AN ASSESSMENT OF THE MICROMETEORITIC COMPONENT
IN THE MARTIAN SOIL

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ABSTRACT

Particles in the mass range from 10^{-7} to 10^{-3} grams contribute 80% of the total mass influx of meteoritic material in the 10^{-13} to 10^{6} gram mass range at Earth (Hughes, 1978). On Earth atmospheric entry all but the smallest particles in the 10^{-7} to 10^{-3} gram mass range, about 60 to 1200 micrometers in diameter, are heated sufficiently to melt of vaporize. Mars, because of its lower escape velocity and larger atmospheric scale height, is a much more favorable site for unmelted survival of micrometeorites on atmospheric deceleration. We calculate that a significant fraction of particles throughout the 60 to 1200 micrometer diameter range will survive atmospheric entry unmelted. Thus returned Mars soils may offer a resource for sampling micrometeorites in a size range uncollectable in unaltered form at Earth.

The addition of meteoritic material to the Mars soils should perturb their chemical composition, as has been detected on for soils on the Moon (Anders, et al., 1973). Using the measured mass influx at Earth and estimates of the Mars/Earth flux ratio, we estimate a mass influx at Mars of between 2,700 and 202,000 metric tons per year. If distributed uniformly into a soil with a mean planetary production rate of 1 meter per billion years, consistent with radar estimates of the soil depth overlaying a bouldered terrain in the Tharsis region (Christensen, 1986), we estimate a meteoritic concentration in the soil ranging from 2 to 58%. This range is consistent with chemical inferences that Mars soil at the Viking sites is fit by a mixture of 60% indiginous rock fragments and 40% meteoritic material (Clark and Baird, 1979).

INTRODUCTION

A number of sources for dust on Mars have been proposed including: chemical and physical weathering of indiginous surface rocks, debris from impact cratering, volcanism, tectonism (Greely, 1986), and weathering of shock-activated meteoritic projectiles from the period of heavy bombardment (Boslough, 1988). However, the contribution from micrometeorites, particles sufficiently small to be slowed without melting on atmospheric deceleration, has only recently been considered (Flynn and McKay, 1988). Particles in the size range which would be expected to survive atmospheric entry on Mars without melting constitute a major fraction of the meteoritic material presently accreting onto the Earth. On Earth, the rate of production of new soil is sufficiently high that unmelted particles are difficult to extract from the soils, however the meteoritic component can be detected by enrichment in Ir (Kyte and Wasson, 1986), and the particles themselves can be recovered from the stratosphere (Brownlee, 1985) and polar ices (Zolensky, et al., 1988), where the terrestrial soil contamination is reduced. Partially melted particles can also be extracted from sea sediments by magnetic concentration (Brownlee, 1985). Although particles in this size range are destroyed on Lunar impact, the Lunar mare soils contain between 1 and 2 percent meteoritic material, inferred from chemical abundances of the volatile and siderophile elements which are abundant in primitive meteorites but rare in the mare rocks (Anders, et al., 1973).

Mars, because of its low surface gravity coupled with an atmosphere of sufficient density to decelerate incoming micrometeorites, is one of the most favorable sites in the solar system for the unaltered survival of micrometeorites on atmospheric entry. The magnitude of the micrometeorite component in the Martian soils will depend on the accretion rate of meteoritic material onto the planet, as well as the rate at which soil is being produced by indiginous processes on Mars. To assess the importance of the micrometeorite component in the soil on Mars, we have:

1) assessed the micrometeorite flux at Mars,

2) estimated the micrometeorite velocity distribution at Mars, and evaluated the survival probability for micrometeorites entering the Martian atmosphere,

3) considerd the chemical perturbations to the indiginous soil produced by micrometeorite addition, and suggested measurements which a Mars Lander spacecraft could make to determine the fraction of meteoritic material in the soils, and,

4) assessd the possibilities for recovery of micrometeorites from the soils returned by a Mars Sample Return mission. and,

Four types of meteoric and/or meteoritic material should be found on Mars:

1) micrometeorites, many of which will survive atmospheric deceleration unmelted, which should fall relatively uniformly over the planet's surface,

2) ablation products from larger meteors and meteorites which ablate, break up and/or burn up in the Mars atmosphere,

3) debris from large, crater forming objects, which, by analogy to terrestrial and lunar impact events, will be concentrated in the crater ejecta blankets (except for rare, large events, such as the proposed C-T event on earth, which can distribute debris on a planetary scale), and

4) debris from the early, intense bombardment, which, in many areas of the planet, may now be incorporated into rocks by geologic processes subsequent to the intense bombardment era.

