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Physical properties of asteroid dust bands and their sources

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Abstract

Disruptive collisions in the main belt can liberate fragments from parent bodies ranging in size from several micrometers to tens of kilometers in diameter. These debris bodies group at initially similar orbital locations. Most asteroid-sized fragments remain at these locations and are presently observed as asteroid families. Small debris particles are quickly removed by Poynting–Robertson drag or comminution but their populations are replenished in the source locations by collisional cascade. Observations from the Infrared Astronomical Satellite (IRAS) showed that particles from particular families have thermal radiation signatures that appear as band pairs of infrared emission at roughly constant latitudes both above and below the Solar System plane. Here we apply a new physical model capable of linking the IRAS dust bands to families with characteristic inclinations. We use our results to constrain the physical properties of IRAS dust bands and their source families. Our results indicate that two prominent IRAS bands at inclinations ≈2.1° and ≈9.3° are byproducts of recent asteroid disruption events. The former is associated with a disruption of a ≈30-km asteroid occurring 5.8 Myr ago; this event gave birth to the Karin family. The latter came from the breakup of a large >100-km-diameter asteroid 8.3 Myr ago that produced the Veritas family. Using an N-body code, we tracked the dynamical evolution of $\approx 10^6$ particles, 1 μm to 1 cm in diameter, from both families. We then used these results in a Monte Carlo code to determine how small particles from each population undergo collisional evolution. By computing the thermal emission of particles, we were able to compare our results with IRAS observations. Our best-fit model results suggest the Karin and Veritas family particles contribute by 5–9% in 10–60-μm wavelengths to the zodiacal cloud's brightness within 50° latitudes around the ecliptic, and by 9–15% within 10° latitudes. The high brightness of the zodiacal cloud at large latitudes suggests that it is mainly produced by particles with higher inclinations than what would be expected for asteroidal particles produced by sources in the main belt. From these results, we infer that asteroidal dust represents a smaller fraction of the zodiacal cloud than previously thought. We estimate that the total mass accreted by the Earth in Karin and Veritas particles with diameters 20–400 μm is ≈15,000–20,000 tons per year (assuming 2 $\mathrm{g\,cm^{-3}}$ particles density). This is ≈30–50% of the terrestrial accretion rate of cosmic material measured by the Long Duration Exposure Facility. We hypothesize that up to ≈50% of our collected interplanetary dust particles and micrometeorites may be made up of particle species from the Veritas and Karin families. The Karin family IDPs should be about as abundant as Veritas family IDPs though this ratio may change if the contribution of third, near-ecliptic source is significant. Other sources of dust and/or large impact speeds must be invoked to explain the remaining ≈50–70%. The disproportional contribution of Karin/Veritas particles to the zodiacal cloud (only 5–9%) and to the terrestrial accretion rate (30–50%) suggests that the effects of gravitational focusing by the Earth enhance the accretion rate of Karin/Veritas particles relative to those in the background zodiacal cloud. From this result and from the latitudinal brightness of the zodiacal cloud, we infer that the zodiacal cloud emission may be dominated by high-speed cometary particles, while the terrestrial impactor flux contains a major contribution from asteroidal sources. Collisions and Poynting–Robertson drift produce the size-frequency distribution (SFD) of Karin and Veritas particles that becomes increasingly steeper closer to the Sun. At 1 AU, the SFD is relatively shallow for small particle diameters D (differential slope exponent of particles with $D \lesssim 100$ μm is ≈2.2–2.5) and steep for $D \gtrsim 100$ μm. Most of the mass at 1 AU, as well as most of the cross-sectional area, is contributed by particles with $D \approx 100$–200 μm. Similar result has been found previously for the SFD of the zodiacal cloud particles at 1 AU. The fact that the SFD of Karin/Veritas particles is similar to that of the zodiacal cloud suggests that similar processes shaped these particle populations. We estimate that there are $\approx 5 \times 10^{24}$ Karin and $\approx 10^{25}$ Veritas family particles with $D > 30$ μm in the Solar System today. The IRAS observation of the dust bands may be satisfactorily modeled using 'averaged' SFDs that are constant with semimajor axis. These SFDs are best described by a broken power-law function with differential power index $\alpha \approx 2.1$–2.4 for $D \lesssim 100$ μm and by $\alpha \gtrsim 3.5$ for 100 μm $\lesssim D \leqslant 1$ cm. The total

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cross-sectional surface area of Veritas particles is a factor of ≈2 larger than the surface area of the particles producing the inner dust bands. The total volumes in Karin and Veritas family particles with $1\ \mu\text{m} < D < 1$ cm correspond to $D = 11$ km and $D = 14$ km asteroids with equivalent masses $\approx 1.5 \times 10^{18}$ g and $\approx 3.0 \times 10^{18}$ g, respectively (assuming $2\ \text{g}\,\text{cm}^{-3}$ bulk density). If the size-frequency and radial distribution of particles in the zodiacal cloud were similar to those in the asteroid dust bands, we estimate that the zodiacal cloud represents $\sim 3 \times 10^{19}$ g of material (in particles with $1\ \mu\text{m} < D < 1$ cm) at ±10° around the ecliptic and perhaps as much as $\sim 10^{20}$ g in total. The later number corresponds to about a 23-km-radius sphere with $2\ \text{g}\,\text{cm}^{-3}$ density.

