A 100,000-Year Periodicity in the Accretion Rate of Interplanetary Dust

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Numerical modeling of the orbital evolution of interplanetary dust particles revealed that, over the past 1.2 million years, the rate of accretion of dust by Earth has varied by a factor of 2 to 3. These variations display a 100,000-year periodicity and are anticorrelated with Earth's changing orbital eccentricity. Extraterrestrial helium-3 concentrations in a deep-sea sediment core display a similar periodicity but are 50,000 years out of phase with the predicted variations. Also, because collisions between large bodies in the asteroid belt are inevitable, it is expected that large-amplitude stochastic variations on 10^7- to 10^8-year time scales would be superimposed on the 10^5-year periodic variations.

The four terrestrial planets of our solar system orbit the sun enveloped in a tenuous cloud of dust known as the zodiacal cloud. Each year, our planet accretes about 3 $\times$ 10^7 kg of interplanetary dust particles (IDPs) from this cloud (*1*), a mass influx about 100 times greater than the influx associated with 10^2- to 10^6-g meteorites (*2*). Some of these accreted IDPs are collected by aircraft flying in the stratosphere and constitute a major source of extraterrestrial material available for laboratory study. However, the origin of these collected IDPs, whether asteroidal or cometary, has been a subject of debate (*3*). Poynting-Robertson light drag and solar wind drag act to dissipate the energy and angular momentum of small micrometer-sized dust particles in the zodiacal cloud. Wyatt and Whipple (*4*) showed that the resulting decay in the semimajor axes a and osculating eccentricities e of their orbits is given by

$$\frac{da}{dt} = -\frac{\eta}{a}\frac{(2 + 3e^2)}{(1 - e^2)^{3/2}} \quad (1)$$

and

$$\frac{de}{dt} = -\frac{5}{2}\frac{\eta}{a^2}\frac{e}{(1 - e^2)^{1/2}} \quad (2)$$

where t is time and η is a parameter dependent on the physical properties of the dust particle, such as size, density, and absorption and emission efficiencies (*5*). Dust particles 10 to 100 μm in size are removed from the zodiacal cloud on time scales of 10^4 to 10^6 years (*6*). Presuming a steady-state zodiacal cloud, continuous replenishment to offset this depletion is a task once thought to be performed almost exclusively by comets (*7*). This viewpoint began to change in 1984 when observations of the zodiacal cloud made with the Infrared Astronomical Satellite (IRAS) revealed prominent bands of dust near the ecliptic (*8*). These dust bands are associated with the three most populated asteroid families—Eos, Themis, and Koronis (*9*). These three asteroid families remain the most abundant sources of dust to be unambiguously linked to observations of the zodiacal cloud (*10*).

The decay rate de/da (the ratio of Eq. 2 to 1) is independent of η, so asteroidal dust particles of all sizes, which initially have moderate e values (typically $e \leq 0.3$), will be on nearly circular orbits by the time they become Earth crossing (typically $e \lesssim 0.1$). Cometary dust particles can have Earth-crossing e values as high as $e = 1$ (*11*). Flynn, following Öpik (*12*), has pointed out that the resulting low geocentric velocities (v_g) of asteroidal dust particles lead to an increase in the effective capture cross section of Earth by a factor of $1 + v_e^2/v_g^2$ because of gravitational focusing (where v_e is the velocity needed to escape Earth). Flynn suggested that this effect would lead to a near-Earth enhancement of asteroidal over cometary dust. We developed a numerical model (*11*) that includes this gravitational focusing effect and also takes into account the varying spatial density (*13*) of dust particles from different sources. Even though estimates of the asteroidal and cometary contributions to the zodiacal cloud vary widely (*10, 14*), we found that probably more than 3/4 of the IDPs being accreted by Earth are asteroidal and that a large and perhaps dominant fraction of these IDPs comes from the Eos, Themis, and Koronis asteroid families (*11*).

Muller and MacDonald (*15*) suggested that a periodic variation in the accretion rate of IDPs might be driving Earth's 100,000-year climate cycle. They proposed that the accretion rate might be linked to the varying inclination of Earth's orbit with respect to the invariable plane of the solar system (*16*). Testing this hypothesis requires an understanding of the structure of the dust bands.