FLUX AT MARS

To estimate the extent of meteoritic addition to indigenous Martian soil, the meteoritic flux at Mars must be known. The meteoritic flux

measured at Earth provides a starting point to estimate the flux at Mars. For particles in the mass range from 10^{-13} grams to 10^6 grams, the size-frequency distribution at Earth has been estimated from satellite, radar meteor and visual meteor observations (Hughes, 1978). Fifty percent of the total mass influx is in the narrow mass range from 10^{-6} grams to 10^{-4} grams (Hughes, 1978), and eighty percent is in the range from 10^{-7} to 10^{-3} grams. The Earth mass influx per decade of mass is shown in Table I. If the size-frequency distribution of meteoritic material at Mars is similar to that at Earth, only 0.53 au away, then an assessment of the Mars flux for material in the 10^{-7} gram to 10^{-3} gram mass range will provide a good estimate of the overall influx of meteoritic material on Mars.

On entering the Earth's atmosphere, most particles in the 10^{-7} gram to 10^{-3} gram mass range are volatilized, producing ionized trails detectable by radar, while some at the lowest end of this mass range are decelerated sufficiently slowly to survive entry unmelted (Brownlee, 1985). Veriani (1973) obtained the density distribution of over 5,000 radar meteors in the 10^{-5} gram to 10^{-3} gram mass range. More than 50% of his meteors fell in the density range of $10^{-0.6}$ gm/cm^3 to $10^{+0.4}$ gm/cm^3, with a mean of the density distribution at 0.8 gm/cm^3. Taking 1 gm/cm^3 as a representative density for the particles, the 10^{-7} gram to 10^{-3} gram mass range corresponds to particles from 60 to 1200 micrometers in diameter. Particles near the lower end of this mass range, up to about 100 micrometers in diameter, have been collected from the Earth's stratosphere, after atmospheric deceleration (Brownlee, 1985). The properties of these micrometeorites, collected in the NASA Cosmic Dust Sampling Program, have been reviewed by Brownlee (1985).

Most of the material in the 100 to 3000 micrometer size range incident on the top of the Earth's atmosphere would be expected to melt of volatilize during atmospheric deceleration (Brownlee, 1985). However Mars is a much more favorable site for particle survival on atmospheric deceleration since:

1) the scale height of the atmosphere on Mars is larger than on Earth, resulting in a longer deceleration time (and lower peak temperature on Mars than on Earth), and

2) the lower planetary mass and surface gravity give rise to less gravitational infall acceleration, thus particles with similar in-space velocities prior to planetary encounter will enter the atmosphere on Mars with lower velocity than on Earth.

The current mass influx at Earth in the 10^{-13} gram to 10^6 gram mass range is estimated, from satellite, radar meteor, and visual meteor observations, at 16,100 tons per year, with 13,000 tons per year in the 10^{-7} gram to 10^{-3} gram mass range (Hughes, 1978). The measurement of Ir, which is believed to be a signature of extraterrestrial material, in atmospheric particulate samples at the South Pole suggest a current flux of extraterrestrial material of 11,000 tons per year (Tuncel and Zoller, 1987), consistent with the mass influx obtained by Hughes (1978).

Measurements of the long term meteoritic influx, by Ir concentrations in Pacific ocean sediments, have given values higher than the current flux. Kyte and Wasson (1986) infer a relatively constant mass influx (except for sharp spikes corresponding to major impact events) of 78,000 tons per year over the past 67 million years from Ir in Pacific seddiments. This is consistent with an earlier value of 110,000 tons per year derived from Pacific sediments by Shedlowsky and Paisley (1966). We will perform our calculations using both the current Hughes (1978) mass influx at Earth, and the Kyte and Wasson (1986) long-term mass influx, which is a factor of five higher than the Hughes value. Literature values for the extraterrestrial mass influx at Earth, which are tabulated in Tuncel and Zoller (1987), exceed even this range. Since the Ir measurements provide no information on the incoming size distribution of the particles, we will assume the current size distribution from Hughes (1978) is also representative of the size distribution of the meteoritic material contributing to the long-term flux determined by Ir concentration (Kyte and Wasson, 1986). Some confirmation

of this assumption is provided by the analysis of the size versus frequency distribution of microcraters on exposed lunar rock surfaces returned by the Apollo missions. For particles larger than 10^{-9} grams, where the effects of secondary impacts are no longer believed to be significant, the shape of the long-term lunar microcrater size versus frequency distribution is generally consistent with the mass distribution inferred from current satellite and meteor measurements (Grun, et. al, 1985).

