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COLLISIONAL AND DYNAMIC EVOLUTION OF DUST FROM THE ASTEROID BELT

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ABSTRACT

The size and spatial distribution of collisional debris from main belt asteroids is modeled over a 10 million year period. The model dust and meteoroid particles spiral toward the Sun under the action of Poynting-Robertson drag and grind down as they collide with a static background of field particles.

INTRODUCTION

Analysis of the solar system dust bands in the IRAS data using the SIMUL model (Dermott and Nicholson, 1989) has established both the bands' origin in the prominent Hirayama families and the transport of asteroidal dust to 1 AU (Dermott *et al.*, 1992). Durda *et al.* (1992) show how the production rate of 1 mm and larger debris from any one family varies stochastically over time. The comminution or collisional break-up of smaller particles and their transport to 1 AU is addressed in this article.

THE ASTEROID COMMINUTE EVOLUTION (ACE) MODEL

The present form of our Asteroid Comminute Evolution (ACE) model accounts for the collision of asteroid fragments with a static background of field particles while the fragments spiral toward the Sun under the action of Poynting-Robertson drag and radiation pressure. The combined effects of gravitational forces due to the planets and radiation forces may be accounted for in future models using a new secular perturbation theory by Gomes and Dermott (1992).

A body of given size and density is in a circular heliocentric orbit of given radius. A collision breaks the body into fragments following a size distribution of the form

$$\frac{dN}{dm} = C\, m^{-(1+\eta)}\,,$$

where dN is the number of fragments in the mass range m to $m + dm$. The exponent η usually equals 0.83 with the largest fragment retaining 30% of the total mass (Fujiwara et al., 1977). Conservation of mass defines the constant C. Fragments in the mass range from 10^{-12} to 10^{18}g (from ß-meteoroids to 4 or 5 km radius asteroids) are divided into 60 logarithmic size bins. For computational convenience, every fragment is assumed to be homogeneous, of equal density, and spherical in shape. To further reduce computational overhead while conserving mass, particles are reassigned a mass equal to the arithmetic mean associated with its bin. Radiation pressure instantly distorts the pre-break-up circular orbit to an ellipse with perihelion at the breakup point. This distortion is important for small bodies and the smallest particles leave the solar system as ß-meteoroids. After break-up, particles within a given mass bin are placed in identical circular orbits at the time averaged heliocentric distance of their orbits. Every particle bin is characterized by the average particle mass and heliocentric distance in a two dimensional matrix. Fragments smaller than the lower cut-off limit and any fragments on orbits beyond 5.425 AU are assumed to escape the solar system, the accumulated mass of such β-meteoroids is recorded. Fragments collide with a population of interplanetary grains represented by the empirical interplanetary flux model of Grün *et al.* (1985). This distribution closely fits fluxes derived from Pioneer 8, 9, and HEOS-2 measurements. The mass distribution is observationally supported up to approximately 100 g corresponding to meteoroids a few cm in radius. As the number of larger field objects is small, their detailed distribution is not decisive to modeling over a few million years. The number of fragments produced by particles in a given size bin in one time step is calculated from the probability for catastrophic collisions per unit time multiplied by the time interval and the number of particles. Average collision probabilities were used in these simulations. In contrast, in the simulations by Durda *et al.* (1992) a random number generator was used to investigate the extent of statistical fluctuations. Fragments instantly move to higher orbits while the surviving particles lose height due to PR-drag at each time step.

RESULTS

The distribution of fragments is immediately distorted as radiation pressure expels the smallest particles as β-meteoroids. Dust sized particles (1 to 100 μm in radius) are initially dispersed on elliptic orbits and reside most of the time outside the orbit of the parent asteroid. PR-drag soon reduces the size and eccentricity of their trajectories and the smallest particles are first to arrive at 1 AU even though radiation pressure originally pushed them furthest out. A supply of fresh debris is constantly produced as larger particles collide with the meteoric complex, break-up, and produce miniature dust clouds analogous to the break-up of the asteroid. The size and spatial distribution changes rapidly at first, but dust below 10^{-8}g (10 μm) reach a nearly steady distribution at 1 AU over the first 10^5 years. Figure 1 shows the size distribution at 1 AU resulting from the break-up of a 100 km radius asteroid, of 2.5 g cm^{-3} density, near the outer edge of the asteroid belt (3 AU). Particles ranging up to approximately 10^{-5}g (100 μm) arrive at 1 AU after 10^6 years (dashed line) and also appear to reach a nearly steady size distribution with larger particles still arriving over the 10^7 year period (solid curve). The distribution of dust from an asteroid on the inner edge of the main belt (2 AU) shown in Figure 2 confirm the overall features shown in Figure 1 and meteoroids in the 10^{-4} to 10^{-5}g range appear to have reached an equilibrium distribution. Meteoroids of 10^{-2}g or about a millimeter arrive from 2 AU after 10^6 years (Figure 2) and their numbers did not change from 10^6 to 10^7 years. Intermediate size meteoroids are destroyed and feed the dust population. While the computations indicate that some millimeter sized meteoroids arrive from a break-up at 3 AU their numbers are so small that they are not seen in Figure 1. The dust size distribution (below 10^{-5}g or 100 μm) established over the first 10^6 years remains remarkably stable in both figures.

