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ATMOSPHERIC ENTRY SURVIVAL OF LARGE MICROMETEORITES: IMPLICATIONS FOR THEIR SOURCES AND FOR THE COMETARY CONTRIBUTION TO THE ZODIACAL CLOUD

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ABSTRACT

Atmospheric entry heating simulations indicate that a large fraction of the micrometeorites larger than 100 μm in diameter which survive atmospheric entry must have entered the Earth's atmosphere with velocities very near the Earth escape velocity. Thus, these particles must have been captured by Earth from heliocentric orbits with small eccentricities and low inclinations, indicating a main-belt asteroidal source. Space exposure ages measured on these large micrometeorites are also consistent with a main-belt asteroidal source. However, dynamical calculations have previously indicated that particles larger than 100 μm in diameter were likely to be destroyed by catastrophic collisions in the time required for orbital evolution from the main-belt to Earth capture by Poynting-Robertson drag. The absence of a large amount of collisional debris in the <50 μm size range indicates these large micrometeorites are not the few, rare survivors of a mostly collisionally disrupted population. The measured space exposure ages, which are about an order of magnitude larger than their calculated catastrophic collision lifetimes, confirm the survival of these large micrometeorites for times much longer than the calculated catastrophic collision lifetimes. Since collisions with cometary dust <20 μm in size were expected to be the major contributor to the collisional destruction of these larger particles the contribution of cometary material to the zodiacal cloud is likely to be much smaller than previously believed.

INTRODUCTION

The atmospheric entry survival of micrometeorites smaller than about 50 μm in diameter ($\sim 10^{-7}$ grams) was suggested by Opik (1937), and confirmed experimentally by the recovery of unmelted micrometeorites from the Earth's stratosphere by balloons and aircraft during the 1970's (Brownlee, 1985). Most micrometeorites larger than ~100 μm in diameter were expected to be vaporized on atmospheric entry (Whipple, 1950; Fraundorf, 1980), and the radar detection of meteor trails from objects as small as 10^{-6} grams (Hughes, 1978) provides experimental confirmation of this predication. The recovery of large quantities of micrometeoritic material from 100 μm to larger than 1000 μm in diameter, both melted and apparently unmelted, from the ocean floor (Brownlee, 1985), lakes in Greenland (Maurette et al., 1988), and the Antarctic ice (Maurette et al., 1991) has resulted in a reexamination of the atmospheric entry heating of large micrometeorites.

PROPERTIES OF LARGE MICROMETEORITES

The extraterrestrial origin of the large (>100 μm in diameter) micrometeorites is established by the presence of spallogenic Ne (Olinger et al., 1990), and the cosmogenic radionuclei ^{10}Be and ^{26}Al (Raisbeck and Yiou, 1987; Raisbeck and Yiou, 1989; Nishiizumi et al., 1991) in both large spherules, assumed to have been melted on atmospheric entry, and large, irregularly shaped particles which appear to be unmelted.

The irregularly shaped, apparently unmelted, particles should best preserve information on the original composition of the large micrometeorites. These particles have major element abundances generally consistent with the CI and/or CM chondritic meteorites, though Ni and S are both significantly depleted from their chondritic values (Maurette et al., 1991). Three of four irregulary shaped micrometeorites from Greenland also have minor/trace element abundances, including the volatile elements Cu, Zn, Ga, and Ge, consistent with the range of chondritic meteorites (Flynn et al., 1991). Sutton et al. (1988) suggest that the compositions of 3 of 9 melted spheres they analyzed were more consistent with ordinary chondrite rather than carbonaceous chondrite material. The major minerals are generally olivine and pyroxene, consistent with the chondritic meteorites (Maurette et al., 1991).

ATMOSPHERIC ENTRY HEATING

The heating experienced by micrometeorites on atmospheric entry can be calculated using the model developed by Whipple (1950). Computer simulations of the Whipple entry heating model, which calculate the temperature profile during atmospheric deceleration for micrometeorites with a range of initial velocities, densities, diameters, and impact parameters, have been developed (Flynn, 1989b; Love and Brownlee, 1991). Entry heating simulations for large micrometeorites indicate that particles larger than 100 μm in diameter must have geocentric velocities <5 km/sec for any significant fraction of them to survive entry (Flynn 1990; Love and Brownlee, 1991). The results for particles 60 μm and 200 μm in diameter are shown in Figure 1 for particles having geocentric velocities, prior to Earth gravitational infall acceleration, of 1, 5, 10, and 20 km/sec. Taking 1600K as the melting temperature, Figure 1 shows that a large fraction of incident 60 μm diameter particles with velocities up to 10 km/sec survive entry unmelted. However, for 200 μm diameter particles only those with large impact parameters survive entry even with a 5 km/sec geocentric velocity.