To extrapolate the mass influx at Earth to the corresponding Mars value requires an estimate of the ratio of the Mars flux to the Earth flux. This ratio depends on the type of orbital evolution experienced by the particles. The orbits of large meteorites are perturbed principly by gravitational interactions with the planets. However, for small particles solar radiation pressure forces cause significant orbital perturbations on time scales comparable to or shorter than the gravitational perturbation time scale (Dohnanyi, 1978).

LARGE OBJECTS

For large, crater producing, objects whose orbits are dominated by gravitational perturbations, the relative crater production rates on the terrestrial planets and the Moon have been assessed to establish chronologies. Anders and Arnold (1965) have estimated the meteoritic input on Mars to be 25 times the Lunar value, while Soderblom, et al. (1974) have estimated the input of meteoritic material on Mars to be only twice that on the Moon. Shoemaker (1977) estimated that the ratio of impact rates of bodies to absolute visual magnitude 18 on Mars and Earth is 2.6. When corrected for differences in impact velocity, and scaled for the planetary surface gravities, Shoemaker (1977) arrived at a cratering rate ratio of 1.6. Hartmann et al. (1981) have reviewed the planetary cratering rate estimates, and they adopt a best value for the crater production rate on Mars of 1.3 that for Earth. Hartmann et al. (1981) indicate there are factor of 2 uncertainties in the cratering rate ratio, however, since the proportions of objects in various types of Earth and Mars crossing orbits are not well established. Since the Hartmann, et al. (1981) best value of the cratering ratio is consistent with the Shoemaker (1977) value, we will adopt the Shoemaker (1977) impact rate ratio of 2.6 as indicative of the ratio of the mass influx for large, gravitationally perturbed, objects at Mars and Earth.

SMALL OBJECTS

Objects whose orbits are dominated by P-R drag may, however, have a different ratio of the Mars to Earth flux. For particles up to 100 micrometers in diameter, the dominant radiation effect is a drag force, Poynting-Robertson (P-R) drag (Dohnanyi, 1978). For objects starting from circular orbits, P-R drag causes them to spiral into the sun. If the initial orbit of the particle is elliptical, P-R drag cause a rapid decrease in the perihelion and a slower decrease in the aphelion, so that the ellipticity of the orbit decreases as the particle falls into the sun.

The initial orbits of the dust particles will be determined by the orbits of the parent objects. The Infrared Astronomy Satellite (IRAS) detected two major types of solar system dust sources: the main belt asteroids (Low, et al., 1984), and comets (Sykes, et al., 1986). The dust bands detected in the main asteroid belt are thought to have been produced by low velocity collisions between main-belt asteroids (Sykes and Greenberg, 1986). Small particles produced in such collisions would spiral in towards the sun under P-R drag. They would pass Mars, providing an opportunity for Mars collection, and later pass Earth. Thus the Earth flux could be used to estimate the Mars flux for particles from this source region.

In the case of the particles emitted by comets, those detected by Sykes, et al. (1986) all had aphelia outside the orbit of Mars, and thus their orbits will also evolve, under P-R drag, through Mars collection and

subsequent Earth collection opportunities. Only if significant dust sources existed between the Earth and Mars, would there be a catagory of particles which, under P-R drag would be collectable at Earth but not at Mars. No such sources were reported in the IRAS survey.

To assess the ratio of the particle flux at Mars to that at Earth, the velocity distribution of the particles must be known at both planets. As shown by Opik (1951), the effective planetary capture cross-section, σ, varies with the velocity of the incident particle, v_p, as:

$$\sigma = \pi R_p^2 \cdot (1 + v_e^2/v_p^2) \qquad \text{(Equation 1)}$$

where v_e is the planetary escape velocity, and R_p is the planetary radius. The velocity distribution at Earth for radar meteors, particles in the 10^{-6} to 10^{-2} gram mass range, has been determined by Southworth and Sekanina (1973) for a set of over 14,000 radar meteors. We have used the Zook (1975) approximation to the Southworth and Sekanina (1973) atmospheric entry velocity distribution at Earth:

