THE DELIVERY OF ORGANIC MATTER FROM ASTEROIDS AND COMETS TO THE EARLY SURFACE OF MARS

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Abstract. Carbon delivered to the Earth by interplanetary dust particles may have been an important source of pre-biotic organic matter (Anders, 1989). Interplanetary dust is shown to deliver an order-of-magnitude higher surface concentration of carbon onto Mars than onto Earth, suggesting interplanetary dust may be an important source of carbon on Mars as well.

1. Introduction

Material from comets and carbonaceous asteroids has been suggested as a major contributor of organic matter to the primitive Earth (Anders and Owen, 1977; Anders, 1989; Chyba, 1987 and Chyba *et al.*, 1990). Chamberlin and Chamberlin (1908) proposed the organic component in planetesimals might have been an important source of pre-biotic organic matter for the early Earth. Oró (1961) suggested a similar role for organic matter from comets. Anders (1989) studied the accretion of objects ranging from dust to large bodies onto the Earth and concluded the major organic contribution is from interplanetary dust small enough to survive atmospheric entry without reaching high temperatures.

2. Accretion rates

Mars has a lower surface gravity than Earth, giving rise to a lower atmospheric entry velocity distribution for interplanetary dust particles at Mars than at Earth. This lower mean entry velocity allows larger particles to decelerate in the atmosphere of Mars without experiencing severe heating. Flynn and McKay (1990) calculate that the fraction of 100 μm diameter particles which survive atmospheric entry at Earth is the same as for 700 μm diameter particles at Mars. This difference is particularly important for the accretion of unmelted meteoritic material onto Mars because the size distribution of interplanetary dust particles is sharply peaked (as shown in Figure 1), with 80% of the continuous, long-term meteoritic mass accreted by the Earth being between 10^{-7} and 10^{-3} grams ($\sim$ 60 to 2700 μm in diameter). Although most particles $>$ 100 μm in diameter melt or vaporize during Earth atmospheric entry, many of these large particles survive atmospheric entry at Mars without melting.

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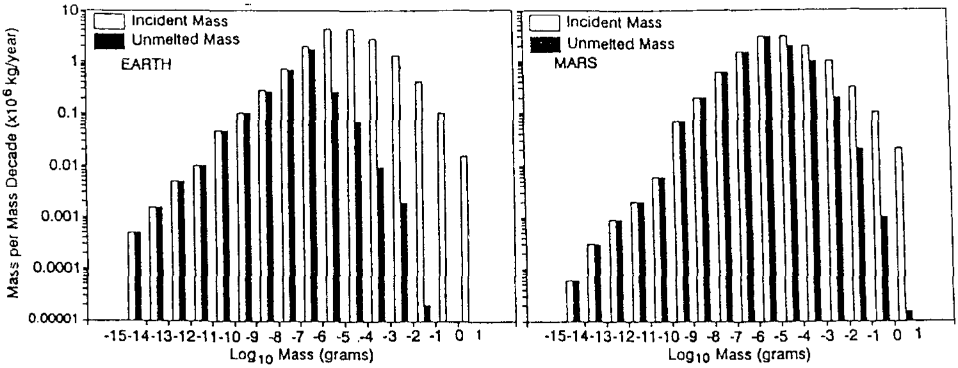

Fig. 1. The micrometeorite flux measured at Earth (Hughes, 1978) (left) and calculated at Mars (right) in each mass decade are shown along with the mass surviving atmospheric entry without melting or vaporizing.

The present flux of interplanetary dust in each mass decade from 10^1 grams to 10^{-15} grams at Mars, shown in Table I, has been modeled by Flynn and McKay (1990) and Flynn (1991) from satellite, radar and visual meteor measurements of the present flux at Earth (Hughes, 1978) and estimates of the Mars/Earth flux ratio. Flynn and McKay (1990) also calculated the expected velocity distribution of interplanetary dust at Mars using the measured velocity distribution for radar meteors at Earth (Southworth and Sekanina, 1973) and a velocity transformation to Mars, using a method developed by Morgan *et al.* (1988). Using the atmospheric entry heating model developed by Whipple (1950) and extended by Fraundorf (1980), the distribution of temperatures reached by particles in each mass decade during Mars atmospheric entry was calculated. Table I gives the surviving mass fraction, the fraction not heated above 1600K (the melting temperature of the dominant silicate phases in meteorites). The mass of meteoritic material which survives Mars atmospheric entry without melting is estimated to be $8.6 \cdot 10^6$ kg/year (see Table I). Particles in the 100 to 700 μm diameter range, which make only a small contribution to the unmelted meteoritic mass accreted by the Earth because most vaporize on atmospheric entry (see Figure 1), constitute 60% of the long term, continuous meteoritic mass accreted by Mars (see Table I).

The accretion rate for unmelted meteoritic material at Mars is almost three times the $3.2 \cdot 10^6$ kg/year of meteoritic material which Anders (1989) calculates is contributed to the Earth by micrometeorites which survive Earth atmospheric entry without vaporizing. However, since Mars is a smaller planet, the surface density of unmelted meteoritic material on Mars is 12 times that on Earth. Thus the accretion of organic matter in interplanetary dust is potentially much more important on Mars than on Earth.