The orbits of the dust band progenitors—members of the Eos, Themis, and Koronis asteroid families—have been differentially precessed about a common plane of symmetry. Two distinct inclinations are used to describe the resulting structure, the proper and forced inclinations. Proper inclination (I_p) is the inclination of an orbit with respect to the common precession plane, and all members of a particular family share the same I_p. Forced inclination (I_f) is the inclination of the common precession plane with respect to a designated reference plane, usually the ecliptic (the plane of Earth's orbit). In the asteroid belt near 3 astronomical units (AU), where the dust bands originate, the common precession plane is essentially Jupiter's orbital plane (*6*). The structure of each asteroid family (I_p and the initial I_f) is inherited by their associated dust bands as dust particles are produced (by gradual comminution of family members) and their orbits decay toward the sun. A cross section of an ideal dust band would therefore resemble a thin wedge of material with an angular width of $2I_p$ and a midplane inclined to the ecliptic by I_f (Fig. 1). In a real dust band, however, time-dependent gravitational perturbations from the planets cause a variation in I_f as the dust particles decay toward the sun, essentially warping the dust band midplane. Furthermore, because da/dt (Eq. 1) is dependent on the physical properties of a dust particle, dust bands composed of different-sized dust particles will exhibit different warping. Dermott *et al.* (*17*) have shown that currently the I_f of the Earth-crossing portion of dust bands composed of 4-, 9-, 14-, and 25-μm-diameter dust particles ranges from about 2° (4 μm) to 5° (25 μm).

We reconstructed the orientation of the Earth-crossing portion of the dust bands back to 1.2 million years ago. Using the planetary orbital element data of Quinn *et al.* (*18*) and the RADAU fifteenth-order integrator program of Everhart (*19*), we

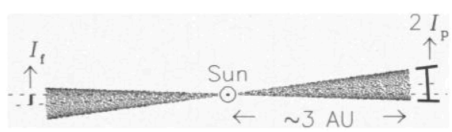

Fig. 1. Cross section of an ideal dust band. The midplane of the dust band is inclined to the ecliptic by I_f. Earth orbits the sun completely embedded within the dust bands. The spatial density of dust particles is enhanced near the extremes in latitude, which results in the near-ecliptic circumsolar "bands" of emission that were observed by IRAS and gave the structures their name.

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simulated the orbital evolution of the dust particles by performing direct numerical integration on the full equations of motion. Our simulations included gravitational interactions with seven planets (Mercury and Pluto were excluded), radiation pressure, Poynting-Robertson light drag, and solar wind drag. We released a wave of 10-μm-diameter dust particles (*20*) from the Eos asteroid family every 20,000 years and allowed their orbits to decay into the inner solar system. At the time when each wave of dust particles became Earth crossing (about 50,000 years after release), we determined the inclination of Earth's orbit ($I_\oplus$) with respect to the midplane of the dust bands (Fig. 2B). The orbits of these Earth-crossing dust particles show no particular affinity for their initial orientation (Fig. 2A). The 100,000-year periodicity present in the initial $I_\oplus$ (Fig. 2A) is absent from the final Earth-crossing $I_\oplus$ (Fig. 2B).

At each 20,000-year time step of the Earth-crossing $I_\oplus$ (Fig. 2B), we used a Monte Carlo approach to determine the capture rate of dust particles from the Eos, Themis, and Koronis dust bands. This was done by analytically decaying a torus of dust particle orbits past Earth's orbit, beginning with the perihelion of the orbits at Earth's aphelion, $a_1(1 - e) = a_\oplus(1 + e_\oplus)$, and concluding with the aphelion of the orbits at Earth's perihelion, $a_2(1 + e) = a_\oplus(1 - e_\oplus)$. For each of 30 steps in a over the range $\Delta a = (a_1 - a_2)$, we revolved Earth once around its orbit at 1° increments in longitude. At each of the 360 discrete longitudes of Earth, we generated a random distribution of 900 dust particle orbits using Earth-crossing e values and I_p values from our earlier work (*11*) [$e = 0.05 \pm 0.05$ (1σ), Eos $I_p = 10.2° \pm 0.6$, and Themis and Koronis $I_p = 2.5° \pm 1.0$]. The capture rates of dust particles for one complete revolution of Earth around its orbit were then calculated, a of the torus was decremented, and the procedure was repeated. The average capture rate $\bar{p}$ of the resulting 9,720,000 orbits at each 20,000-year time step was normalized to the maximum value over the 1.2-million-year period we studied (Fig. 2, D and E) (Eos $\bar{p}_{max}$ = 181 per 10^9 years and Themis and Koronis $\bar{p}_{max}$ = 1340 per 10^9 years).