$$F(v) = 3.822 \times e^{-0.2468v} \qquad \text{(Equation 2)}$$

where $F(v)$ is the fraction of the particles having a velocity v. This distribution is shown in Figure 1. We then followed the same procedures used by Morgan, et al. (1988), who calculated the meteoritic velocity distribution at Mercury, to calculate the velocity distribution at Mars. First, the Earth entry velocity distribution was corrected to an in-space distribution at 1 au by removing the near-earth gravitational focusing in each velocity increment, and removing the effect of earth infall acceleration. Next, the resulting velocity distribution was transformed to 1.53 au. At this time, the difference in flux at 1.53 au was also accounted for, taking the flux fall off with increasing heliocentric distance to vary as $r^{-1.5}$, as determined from zodiacal light observations (Hanner, et al., 1976; Schuerman, 1980). We then transformed the space velocity distribution at 1.53 au to a Mars atmospheric entry velocity distribution taking into account both the Mars gravitational focusing effect and the gravitational infall acceleration. The resulting atmospheric entry velocity distribution is shown in Figure 1. The ratio of the area under the curve of Earth entry velocity, which was normalized to 1.0, to the area under the Mars velocity distribution curve (0.57) is the flux ratio. This flux ratio must be multiplied by the planetary cross-sectional area ratio, equal to 0.29, to obtain the mass influx ratio. Thus, we estimate that, for a population dominated by P-R drag, the ratio of the mass influx at Mars to that at Earth would be 0.17.

The time for an equivalent amount of orbital evolution under P-R drag increases linerally with particle diameter if the density and reflectivity remain constant. Thus, as particles become larger they are more likely to be gravitationally perturbed from their orbits or destroyed by catastrophic collisions before P-R drag produces a significant change in the orbit. Estimates of the catastrophic collision lifetimes for particles in the main asteroid belt (Dohnanyi, 1978) and in space at 1 au (Grun, et al., 1985) both suggest that particles larger than about 100 micrometers in diameter will be destroyed by collisions before their orbits are perturbed into the sun. Uncertainties in the flux of particles producing collisional destruction might change this size limit.

FLUX ASSESSMENT

Thus particles larger than 100 micrometers diameter, which contribute 75% of the mass influx at earth, are expected to be only slightly larger than the size range whose orbital evolution is dominated by P-R drag. The actual ratio of the Mars to Earth flux is thus likely to be somewhere between that which we have calculated for P-R drag dominated particles, and

the value obtained by Shoemaker (1977) for larger objects whose orbital evolution is dominated by gravitational perturbations.

In assessing the meteoritic infall on Mars, we will take as a lower estimate the a value of 2700 tons per year obtained using the Hughes (1978) earth flux coupled with our P-R drag dominated flux ratio. An upper estimate of the Mars infall, of 202,000 tons per year, was obtained using the Kyte and Wasson (1986) terrestrial flux and the (Shoemaker, 1977) flux ratio. The large range in values reflects the uncertainties in the Earth flux and the Mars/Earth flux ratio.

If distributed uniformly over the planet, the corresponding mass accretion rates range from 18 grams per square meter per million years to 1350 grams per square meter per million years. For density 1 gm/cm^3 material, these correspond to the addition of between 1.8 cm/billion years and 1.35 meters/billion years of meteoritic material to the Martian surface. Even the lower estimate would be expected to produce some detectable perturbationa in the soil composition, unless the indiginous materials are very similar to meteoritic composition or the soil production rate far exceeds that on Earth.

Of this infalling mass, about 80% would be expected to be in the 10^{-7} gram to 10^{-3} gram mass range.

MICROMETEORITE SURVIVAL

Deceleration in the atmosphere of the Earth heats most of the particles in the 10^{-6} gram to 10^{-3} gram mass range above their melting temperature. Some particles in this mass range are recovered as melted spherules from the ocean bottom (Brownlee, 1985) and from pools in Greenland (Maurette, et al., 1988). However no extraterrestrial particle larger than approximately 50 micrometers in diameter has been recovered unmelted, and intact in the NASA Cosmic Dust Collection Program (Zolensky, pers. comm.).

Brownlee (1985) estimates the melting temperature for micrometeoritic material at about 1600 K. The distribution of peak temperatures reached by a micrometeorite on atmospheric entry can be predicated using an entry heating model developed by Whipple (1950) and extended by Fraundorf (1980). This temperature distribution is generally expressed as the fraction of particles heated above any given temperature. We show in Figure 2, the calculated fraction of incident particles of diameter 10 microns, 100 microns, and 1000 microns, heated above temperatures from 300 K to 2000 K on Earth atmospheric entry. The calculations use the Fraundorf (1980) equations, and assume the Southworth and Sekanina (1973) entry velocity distribution, a particle density of 1 gm/cm^3, and a value of 1 for the parameters charactarizing drag, kinetic energy transfer, and emmissivity. The reasons for this latter assumption are examined in Flynn (1988).