3. Unaltered organics

Anders (1989) points out some organic matter contributed to Earth by interplanetary dust may be destroyed or altered by exposure to solar ultraviolet radiation or by the temperatures reached on atmospheric entry. Both of these effects are likely to be smaller for Mars than Earth. Ultraviolet radiation has a shallow penetration depth into these black particles. Since larger interplanetary dust particles survive Mars entry than survive Earth entry without melting, the fraction of organic matter located close enough to the surface of a particle to be altered by solar ultraviolet radiation will be smaller in the case of material accreting onto Mars. In addition, since interplanetary dust particles of the same size and space velocity are heated less on Mars entry than on Earth entry, a larger fraction of the organic matter survives Mars entry without thermal alteration.

The amount of organic matter not altered by entry heating can be estimated by considering the fraction of meteoritic material accreted onto Mars without reaching the pyrolysis temperature of the organic matter it contains. Anders (1989) estimates the average pyrolysis temperature of carbonaceous material from meteorites is $\sim$ 600°C, and Chyba *et al.* (1990) calculate that most of the organic material in carbonaceous chondrite meteorites can survive temperatures up to 850K for $\sim$ 1 second. A typical interplanetary dust particle spends only a few seconds within 100K of its peak temperature on atmospheric entry (Flynn 1989). Calculating the fraction of particles not heated above 900K on atmospheric entry, a total of $2.4 \cdot 10^6$ kg/year of meteoritic material, mostly in particles from 60 to 270 μm in diameter, accretes onto Mars with its organic matter intact (see Table I). This is likely to be a lower limit on the number of particles which carry unaltered organic carbon to the surface of Mars since the Whipple (1950) entry heating model only determines the surface temperature of the particle. Particles with surface temperatures over 900K may have lower interior temperatures because of endothermic phase transitions, e.g. alteration of carbonaceous material or dehydration of layer-silicates near the surface (Flynn, 1995), and the organic component may be destroyed in only an outer layer. Textural zoning (Sutton *et al.*, 1992), attributable to temperature gradients, observed in 50 to 100 μm diameter micrometeorites recovered from terrestrial polar ices suggests a mechanism exists to allow the interior to remain cool.

The average carbon content of interplanetary dust particles (5 to 30 μm in diameter) collected from the stratosphere of the Earth has been measured as 10 to 12% (Thomas *et al.*, 1993, and Schramm *et al.*, 1989), which is

TABLE I
Meteoritic Contribution to Carbon on Mars

Mass Range (grams)	Size Range (μm)	Mass Flux (kg/year)	Unmelted Fraction T<1600K	Unmelted Mass (kg/year)	Fraction T<900K	Unaltered Carbon (kg/year)
$10^{1} - 10^{0}$	12400–26800	$0.02 \cdot 10^{6}$	0	0	0	0
$10^{0} - 10^{-1}$	5760–12400	$0.1 \cdot 10^{6}$	0.01	$0.01 \cdot 10^{5}$	0	0
$10^{-1} - 10^{-2}$	2680–5760	$0.3 \cdot 10^{6}$	0.05	$0.2 \cdot 10^{5}$	0	0
$10^{-2} - 10^{-3}$	1240–2680	$1 \cdot 10^{6}$	0.2	$2 \cdot 10^{5}$	0	0
$10^{-3} - 10^{-4}$	580–1240	$2 \cdot 10^{6}$	0.5	$10 \cdot 10^{5}$	0.01	$0.2 \cdot 10^{5}$
$10^{-4} - 10^{-5}$	270–580	$3 \cdot 10^{6}$	0.7	$20 \cdot 10^{5}$	0.07	$2.1 \cdot 10^{5}$
$10^{-5} - 10^{-6}$	120–270	$3 \cdot 10^{6}$	0.9	$30 \cdot 10^{5}$	0.24	$7.2 \cdot 10^{5}$
$10^{-6} - 10^{-7}$	60–120	$1.5 \cdot 10^{6}$	0.98	$15 \cdot 10^{5}$	0.46	$6.9 \cdot 10^{5}$
$10^{-7} - 10^{-8}$	27–60	$0.6 \cdot 10^{6}$	1	$6 \cdot 10^{5}$	0.75	$4.5 \cdot 10^{5}$
$10^{-8} - 10^{-9}$	12–27	$0.2 \cdot 10^{6}$	1	$2 \cdot 10^{5}$	0.88	$1.8 \cdot 10^{5}$
$10^{-9} - 10^{-10}$	6–12	$0.07 \cdot 10^{6}$	1	$0.7 \cdot 10^{5}$	0.95	$0.7 \cdot 10^{5}$
$10^{-10} - 10^{-11}$	3–6	$0.006 \cdot 10^{6}$	1	$0.06 \cdot 10^{5}$	1	$0.06 \cdot 10^{5}$
$10^{-11} - 10^{-12}$	1–3	$0.002 \cdot 10^{6}$	1	$0.02 \cdot 10^{5}$	1	$0.02 \cdot 10^{5}$
$10^{-12} - 10^{-13}$	0.6–1	$0.0009 \cdot 10^{6}$	1	$0.009 \cdot 10^{5}$	1	$0.009 \cdot 10^{5}$
$10^{-13} - 10^{-14}$	0.3–0.6	$0.0003 \cdot 10^{6}$	1	$0.003 \cdot 10^{5}$	1	$0.003 \cdot 10^{5}$
$10^{-14} - 10^{-15}$	0.1–0.3	$0.00006 \cdot 10^{6}$	1	$0.0006 \cdot 10^{5}$	1	$0.0006 \cdot 10^{5}$
TOTALS		$12 \cdot 10^{6}$		$8.6 \cdot 10^{6}$		$2.4 \cdot 10^{6}$