At the points where $I_\oplus$ rises above the mean Earth-crossing I_p of the Themis and Koronis dust bands (Fig. 2B), Earth is actually outside most of the dust band material for some period of time each year. During these years, the capture rate of Themis and Koronis material falls (Fig. 2D). The higher I_p of the Eos dust band ensures that Earth is always within that dust band, and so the capture rate of Eos dust particles does not show a correlation with $I_\oplus$ (Fig. 2E). The capture rates of dust particles from all three dust bands are anticorrelated with Earth's varying orbital eccentricity ($e_\oplus$, Fig. 2C). The transition from an inclination- to eccentricity-driven accretion rate is complete for $I_p \geq 4°$ (*11*). Because the mean I_p for the asteroid belt (about equal to the mean I_p for the Eos family) is well above 4°, we expect variations in the accretion rate of most asteroidal dust particles to also be anticorrelated with $e_\oplus$. It follows that variations in the accretion rate of most asteroidal dust particles will be independent of the size of the particles.

Farley and Patterson (*21*) measured the concentration of extraterrestrial ^{3}He in a deep-sea sediment core dating from 250,000 to 450,000 years ago. They found that the flux of IDPs to the sea floor has varied in the past by a factor of 2 to 3 with a period near 100,000 years. They interpret these variations as indicative of a variable dust accretion rate on a global scale. Modeling of atmospheric entry heating of IDPs has shown that dust particles in the limited size range of 7- to 20-μm diameter will be responsible for transporting most of the ^{3}He to the sea floor (*22*). To cover this size range, we also modeled the capture rate of 20-μm-diameter dust particles (*20*) over the shorter time span of 250,000 to 450,000 years ago. For the 10-and 20-μm-diameter dust particles, the Themis and Koronis capture rate (Fig. 3C) is controlled by $I_\oplus$ and $e_\oplus$. The capture rate of Eos dust particles (Fig. 3D) is controlled by $e_\oplus$ and is therefore independent of the size of the dust

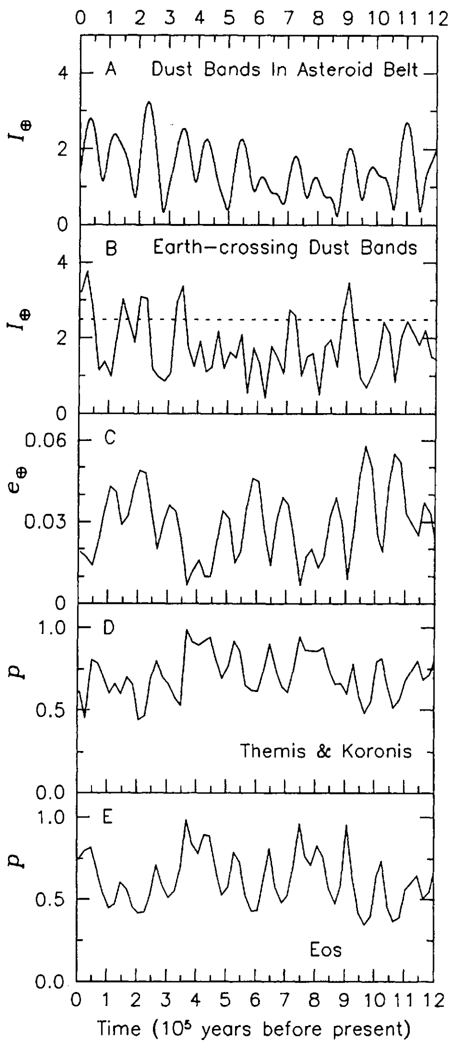

Fig. 2. (**A**) Inclination of Earth's orbit ($I_\oplus$) with respect to the midplane of the dust bands in the asteroid belt. (**B**) $I_\oplus$ with respect to the midplane of the Earth-crossing dust bands. The dashed line marks the mean Earth-crossing I_p of the Themis and Koronis dust bands, which are indistinguishable at 1 AU. (**C**) Earth's orbital eccentricity ($e_\oplus$). Normalized average capture rates ($p = \bar{p}/\bar{p}_{max}$) for 10-μm-diameter dust particles (*20*) from the Themis and Koronis families (**D**) and the Eos family (**E**).