The general validity of the Fraundorf (1980) entry heating model can be verified by noting that, if 1600 K is taken as the critical temperature for unmelted survival, essentially all 10 micron particles, about half of the 100 micron particles, and essentially none of the 1000 micron particles would be expected to survive Earth atmospheric entry unmelted. This is consistent with the size cutoff on unmelted particles recovered from the stratosphere, and the observation that larger meteoritic material recovered from sediments is mostly melted.

We have applied the Fraundorf (1980) entry heating model to the Mars atmosphere. Within 30 km of the surface, the atmospheric scale height measured by Viking 1 was 11.70 km, and by Viking 2 was 11.36 km (Seif and Kirk, 1977). However spacecraft deceleration data for the atmosphere from 30 km to 120 km (Seif and Kirk, 1977) give a scale height in this region of 7.9 km. Since particles in the size range of interest reach their maximum deceleration in the upper region, we have used a scale height of 7.9 km. The velocity distribution which we inferred for Mars entry (Figure 1) was used, and the particle size, density, and interation parameters were the

same as for the Earth atmospheric entry calculations. These results are also shown in Figure 2.

Unlike the Earth case, almost 90% of the 100 micron diameter particles would be expected to survive Mars atmospheric entry without melting. For the 1000 micron diameter particles, 30% would be expected to survive atmospheric entry unmelted. Micrometeorites in this size range which have survived atmospheric entry are rare in the Earth collections. Since these larger particles from Mars orbital distance are likely to sample different sources than the smaller micrometeorites collected at 1 a.u. in the cosmic dust sampling program on Earth (Flynn, 1988; Zook and McKay 1986), returned Mars soils may provide a unique resource for micrometeorite analysis.

We have used our calculated Mars atmospheric entry velocity distribution, and the Fraundorf (1980) entry heating model, to plot the predicted fraction of incoming micrometeorites not heated above temperature T on Mars atmospheric deceleration for temperatures ranging from 700 K to 1900 K. These results are shown for particles diameters from 10 to 1000 micrometers in Figure 3. We have used this survival fraction (those not heated above 1600 K at each size), coupled with the size-frequency distribution of micrometeorites from Hughes (1978), and our high and low estimates of the total mass influx at Mars to calculate the micrometeorite addition rate (particles per square meter of surface per year) to the Martian soils. Since each decade of mass spans only a factor of 2.1 in particle diameter, and since the particle abundance is a rapidly decreasing function of mass, all particles within each mass decade are taken to be at the smallest diameter in that decade. Particles are assumed to have a density of 1 gm/cm^3, consistent with the range of 0.7 to 2.2 gm/cm^3 measured for the smaller micrometeorites recovered from the Earth's stratosphere (Fraundorf, et al., 1982). These results of these calculations are reported in Table II. The expected abundance of micrometeorites in a returned Mars soil sample could be estimated from these results if the soil production rate on Mars were known.

Estimates of the thickness of the Martian regolith vary widely, from only twice as thick as the lunar regolith (Soderbloom, et al., 1974) to as deep as 2 km (Fanale, 1976). However, much of the planetary regolith was very likely generated during the intense bombardment era. Depending on the mixing depth, the present meteoritic infall may or may not be mixed into the soil of that early regolith.

Various physical properties of the Martian surface can be used to constrain the thickness of the current dust deposits. The low thermal inertia of the deposits requires a minimum thickness of order 0.1 meters (Harmon, et al., 1982). Harmon, et al. (1982) also suggest that the presence of exposed rocks and the degree of visible mantling indicate the dust thickness is less than 5 meters. Dual-polarization radar measurements in the Tharsis region indicate a rough texture, which suggests that a relatively thin dust layer covers near-surface rocks. Based on radar penetration properties, Christensen (1986) estimates a dust mantle thickness of only 1 to 2 meters. Arvidson (1986) suggests that most of the sedimentary debris on Mars was produced relatively early, perhaps in the first billion years. In more recent times, the preservation of a large number of pristine-looking, small bowl shaped craters at the Viking 1 lander site suggests a rate of rock breakdown and removal of only meters per billions of years (Arvidson, 1986).

Thus, while the regolith itself could be quite deep (Fanale, 1976), much of it is likely to have been produced during the intense bombardment of the planet. The surface soil into which the last billion years of meteoritic material may be concentrated, could be only a few meters deep.