IMPLICATIONS FOR SOURCES

Geocentric velocities less than 5 km/sec are characteristic of particles arriving at Earth in heliocentric orbits of low eccentricity and inclination. Flynn (1989a) has shown that for small particles evolving under the influence of solar gravity and Poynting-Robertson drag, such low geocentric velocities are possible for particles derived from main-belt asteroidal parent bodies, but are inconsistent with the geocentric velocities calculated for even the most favorable presently active comet (Comet Kopff). Comet Schwassmann-Wachmann 1, which is in a nearly circular orbit of low eccentricity, would contribute dust with orbital parameters similar to the main-belt asteroids,

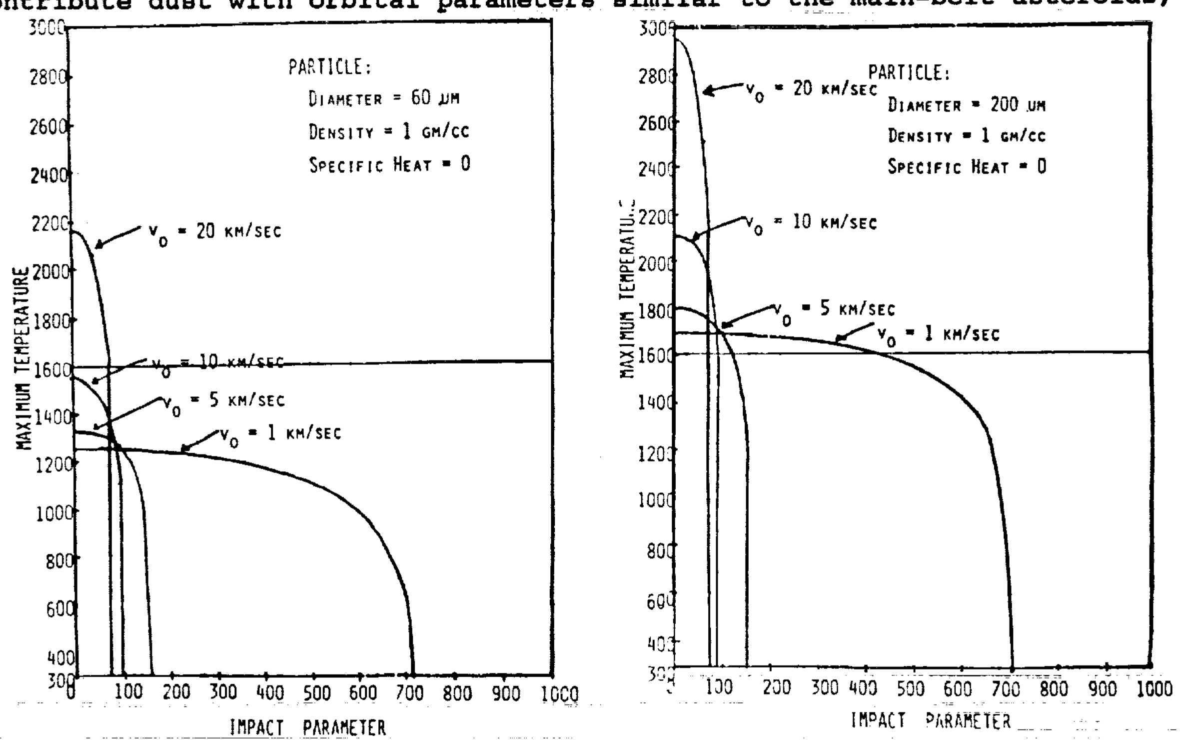

Figure 1: Maximum temperature (K) reached on atmospheric entry versus impact parameter (x 10^5 meters) for particles of 60 μm diameter (left) and 200 μm diameter (right).

but Schwassmann-Wachmann 1 has a low dust emission rate (Jewitt, 1990). Orbital evolution simulations including the effect of planetary gravitational perturbations confirm that very few cometary particles arrive at Earth with geocentric velocities lower than 5 km/sec (Gustafson et al., 1987), while a large fraction of the main-belt asteroidal particles do arrive at Earth with such low velocities. Thus, most large ($\geq$ 200 μm) micrometeorites which survive Earth atmospheric entry unmelted are likely to be derived from main belt asteroidal parent bodies (Flynn 1990; Love and Brownlee, 1991).

The exposure ages inferred from radiogenic nuclei (Raisbeck and Yiou, 1989; Nishiizumi et al., 1991) and spallogenic ^{21}Ne (Olinger et al., 1990) are in the 10^5 to $2x10^7$ year range, consistent with the Poynting-Robertson orbital evolution times from the main-belt to Earth for particles in this size range. In addition, the radiogenic nuclei confirm that the large micrometeorites were irradiated in space in roughly the sizes we see them now, indicating they are not debris from much larger meteors which fragmented either just before or during Earth atmospheric entry (Raisbeck and Yiou, 1989; Nishiizumi et al., 1991). Nishiizumi et al. (1991) have further inferred that the exposure must have been in the inner solar system, eliminating particles in the highly elliptical orbits charactaristic of cometary material.