about 2.5 to 3 times the carbon content of the most carbon rich meteorites, the CI carbonaceous chondrites. A carbon content of 45% was reported for one interplanetary dust particle (Thomas *et al.*, 1993). The small masses of interplanetary dust particles ($\sim 10^{-8}$ grams) have, thus far, precluded quantitative determination of the fraction of this carbon that is present in organic molecules. However Clemett *et al.* (1993) detected polycyclic aromatic hydrocarbons in interplanetary dust particles, confirming the presence of an organic component. Radicati di Brozolo *et al.* (1986) detected carbon clusters (C_2-C_{15}) and protonated species, and Rietmeijer (1990) has identified turbostatic carbon which he suggests may have been formed by dehydrogenation of organic compounds originally present in the interplanetary dust. Gibson (1992) reviewed the identifications of carbon compounds in interplanetary dust particles.

The carbon content of the larger micrometeorites (> 50 μm in diameter) is not well established since most of these particles melt or vaporize on Earth atmospheric entry. However, Yates *et al.* (1991) have extracted carbon from melted meteoritic spherules recovered from the terrestrial polar ices. The carbon isotopic composition is consistent with that of the macromolecular organic material from carbonaceous chondrite meteorites (Yates *et al.*, 1991). Carbon abundances from 200 ppm to 5000 ppm were measured in the spherules (Yates *et al.*, 1991). However, much of the pre-atmospheric carbon may have been lost when these particles melted on atmospheric entry.

Assuming, following Anders (1989), that the average carbon content of interplanetary dust is 10%, then the present accretion rate of unaltered meteoritic carbon onto Mars is $2.4 \cdot 10^5$ kg/year. If this accretion rate were constant over the age of the Solar System, meteoritic material would have contributed a total of $1 \cdot 10^{15}$ kg of carbon to the surface of Mars, an amount comparable to estimates of the current terrestrial biomass ($6 \cdot 10^{14}$ kg; Chyba *et al.*, 1990).

The total accretion of meteoritic carbon onto the surface of Mars must be even higher, since the meteoritic flux was as much as 10^3 times the present flux during the first half-billion years of the Solar System (Anders, 1989). The accretion of meteoritic matter onto the Moon is fit by a two component model: a rapidly decaying component ($t_{1/2}$ = 40 million years) exceeding the present flux by an order-of-magnitude or more 4.0 billion years ago, and a relatively constant flux near the present value over the past 3.6 billion years (Wasson *et al.*, 1975). Thus, during its early history, the accretion of meteoritic material onto Mars is likely to have substantially exceeded the value calculated using current flux estimates.

4. Martian biogenesis

The failure of the Viking gas chromatograph experiments to detect organic carbon (Biemann *et al.*, 1977) at the two landing sites sampled on Mars places an upper limit on the surviving organic component in the present surface soils. However, Banin (1988) has suggested that the high redox potential on the present surface of Mars may cause the decomposition of organic matter contributed by meteoritic infall. In addition, Stoker *et al.* (1989) have shown in laboratory simulations that organic matter would decompose due to solar ultraviolet radiation on the present surface of Mars more rapidly than the calculated current accretion rate.

The conditions on the surface of Mars early in its history are likely, however, to have been considerably different from the current conditions. McKay and Stoker (1989) suggest that about 3.5 billion years ago conditions on the surface of Mars may have been suitable for the origin of life. This is just at the end of the era when the accretion of organic material from interplanetary dust particles is expected to have been at its highest. During this period the atmospheric density on Mars may have been much higher than at present, and the atmospheric composition may have differed considerably from the present composition. These factors are likely to have allowed the survival of organic matter for considerably longer during that earlier era. In addition, Anders (1989) suggests, for the terrestrial case, that moderate ultraviolet exposure could make the organic material more rather than less interesting. The presence of liquid water on the surface of Mars (Carr, 1979) during this era, coupled with the continuous, planet-wide infall of organic matter from the interplanetary dust may have provided conditions appropriate for the development of life on Mars. Boston *et al.* (1992) have suggested that if microorganisms developed in antiquity on the surface of Mars, they might later have migrated to deeper levels where they would be protected from the present harsh surface conditions.

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