DIRECT COLLECTION

We calculate the expected concentration of micrometeorites in a soil whose planetary average production rate is 1 meter per billion years. The concentrations obtained can then be scaled to other assumed soil production

rates by multiplying by (1 meter/billion years)/(production rate). Table III shows the number of unmelted micrometeorites in each size range expected in an average 10 gram Mars soil sample. These results suggest that returned Mars samples may offer a new resource for the study of micrometeorites. These micrometeorites may sample a different parent population than the smaller particles recovered from the Earth's stratosphere. The survival lifetime of micrometeorites deposited in the harsh Martian enviornment is unknown, however on Earth millimeter size fragments of meteoritic material, both unmelted and melted, have been recoved from late Pliocene deep sea sediments (Brownlee, et al., 1982), demonstrating that survival is possible on Earth for several million years.

The soils would also be expected to contain melted micrometeorites in the larger sizes. On Earth, such particles can easily be extracted from the ocean bottom by magnetic separation, due to the formation of magnetic minerals on atmospheric entry (Brownlee, 1985). Depending on the abundance of indiginous magnetic minerals in the Mars soil, a magnetic separation may permit recovery of the melted particles to determine if the meteoritic concentration is sufficient for search and extraction of unmelted particles.

COLLECTING SITES FOR MICROMETEORITES

Martian surface processes (weathering and wind erosion, transport, and deposition) may fractionate the dust by size, density or composition providing regions of increased local concentration, suggesting even more suitable sites for micrometeorite sampling than the average soil. These sites may include placer catch basins or lag surfaces which may accumulate high density micrometeorites or their derived and altered minerals. Conversely, low density micrometeorites may be wind segregated along with finer Martian dust and may constitute a relatively coarse-grained component of that dust at its deposition sites. By analogy with Antarctica, meteorites of all size ranges may be relatively concentrated in Martian polar regions, although the concentration mechanisms may be different.

MICROMETEORITES AS A TOOL

Assuming that micrometeorites could be identified in returned soil samples, this addition of micrometeorite material to the uppermost Martian regolith at a constant rate could conceivably provide a powerful tool for tracking rates of erosion, deposition, and weathering. On Mars Sample Return missions, an attempt should be made to collect soils from different geologic sites (catch basins, lag surfaces, flat high plains, valley bottoms, etc.) so as to provide a variety of soils of different sedimentary environments. One of the important differences among these environments might be the proportion of petrographically or chemically identifiable micrometeorites mixed into the soil.

CHEMICAL SIGNATURES

The possibility that detectable micrometeorites and their remains can be found in the Martian soils depends on the relative rates of infall, weathering and alteration, transportation, and mixing. These rates are not yet known reliably enough to allow us to predict with certainty whether identifiable micrometeorites will be found. While they may be relatively quickly destroyed by Martian weathering, the chemical signatures, particularly siderophiles and volatiles, may persist in the soils, as they have in the lunar regolith (Anders, et al., 1973), and in Earth sediments where Ir anomalies are detected (Kyte and Wasson, 1986). All of the meteoritic material collected by the planet, whether it reaches the surface unmelted, or if it melts or vaporizes on atmospheric entry, should eventually be added to the soils. We have estimated a mass influx on Mars ranging from 2,700 to 202,000 tons per year. If spread uniformly over

the surface of the planet, this corresponds to an addition rate from 1.8×10^{-5} gm/m^2·year to 1.4×10^{-3} gm/m^2·year. For material of density 1 gm/cm^3, this corresponds to an accretion rate which ranges from 1.8 centimeters per billion years to 1.4 meters per billion years.

If the soil production rate on Mars is of order 1 meter per billion years, these meteoritic accretion rates would give rise to meteoritic concentrations ranging from 2% to 58% in the average Martian soil. Boslough (1988) and Clark and Baird (1979), applying the subtraction method to the Viking chemical data, suggest the Mars regolith can be fit by a mixture of 40% CI meteorite and 60% planetary rock fragments. Boslough (1988) suggests the meteoritic component is ancient. But it could equally well be the micrometeorite component, which dominates the ancient component in lunar mare soils. In the lunar case the composition of the non-indigenous material was taken as the residual after subtracting rock composition from soil composition. Two meteoritic components were detected. In mature soils the residual has a trace element composition consistent with the addition of 1.5% CI meteoritic material, attributed to the long term micrometeorite infall (Anders et al., 1973). Less mature highland soils also show a second component, characterized by fractionated siderophile content and low volatiles, attributed to ancient bombardment (Anders et al., 1973).

