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An Assessment of the Meteoritic Contribution to the Martian Soil

GEORGE J. FLYNN

Department of Physics, State University of New York at Plattsburgh

DAVID S. MCKAY

NASA Johnson Space Center, Houston, Texas

The addition of meteoritic material to the Mars soils should perturb their chemical compositions, as has been detected for soils on the Moon [Anders et al., 1973] and sediments on Earth [Kyte and Wasson, 1986]. Using the measured mass influx at Earth and estimates of the Mars/Earth flux ratio, we estimate the continuous, planet-wide meteoritic mass influx on Mars to be between 2700 and 59,000 t/yr. If distributed uniformly into a soil with a mean planetary production rate of 1 m/b.y., consistent with radar estimates of the soil depth overlaying a bouldered terrain in the Tharsis region [Christensen, 1986], our estimated mass influx would produce a meteoritic concentration in the Mars soil ranging from 2 to 29% by mass. Analysis of the Viking X ray fluorescence data indicates that the Mars soil composition is inconsistent with typical basaltic rock fragments but can be fit by a mixture of 60% basaltic rock fragments and 40% meteoritic material [Clark and Baird, 1979]. The meteoritic influx we calculate is sufficient to provide most or all of the material required by the Clark and Baird [1979] model. Particles in the mass range from 10^{-7} to 10^{-3} g, about 60-1200 µm in diameter, contribute 80% of the total mass flux of meteoritic material in the 10^{-13} to 10^{6} g mass range at Earth [Hughes, 1978]. On Earth atmospheric entry all but the smallest particles (generally $\leq$ 50 µm in diameter) in the 10^{-7} to 10^{-3} g mass range are heated sufficiently to melt or 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 60-1200 µm diameter range will survive Mars atmospheric entry unmelted. Thus returned Mars soils may offer a resource for sampling micrometeorites in a size range which is not collectable in unaltered form at Earth.

INTRODUCTION

A number of indigenous sources for dust on Mars have been proposed including chemical and physical weathering of indigenous surface rocks, debris from impact cratering, volcanism, and tectonism [*Greely*, 1986]. However, the possible contributions from meteorites and micrometeorites have not been considered in the same detail.

At Earth the mass influx of extraterrestrial materials, shown in Figure 1, exhibits two distinct peaks. The lower mass peak, centered at 10^{-5} g, corresponds to micrometeorites and small meteors which give rise to a continuous, planet-wide accretion of extraterrestrial material. Chemical perturbations, particularly in Ir, attributed to this meteoritic component have been detected in terrestrial sediments [*Kyte and Wasson*, 1986]. The peak at higher mass, impactors $>10^{14}$ g, is from the infrequent impacts of kilometer sized objects on Earth. These impacts produce local or, in the most extreme cases such as the event at the Cretaceous-Tertiary boundary, planet-wide debris layers. These events are recorded on Earth as spikes in the Ir enrichment superimposed on the continuous Ir background level contributed by particles in the lower mass peak.

Following the return of lunar samples, direct comparisons of the compositions of lunar mare "soils" with those of nearby rocks showed an excess of volatile and siderophile elements in the soils. Here soil is taken to indicate the fines component of the regolith. These soil enrichments in elements abundant in primitive meteorites but rare in mare rocks are consistent with the addition of between 1% and 2% meteoritic material to the indigenous mare soils [*Anders et al.*, 1973]. The meteoritic component is attributed to the impact of small meteoroids on the lunar surface [*Anders et al.*, 1973].

Comparison of the meteoritic impact rate on Mars with that on the Moon and on Earth suggests that the Mars impact rate exceeds the lunar rate and perhaps even the Earth rate [*Hartmann et al.*, 1981]. The preservation of ancient impact craters on the surface of Mars argues that the rate of production of soil by erosion of rock formations on Mars is much lower than on Earth and not significantly higher than on the Moon. This suggests that the meteoritic component should perturb the composition of the soils on Mars to a much higher degree than on Earth and to similar extent as on the Moon. *Boslough* [1988] has proposed a Martian meteoritic component derived from weathering of shock-activated meteoritic projectiles from the period of heavy bombardment, and *Flynn and McKay* [1988] have described the contribution from micrometeorites, particles sufficiently small to be slowed without melting on deceleration by the atmosphere of Mars.

To evaluate the importance of the meteoritic component in the soil on Mars, we have (1) assessed the flux of meteoritic material at Mars, (2) considered the chemical

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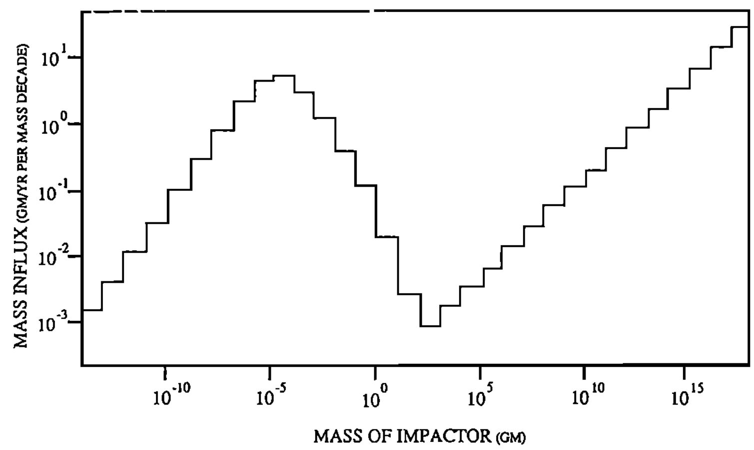

Fig. 1. The mass influx distribution of meteoritic material at Earth exhibits two peaks: one centered at 10^{-5} g corresponding to the continuous, planet-wide flux of micrometeorites and small meteors, and the second corresponding to the rare impacts of objects larger than 10^{14} g. (Figure adapted from *Kyte and Wasson* [1986].

perturbations to the indigenous soil produced by micrometeorite addition, and (3) suggested measurements which a Mars lander spacecraft could make to determine the fraction of meteoritic material in the soils.

