. 606 pp.

Napier W. M. (2001) The influx of comets and their debris. In *Accretion of Extraterrestrial Matter Throughout Earth's History* (B. Peucker-Ehrenbrink and B. Schmitz, eds.), pp. 51–74. Kluwer, New York.

Nier A. O. and Schlutter D. J. (1993) The thermal history of interplanetary dust particles collected in the Earth's stratosphere. *Meteoritics, 28,* 675–681.

Peucker-Ehrenbrink B. (2001) Iridium and osmium as tracers of extraterrestrial matter in marine sediments. In *Accretion of Extraterrestrial Matter Throughout Earth's History* (B. Peucker-Ehrenbrink and B. Schmitz, eds.), pp. 163–178. Kluwer, New York.

Peucker-Ehrenbrink B. and Schmitz B., eds. (2001) *Accretion of Extraterrestrial Matter Throughout Earth's History*. Kluwer, New York. 492 pp.

Pravec P. and Harris A. W. (2000) Fast and slow rotation of asteroids. *Icarus, 148,* 12–20.

Pravec P. and Harris A. W. (2001) Asteroid rotations (abstract). In *Asteroids 2001: From Piazzi to the Third Millenium,* p. 59. Osservatorio di Palermo, Sicily.

Pravec P., Harris A. W., and Michałowski T. (2002) Asteroid rotations. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Rajan R. S., Brownlee D. E., Tomandl D., Hodge P. W., Farrar H., and Britten R. A. (1977) Detection of ^{4}He in stratospheric particles gives evidence of extraterrestrial origin. *Nature, 267,* 133–134.

Rampino M. R., Self S., and Stothers R. B. (1988) Volcanic winters. *Annu. Rev. Earth. Planet. Sci., 16,* 73–99.

Reach W. T., Franz B. A., and Weiland J. L. (1997) The threedimensional structure of the zodiacal dust bands. *Icarus, 127,* 461–484.

Reach W. T., Franz B. A., Weiland J. L., Hauser M. G., Kelsall T. N., Wright E. L., Rawley G., Stemwedel S. W., and Spiesman W. J. (1995) Observational confirmation of a circumsolar dust ring by the COBE satellite. *Nature, 374,* 521–523.

Richardson D. C., Leinhardt Z. M., Melosh H. J., Bottke W. F. Jr., and Asphaug E. (2002) Gravitational aggregates: Evidence and evolution. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Rietmeijer F. J. M. (1988) Interplanetary dust particles. In *Reviews in Mineralogy, Vol. 36: Planetary Materials* (J. J. Papike, ed.), pp. 2.1–2.95. Mineralogical Society of America, Washington.

Robock A. (2000) Volcanic eruptions and climate. *Rev. Geophys., 38,* 191–219.

Schramm L. S., Brownlee D. E., and Wheelock M. M. (1989) Major element composition of stratospheric micrometeorites. *Meteoritics, 24,* 99–112.

Stothers R. B. (1993) Flood basalts and extinction events. *Geophys. Res. Lett., 20,* 1399–1402.

Sykes M. V. (1990) Zodiacal dust bands: Their relation to asteroid families. *Icarus, 84,* 267–289.

Sykes M. V. and Greenberg R. (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. and Walker R. G. (1992) Cometary dust trails. I. Survey. *Icarus, 95,* 180–210.

Thomas K. L., Keller L. P., Blanford G. E., and McKay D. S. (1994) Quantitative analyses of carbon in anhydrous and hydrated interplanetary dust particles. In *Analysis of Interplanetary Dust* (M. E. Zolensky et al., eds.), pp. 165–172. AIP Conference Proceedings 310.

Thomas K. L., Keller L. P., and McKay D. S. (1996) A comprehensive study of major, minor, and light element abundances in over 100 interplanetary dust particles. In *Physics, Chemistry, and Dynamics of Interplanetary Dust* (B. Å. S. Gustafson and M. S. Hanner, eds.), pp. 283–286. ASP Conference Series 104.

Toon O. B., Zahnle K., Turco R. P., and Covey C. (1994) Environmental perturbations caused by impacts. In *Hazards Due to Comets and Asteroids* (T. Gehrels, ed.), pp. 791–826. Univ. of Arizona, Tucson.

Vokrouhlický D., Brož M., Morbidelli A., Nesvorný D., and Bottke W. F. Jr. (2001) Long-term dynamical diffusion in asteroid families via the Yarkovsky effect (abstract). In *Asteroids 2001: From Piazzi to the Third Millenium,* p. 225. Osservatorio di Palermo, Sicily.

Whipple F. L. (1967) On maintaining the meteoritic complex. In *The Zodiacal Light and the Interplanetary Medium* (J. L. Weinberg, ed.), pp. 409–426. NASA SP-150, Washington, DC.

Wyatt S. P. Jr. and Whipple F. L. (1950) The Poynting-Robertson effect on meteor orbits. *Astrophys. J., 111,* 134–141.

Wyatt M. C., Dermott S. F., Telesco C. M., Fisher R. S., Grogan K., Holmes E. K., and Piña R. K. (1999) How observations of circumstellar disk asymmetries can reveal hidden planets: Pericenter glow and its application to the HR 4796 disk. *Astrophys. J., 527,* 918–944.

Zappalà V. and Cellino A. (1993) Asteroid families. In *Asteroids, Comets, Meteors 1993* (A. Milani et al., eds.), pp. 395–414. Kluwer, Dordrecht.

Zappalà V., Bendjoya P. H., Cellino A., Farinella P., and Froeschlè C. (1995) Asteroid families: Search of a 12,487 asteroid sample using two different clustering techniques. *Icarus, 116,* 291–314.

Zappalà V., Cellino A., Gladman B. J., Manley S., and Migliorini F. (1998) Asteroid showers on Earth after family breakup events. *Icarus, 134,* 176–179.

Zolensky M. E. (1987) Refractory interplanetary dust particles. *Science, 237,* 1466–1468.

Zolensky M. E. and Barrett R. A. (1994) Compositional variations of olivines and pyroxenes in chondritic interplanetary dust particles. *Meteoritics, 29,* 616–620.

Zolensky M. E. and McSween H. Y. Jr. (1988) Aqueous alteration. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, eds.), pp. 114–143. Univ. of Arizona, Tucson.

Zolensky M. E., Wilson T. L., Rietmeijer F. J. M., and Flynn G. J., eds. (1994) *Analysis of Interplanetary Dust.* AIP Conference Proceedings 310. 371 pp.

Zook H. A. (2001) Spacecraft measurements of the cosmic dust flux. In *Accretion of Extraterrestrial Matter Throughout Earth's History* (B. Peucker-Ehrenbrink and B. Schmitz, eds.), pp. 75–92. Kluwer, New York.