The observations of Boslough (1988) and Clark and Baird (1979) are consistent with the Mars soil at the Viking sites containing a substantial meteoritic component. The meteoritic concentration they infer is consistent with the range of concentrations we calculate from micrometeorite influx, provided the rate of production of soil on Mars is no more than a few meters per billion years. The possibility exists that the Martian soils contain a substantial fraction of meteoritic material. On Earth and on the Moon, the Ni/Fe ratio and the Ir abundance have proven to be diagnostic indicators of the meteoritic component, since Ir and Ni are enriched in CI meteorites but depleted in crustal materials. Direct spacecraft measurement of the Ni and/or Ir abundances in the Mars regolith should help determine the meteoritic content of the soil.

CONSTRAINTS FROM VIKING MEASUREMENTS

The major meteoritic component in the Lunar mare soils is similar, in siderophile and volatile element composition, to the CI carbonaceous chondrite meteorites. These meteorites contain an average of 3 to 5% carbon (Wasson, 1974), some in the form of organic matter. The cosmic dust particles collected from the Earth's stratosphere contain carbon at or above CI concentrations (Blanford, et al., 1988), some of which may be in the form of polycyclic aromatic hydrocarbons (Allamandola, et al., 1987). If the Martian soil contained a substantial abundance of unmodified CI carbonaceous chondrite material, the Viking gas chromatograph mass spectrometer should have detected its presence.

Biemann, et al. (1977) found no detectable organic material in four Martian samples, one surface and one subsurface at each of the two Viking sites. Using the laboratory version of the Viking gas chromatorgaph mass spectrometer, they detect naphthalene at a level of about 1 ppm in CI carbonaceous chondrite samples (Biemann, et al., 1977). They report a detection limit of 0.5 ppb for naphthalene at the Viking 1 site and 0.015 ppb for Viking 2 (Biemann, et al., 1977). If the concentration of naphthalene were the same in the infalling meteoritic material as in their carbonaceous chondrite sample, then the corresponding upper limits on the meteoritic mass fraction in the analyzed Viking samples would be 0.05% at the Viking 1 site, and 0.0015% at the Viking 2 site.

The organic content of the micrometeorites in the 10^{-6} to 10^{-2} gram mass range has never been established, since the particles in this mass range collected on Earth are melted on atmospheric entry. Furthermore, as pointed out by Banin (1988), the high redox potential of the Martian soil may have caused the decomposition of any organic matter from meteoritic infall.

MARTIAN AGGLUTINATES AND SOIL MATURITY

If, as we calculate, micrometeorites are all slowed down by the Martian atmosphere, and assuming that most lunar agglutinates are made by micrometeorite impacts, no analogous Martian agglutinates would be expected (unless there were an era in which the atmosphere was considerably less dense than at present). However, many types of impact glasses would be expected from larger impacts, and some of these glasses may resemble lunar agglutinates in some respects.

Gault and Baldwin (1970) have estimated a minimum impact crater size of 50 meters, taking into account fragmentation and ablation of the incoming projectiles as well as atmospheric deceleration. The smallest craters noted in Viking orbiter images are about 100 meters in diameter (Blasius, 1976), but smaller craters beyond the resolution limit of the photographs may still be present. Dycus (1969) predicts that projectiles as small as 10 gm would still form craters. However, craters too small to be seen from the orbiter are not apparent in Viking lander images. Impact gardening associated with the 50 meter and larger craters predicted by Gault and Baldwin (1970) would determine regolith turnover rates and cause comminution of rocks into soils. The addition of micrometeorites would affect the petrology and chemistry of Martian soil. Weathering and sedimentary processes on Mars would also process the regolith components. The overall effect would be to make an exceedingly complex regolith. A new maturation scale will be necessary for Martian regolith. This scale will have to include terms which reflect (1) impact reworking, (2) addition of micrometeorites, and (3) Martian surface weathering and alteration. For example, if concentration mechanisms can be factored out, the abundance of micrometeorites (identified petrographically or chemically) in a soil layer might be directly related to its near-surface exposure time in a manner analogous to the abundance of agglutinates in lunar soils. In addition to soil evolution through maturation, physical mixing of soils of differing maturities should be common.

CONCLUSIONS

Micrometeorites in the 10^{-7} to 10^{-3} gram mass range should be a major contributor to the meteoritic input on Mars. Unlike the Earth, where most particles above 10^{-6} grams are melted or vaporized on atmospheric entry, a large fraction of these particles are expected to survive entry into the atmosphere of Mars unmelted. The addition of this meteoritic material to the Martian regolith could significantly perturb the chemical abundances in the soils, particularly the abundances of volatile and siderophile elements which are abundant in CI meteorites but depleted in crustal materials, and of noble gases (and possibly hydrogen) which are implanted in micrometeorites during space exposure and carried into the soils with the particles.