The chemical compositions of the large micrometeorites are consistent with an asteroidal source for this material (Maurette et al., 1988). The isotopic composition of carbon in melted micrometeorites from Greenland and Antarctia is also consistent with the macromolecular material in CI and CM carbonaceous meteorites, suggesting these are asteroidal particles (Yates et al., 1991). The evidence indicates most large micrometeorites, which survive atmospheric entry melted or unmelted, are from main-belt asteroidal parent bodies.

COLLISIONAL LIFETIMES OF MAIN-BELT ASTEROIDAL DUST

The contribution of main-belt asteroids to the flux of large ($\geq$200 μm) particles at Earth has previously been assumed to be very small (Flynn 1989a; Zook and McKay, 1986) because the calculated catastrophic collision lifetimes (~10^4 to 10^5 years for a 100 μm diameter particle) were substantially shorter than the times required for Poynting-Robertson orbital evolution from the main-belt to an Earth intersecting orbit (>10^6 years for a 100 μm diameter particle) as shown in Figure 2.

The longest catastrophic collision lifetime estimates for 100 μm to 10,000 μm diameter particles are an order-of-magnitude less than the Poynting-Robertson lifetimes (see Figure 2), indicating that most of the main-belt dust in this size range should be destroyed by collisions long before reaching Earth. Since more than ten collisional lifetimes would have elapsed during the orbital evolution, the particle flux would be reduced by at least a factor of 2^{10} = ~1000. The debris resulting from these collisions would then be collectable at Earth, since, for particles smaller than 100 μm in diameter the Poynting-Robertson lifetimes are smaller than the collisional lifetimes (Dohnanyi, 1978). This assumes the debris orbits do not differ dramatically from the orbit of the original particle, so the near-Earth gravitational

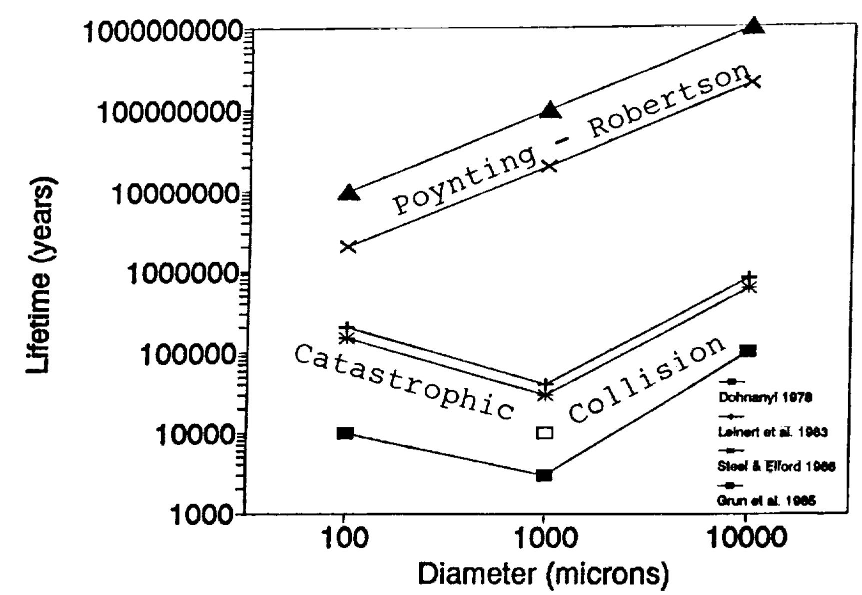

Figure 2: Poynting-Robertson and catastrophic collision lifetimes for particles from 100 μm to 10,000 μm in diameter.

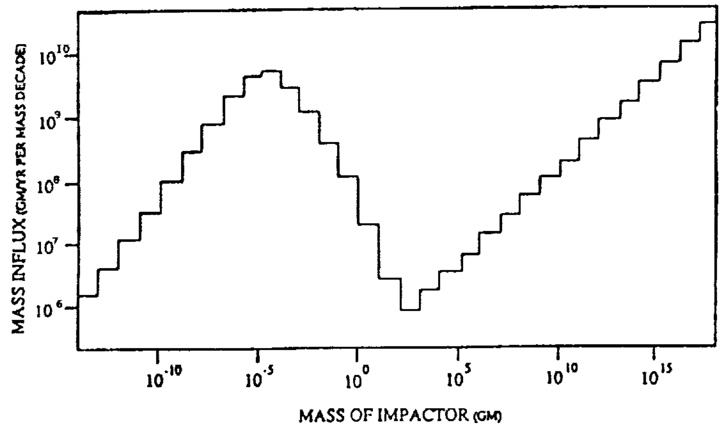

Figure 3: Meteoritic mass influx per mass decade at Earth (adapted from Kyte and Wasson, 1986).

enhancement factor is similar for both debris and survivors. The large momentum of the micrometeorite, which has about 1000 times the mass of the disrupting particle, should assure this condition is met. The required debris is not seen.