Keywords: Zodiacal light; Infrared observations; Meteoroids; Asteroids; Collisional physics

1. Introduction

The Solar System is dusty. Small dust particles and larger micrometeoroids are produced by the sublimation and outgassing of comets, collisions within the asteroid and Kuiper belts, and by impacts onto planetary moons. They also arrive in the Solar System from interstellar sources. Meteor showers and the zodiacal light provide the most spectacular appearances of tiny interplanetary particles to a naked-eye observer.

There are many active areas in research of interplanetary particles at this time. Some probe their mineralogical and elementary compositions, while others study their spatial, velocity and size distributions. The goals are to place Interplanetary Dust Particles (IDPs) and micrometeorites in our collections into the appropriate geologic context, determine collision and dynamical evolution of dust particles and micrometeoroids in the interplanetary space, understand the hazard posed by these projectiles to spacecraft missions, etc.

Observations of interplanetary particles have been made using several different methods: direct impacts of particles onto detectors located onboard spacecrafts such as the Long Duration Exposure Facility (LDEF; Love and Brownlee, 1993; see Grün et al., 2001, for a review of in situ spacecraft measurements); thermal infrared observations by facilities like the Infrared Astronomical Telescope (IRAS), the Cosmic Background Explorer (COBE), the Infrared Space Observatory (ISO), and the Spitzer Space Telescope (Low et al., 1984; Hauser et al., 1984; Kelsall et al., 1998; Reach et al., 1995, 2003; Sykes et al., 2005, in preparation); in scattered and reflected visible light (Ishiguro et al., 1999; Hahn et al., 2002), and by radar (e.g., Brown and Jones, 1999; Mathews et al., 2001; Janches et al., 2001; Hunt et al., 2004). About 20,000–60,000 tons of IDPs with sizes ranging from ≈20 to 400 μm in diameter (Love and Brownlee, 1993; Taylor et al., 1996) are annually accreted by the Earth. These and smaller interplanetary particles are collected by aircraft in the Earth's stratosphere, in the polar ice (Taylor et al., 1996), are traced using rare isotopes in deep-ocean sediments (Farley et al., 1998, 2006), and produce meteors (e.g., Brown and Campbell-Brown, 2003; see Ceplecha et al., 1998, for a review).

To explain these observations, researchers have developed physical models of interplanetary dust (Dermott et al., 1984, 1994; Grün et al., 1985; Sykes and Greenberg, 1986; Sykes, 1990; Reach et al., 1997; Durda and Dermott, 1997; Grogan et al., 1997, 2001; Kelsall et al., 1998; Moro-Martín and Malhotra, 2003; Mahoney-Hopping et al., 2003, 2004; see also the reviews by Dermott et al. (2001) and Sykes et al. (2005), and references therein). These models account for a variety of dynamical (e.g., planetary perturbations, Poynting–Robertson (P–R) and solar wind drag forces, radiation pressure, electromagnetic forces on charged particles) and physical processes (e.g., collisions, sublimation, sputtering) that determine the behavior of particles in interplanetary space and their interaction with a detector (e.g., ablation of micrometeorites in the Earth's atmosphere, ^{3}He retention, thermal radiation, light scattering).

In this paper, we will concentrate on modeling of the particles that produce the *zodiacal dust bands*. The zodiacal dust bands are extended sources of infrared (IR) emission roughly parallel to the ecliptic. They were discovered by IRAS observations in 1983 (Low et al., 1984). Originally, the major dust bands detected by IRAS were thought to be associated with three prominent asteroid families (Eos, Koronis, and Themis; Dermott et al., 1984; Sykes, 1986). More recently, using young asteroid families as tracers of recent disruptions in the main belt, Nesvorný et al. (2002, 2003) identified alternative sources of two of the brightest dust bands.

Nesvorný et al. proposed that the dust band with inclination 9.35° comes from the Veritas asteroid family at 3.17 AU, while the 2.1° band comes from the Karin family located inside the Koronis asteroid family at 2.865 AU. The Veritas and Karin families formed via collisional disruptions of >100- and ≈30-km-diameter parent bodies at 8.3 ± 0.5 and 5.75 ± 0.05 Myr ago, respectively (Nesvorný et al., 2002, 2003; Nesvorný and Bottke, 2004). See Durda et al. (2005) and Nesvorný et al. (2005b) for estimates of parent bodies' diameters derived from Smooth-Particle Hydrodynamic simulations of asteroid impacts.[1]

Recent disruption events are thought to be a stronger present-day source of dust particles than older, more prominent asteroid families (Sykes and Greenberg, 1986). Older families like Eos, Koronis, and Themis reached collisional equilibrium for $D < 5$ km bodies (Morbidelli et al., 2003; Bottke et al., 2005). This means their present ability to produce large quantities of dust particles is generally limited. Conversely, recently formed families should still contain large quantities of $\gtrsim$1-cm-diameter particles that can feed populations of <1-cm-diameter particles through the collisional cascade.

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[1] The Veritas family's parent body may have been ≈160 km in diameter (Durda et al., 2005), or smaller if (490) Veritas is an interloper in its own family (see discussion in Nesvorný et al., 2003).