Uncertainties micrometeorite flux at Mars as well as the rate of production of soil through weathering processes on the planet give rise to large uncertainties in the meteoritic concentration in the Martian soils. However, our estimates are not incompatible with the suggestion by Boslough (1988) that the soils analyzed by Viking are 40% meteoritic.

The first returned soil samples from Mars should provide the opportunity for recovery and analysis of unaltered micrometeorites larger than any sampled on earth, assessment of the magnitude of the meteoritic component, and and possibly an estimate of the rate of soil production on the planet. The larger micrometeorites which enter the atmosphere of Mars without melting may sample a different source population than is sampled by the smaller particles collected from the Earth's stratosphere.

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Table I

Mass Influx at Earth[*]

Mass Range (grams)	Particle Diameter (microns)[+]	Mass Influx (kg/year)	Fraction of Total Mass[#]
10^{-7} to 10^{-6}	58 to 124	2.0×10^6	.12
10^{-6} to 10^{-5}	124 to 268	4.2×10^6	.26
10^{-5} to 10^{-4}	268 to 576	4.2×10^6	.26
10^{-4} to 10^{-3}	576 to 1240	2.7×10^6	.17
10^{-3} to 10^{-2}	1240 to 2600	1.3×10^6	.08

[*] Data, except for particle diameters, from Hughes (1978).
[#] Ratio of mass in this decade to total mass influx from 10^{-13} to 10^6 grams.
[+] Diameters calculated for spheres of density 1 gm/cm^3.

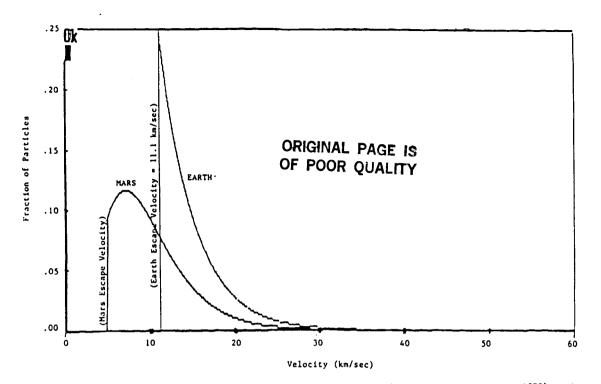## Table II

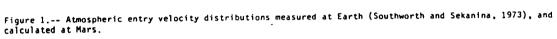### Particles Surviving Mars Atmospheric Entry Unmelted

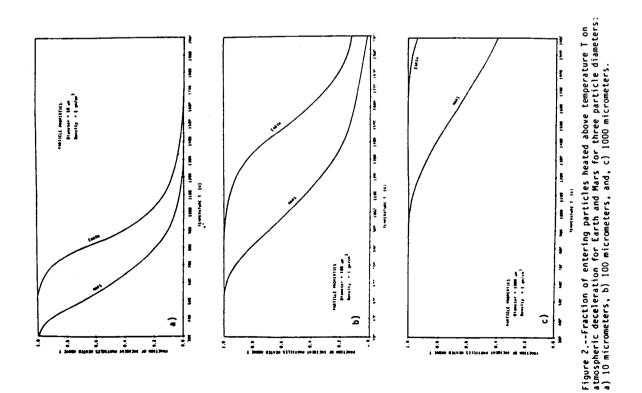| Size Range (micrometers)	Upper Estimate (particles/$m^2 \cdot$year)	Lower Estimate (particles/$m^2 \cdot$year)
56 to 124	1.6×10^3	2.1×10^1
125 to 268	3.2×10^2	4.3
269 to 576	2.7×10^1	3.6×10^{-1}
577 to 1240	1.2	1.6×10^{-2}
1241 to 2600	3.1×10^{-2}	4.1×10^{-4}

Table III

Number of Unmelted Micrometeorites Expected in 10 gram Average Soil Sample

Size Range (micrometers)	Upper Estimate	Lower Estimate
56 to 124	16,000	210
125 to 268	3,200	43
269 to 576	270	4
577 to 1240	12	< 1
1241 to 2600	3	< 1

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Figure 1.-- Atmospheric entry velocity distributions measured at Earth (Southworth and Sekanina, 1973), and calculated at Mars.

Figure 2.--Fraction of entering particles heated above temperature T on atmospheric deceleration for Earth and Mars for three particle diameters: a) 10 micrometers, b) 100 micrometers, and, c) 1000 micrometers.

Figure 3.-- Mars atmospheric entry temperature distribution for particles having the Mars entry velocity distribution shown in Figure 2. Particles have a density of 1 gm/cm³, and a thermal emissivity of 1.