Particles in the 100 to 1000 μm size range are at the peak of the mass-frequency distribution (Hughes, 1978) as shown in Figure 3. Yiou et al. (1989) estimate the global input of cosmic spherules in polar ice cores to be ~1500 tons/year, while Maurette et al. (1991) infer an even higher accretion rate. This indicates that a minimum of 10% of the mass influx of 100 μm to 1000 μm particles survives entry while the remainder forms meteors. Since less than 1/1000 of the starting mass in the 100 to 10,000 μm diameter range would be expected to survive collisional processes and reach Earth, we would expect to find 1000 x 1,500 tons/year = 1.5 x 10^6 tons/year of debris in the form of particles <50 μm in size. The total mass accretion rate at Earth for particles <50 μm in diameter is only ~10^3 tons/year based on satellite flux measurements (Hughes, 1978), a factor of 1000 less than required by the calculated collision lifetimes.

The absence of large quantities of debris smaller than 50 μm in diameter confirms that the large micrometeorites are not the few, rare survivors of a starting population which was mostly disrupted by collisions.

The space exposure ages measured by radiogenic nuclei and spallogenic ^{21}Ne confirm that particles 100 μm and larger have space residence times longer than 10^6 years. Raisbeck and Yiou (1989) have noted the measured space exposure ages substantially exceed the catastrophic collision lifetimes calculated by Dohnanyi (1978). Although more recent modeling has increased the calculated catastrophic collision lifetimes, as shown in Figure 3, these new values still fall an order-of-magnitude or more short of the Poynting-Robertson evolution times and the measured space exposure durations. Thus, the calculated catastrophic collision lifetimes for 100 μm to 1000 μm particles are likely to underestimate the true lifetimes by an order-of magnitude or more.

THE COMETARY CONTRIBUTION TO THE ZODIACAL CLOUD

Dohnanyi's (1978) calculations show that the catastrophic collision lifetimes of these large particles are dominated by collisions with smaller (<20 μm) cometary particles. For a 100 μm particle orbiting in the main-belt Dohnanyi (1978) calculates the collisional lifetime with small cometary particles to be ~10^5 years while the collisional lifetime with other main-belt asteroidal particles is ~10^9 years. This results, in part, from the fact that the collisional velocities between asteroidal particles and cometary particles are much larger than between two asteroidal particles, so smaller, more abundant, cometary particles are capable of causing a catastrophic collision.

Since the cometary flux assumed by Dohnanyi (1978) was that needed for steady state resupply of the zodiacal cloud by cometary material, the observed space exposure times for large micrometeorites require the recent (~10^6 years) flux of cometary material is insufficient to resupply the zodiacal cloud. Raisbeck and Yiou (1989) have suggested the interplanetary dust complex may not be in secular equilibrium. Alternatively, the resupply of the zodiacal cloud may come from a non-cometary source. The discovery of dust bands in the main-belt (Low et al., 1984), presumably from asteroid-asteroid collisions, suggests an asteroidal source for at least some of the zodiacal cloud material. Direct examination of the 5 to 30 μm size dust collected from the

Earth's stratrosphere suggests a substantial fraction of this dust is dervied from main-belt asteroidal parent bodies. Space exposure ages inferred from solar flare track densities (Sandford, 1986) and the distribution of peak temperatures reached on atmospheric entry, inferred from the presence of volatile elements, low-temperature minerals, and unannealed solar flare tracks (Flynn, 1989a; Sandford and Bradley, 1990) all suggest a large fraction of the cosmic dust recovered from the Earth's stratosphere is from main-belt asteroidal sources. Mineralogical evidence, in particular aqueous alteration, also suggests that the flux of asteroidal particles exceeds that of cometary particles for the cosmic dust recovered from the Earth's stratosphere (Schramm et al., 1989).

The survival of large micrometeorites in the inner solar system for 10^6 to 10^7 years indicates that the recent (~10^6 to 10^7 year) cometary contribution to the smaller interplanetary dust particles is insufficient for steady-state resupply of the zodiacal cloud. If the zodiacal cloud is presently in equilibrium then main-belt asteroidal material is likely to be the major contributor to the zodiacal dust.

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