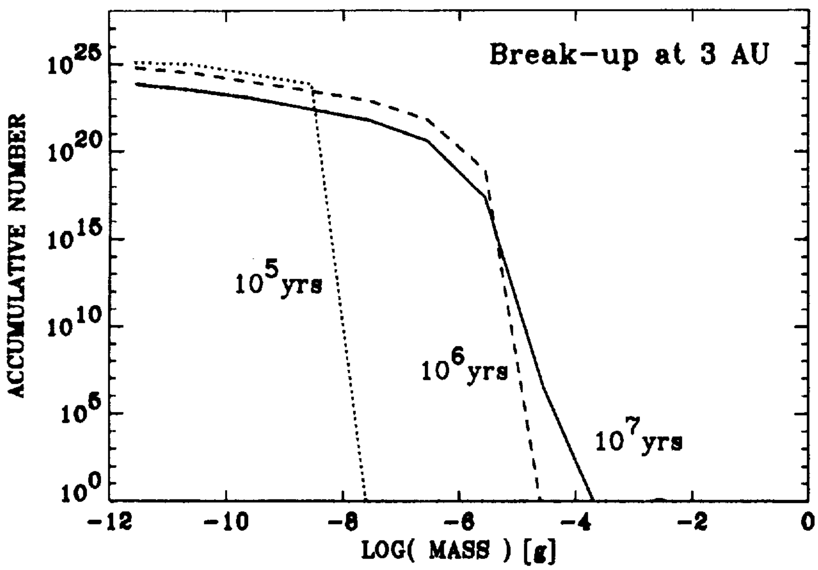

Figure 1. Size distribution of collisionally evolved asteroidal debris at 1 AU, 10^5, 10^6, and 10^7 years after the break-up of an asteroid near the outer edge of the main belt. The original power law size distribution is altered as debris collide, grind down, and spiral in to Earth's orbit under the action of PR-drag. Fragments in the size range 10^{-5} to 10^{-11}g (or 100 to 1 μm) reach 1 AU within the first 10^6 years and their size distribution then remains remarkably stable.

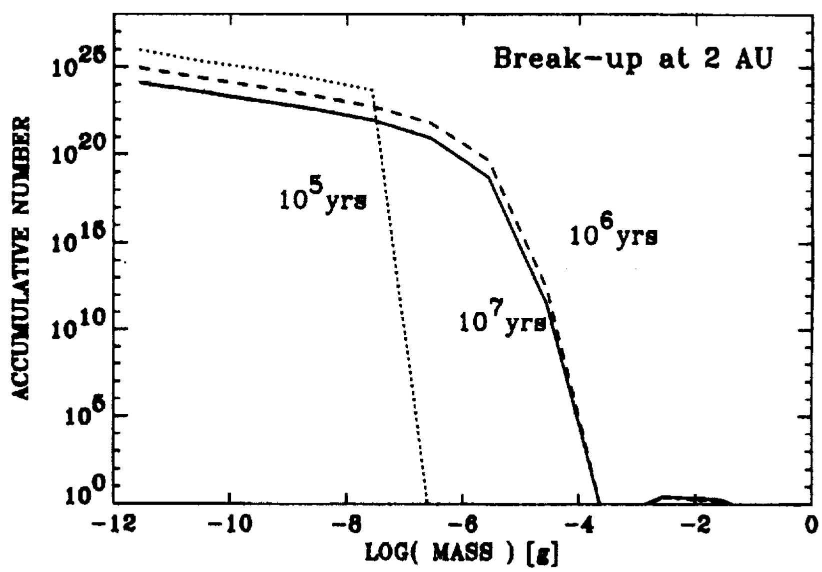

Figure 2. Size distribution at 1 AU of collisionally evolved debris from an asteroid that broke up near the inner edge of the asteroid belt. A nearly steady size distribution is attained within the first million years after the break-up. Meteoroids in the 10^{-2}g or 1 mm size range reach the Earth's orbit after 10^6 years but intermediate size particles are ground down before they reach the Earth.

These are significant results as particles in the 10 to 100 μm size range are thought to produce most of the zodiacal light (Röser and Staude, 1978). Particles in this size range are also routinely collected in the stratosphere (Brownlee, 1985) where atmospheric entry heating favors the survival of asteroidal debris over cometary dust (Flynn, 1992). Asteroids including the major Hirayama families may have extended associated dust populations reaching 1 AU produced as member asteroids collide, as suggested from analysis of the IRAS solar system dust bands (Dermott *et al.*, 1992). Collisions with the meteoric complex generally break fragments into smaller pieces before they reach 1 AU and alter the original size distribution but do not preclude significant amounts of collisionally evolved asteroid dust from reaching the Earth's orbit. This is also the size range particles to be collected by the Cosmic Dust Collection Facility (CDCF) planned to fly on the Space Station Freedom. The CDCF might be expected to collect asteroidal dust particles for analysis.

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