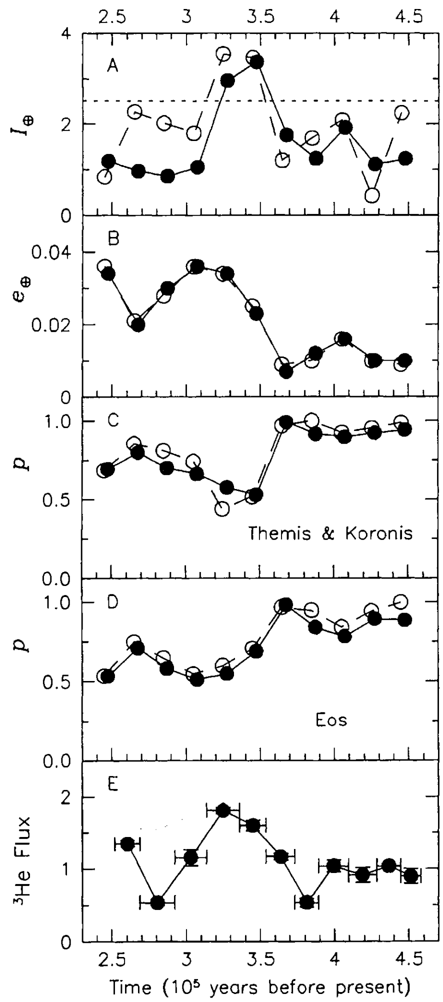

Fig. 3. (**A** to **D**) Same as Fig. 2, B, C, D, and E, respectively, except for a shorter time span. Solid and open circles are for 10- and 20-μm-diameter dust particles (*20*), respectively. (**E**) Extraterrestrial ^{3}He flux (10^{-12} cm^3 at standard temperature and pressure per square centimeter per 1000 years) as published by Farley and Patterson (*21*).

particles. The variation in the capture rate of Eos dust particles has an amplitude and period comparable with that of the ^{3}He flux data (Fig. 3E), but the two curves are about 50,000 years out of phase. Marcantonio *et al.* (*23*) measured the concentrations of extraterrestrial ^{3}He and terrestrial ^{230}Th in deep-sea sediments dating back to 250,000 years ago. They found the variations in the extraterrestrial ^{3}He abundances to be correlated with variations in the terrestrial ^{230}Th abundances. They also found these variations to be related to Earth's climate record and suggested that the cause of the variations was climate-driven changes in deep ocean currents, which may redistribute and concentrate sediments. Such redistributions may explain why our predictions do not match the ^{3}He flux data. Alternatively, Dermott *et al.* (*24*) suggested that accretion from Earth's resonant ring of asteroidal dust (*25*) might be substantial and variable, but the importance of this mechanism has not yet been determined.

Farley (*26*) and Schmitz *et al.* (*27*) have found evidence for variations in the accretion rate over 10^7- to 10^8-year time scales that they suggest may be due to the breakup of asteroids. Recent work (*28*) suggests that asteroids down to a few hundred meters across may be "rubble piles"—conglomerations of collisional debris held together only by self-gravity. If all the dust particles in the zodiacal cloud were deposited on the surface of an asteroid with radius R = 100 km, then the depth of the resulting regolith would be given by $D = rA/3\pi R^2$, where r is the radius of the dust particles and A is the total cross-sectional area of dust in the zodiacal cloud [$A \sim 10^{10}$ km^2 (*29*)]. If r ranges from 1 to 100 μm, then D ranges from 0.1 to 10 m. Therefore, the occasional catastrophic disruption of 10- to 100-km radius rubble pile asteroids, which are essentially regolith throughout, would instantaneously liberate a mass of dust several orders of magnitude higher than that associated with the current zodiacal cloud. Within $\sim 10^4$ years of one of these breakups, the initial population of ~10-μm-sized dust particles would reach 1 AU, with larger dust particles and subsequent generation smaller ones arriving over 10^5 to 10^6 years. During these times, Earth would be accreting micrometer-sized dust particles directly into its stratosphere at a rate perhaps in excess of $\sim 10^{10}$ kg year^{-1}, an annual amount comparable to the stratospheric loading of dust and aerosols due to explosive volcanic eruptions (*30*). Continuous accretion of such large amounts of dust may lead to substantial changes in Earth's climate lasting for many millions of years. The initial asteroid disruption might inject large kilometer-sized fragments into regions of resonance in the asteroid belt, where they are perturbed into Earth-crossing orbits in a mean time of $\sim 10^6$ years (*31*), longer than the time required for the initial wave of dust particles to reach the vicinity of Earth. During these periods of enhanced dust accretion, Earth would be at a greater risk of impact from an increased number density of Earth-crossing asteroids. The consequences of such a scenario may be gradual mass extinctions lasting on the order of 10^6 years, some of which (although possibly not all) might be followed by or punctuated with single or multiple asteroid impacts (*32*).

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36. We thank G. Wetherill, A. Boss, and two anonymous reviewers for their comments.

1 December 1997; accepted 16 March 1998