Much of this meteoritic contribution to the soils of Mars should come from particles in the lower mass peak seen in Figure 1. Because of its low surface gravity coupled with an atmosphere of sufficient density to decelerate incoming micrometeorites, Mars may be one of the most favorable sites in the solar system for the unaltered survival of micrometeorites on atmospheric entry. Though most particles larger than 100 µm in diameter are melted on entry into the Earth's atmosphere, they may survive Mars atmospheric entry without significant melting. Since larger micrometeorites are likely to sample different sources than the smaller ones ($\leq$ 100 µm in diameter) collected on Earth [*Flynn*, 1989; *Zook and McKay*, 1986], returned Mars samples could provide a unique resource for micrometeorite analysis.

To determine if Mars is a more favorable site for the collection of unaltered micrometeorites than is Earth, we have (1) estimated the micrometeorite velocity distribution at Mars, (2) evaluated the survival probability for micrometeorites entering the Martian atmosphere, and (3) assessed the possibilities for recovery of micrometeorites from the soils returned by a Mars sample return mission.

Flux at Mars

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 K-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.

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} to 10^{6} g, the current size-frequency distribution at Earth has been determined from satellite, radar meteor, and visual meteor observations [*Hughes*, 1978]. Eighty percent of the total mass influx in the 10^{-13} to 10^{+6} g mass range is in the narrow range from 10^{-7} to 10^{-3} g [*Hughes*, 1978].

The mass influx of meteoritic material onto the Earth per decade of mass is shown in Table 1. The current mass influx at Earth in the 10^{-13} g to 10^{6} g mass range is estimated, from satellite, radar meteor, and visual meteor observations, at 16,100 t/yr, with 13,000 t/yr in the 10^{-7} to 10^{-3} g 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 suggests a current flux of extraterrestrial material of 11,000 t/yr [*Tuncel and Zoller*, 1987], consistent with the mass influx reported by *Hughes* [1978].

The contribution made by objects larger than 10^{6} g is less certain, but cratering statistics indicate that the mass influx from very large objects ($>10^{14}$ g) exceeds that of the small meteorites as shown in Figure 1 [*Kyte and Wasson*, 1986]. These large objects produce major impact events, but the frequency of these events is low. For example, Figure 1 shows an average mass influx of 10^{10} g/yr for objects having a mass of 10^{15} g, indicating an impact rate of one event every 10^{5} years. Since these events are discrete, rather than continuous, and only the largest are planet-wide, they are reflected in the Ir record by local or planet-wide layers of higher than normal Ir concentration. The mass influx inferred from long-term averages of the Ir in terrestrial sediments should include this contribution as well as the continuous contribution from the smaller particles.

TABLE 1. Mass Influx at Earth

Mass Range, g	Particle Diameter,* μm	Mass Influx, kg/yr	Fraction of Total Mass+
10^{-10} to 10^{-9}	6-12	1.0×10^5	0.01
10^{-9} to 10^{-8}	12-27	2.8×10^5	0.02
10^{-8} to 10^{-7}	27-58	7.3×10^5	0.05
10^{-7} to 10^{-6}	58-124	2.0×10^6	0.12
10^{-6} to 10^{-5}	124-268	4.2×10^6	0.26
10^{-5} to 10^{-4}	268-576	4.2×10^6	0.26
10^{-4} to 10^{-3}	576-1240	2.7×10^6	0.17
10^{-3} to 10^{-2}	1240-2680	1.3×10^6	0.08
10^{-2} to 10^{-1}	2680-5760	4.1×10^5	0.02

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

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 t/yr over the past 67 m.y. from Ir in Pacific sediments. This is consistent with an earlier value of 110,000 t/yr derived from Pacific sediments by *Shedlowsky and Paisley* [1966]. This may indicate that the long-term average meteoritic infall is higher than the current rate determined by satellite and meteor measurements.

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 5 higher than the Hughes value. Literature values for the extraterrestrial mass influx at Earth, which are tabulated by *Tuncel and Zoller* [1987], exceed even this range; however, recent measurements seem to cluster in 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} g, 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. Two significant mechanisms exist for perturbation of particles from the asteroid belt into Mars intersecting orbits: Poynting-Robertson drag (P-R drag) [*Dohnanyi*, 1978] and planetary gravitational perturbations [*Zimmerman and Wetherill*, 1973; *Wetherill*, 1974]. The orbits of large meteorites are perturbed principally by gravitational interactions with the planets [*Wetherill*, 1974]. However, for small particles, P-R drag causes significant orbital changes 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 for the cratered regions observed in the Viking orbiter photos. Early estimates of the meteoritic flux at Mars varied widely. *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. More recently, *Shoemaker* [1977] has estimated that the ratio of impact rates of bodies to absolute visual magnitude 18 on Mars and Earth is 2.6. *Shoemaker*'s [1977] cratering rate is consistent with the value adopted by *Hartmann et al.* [1981], who have reviewed the planetary cratering rate estimates in order to derive ages of geologic features. *Hartmann et al.* [1981] indicate there are factor of 2 uncertainties in this cratering rate ratio, however, since the proportions of objects in various types of Earth and Mars crossing orbits are not well established. 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, though it may be uncertain by about a factor of 2. When this cratering rate ratio is adjusted for the difference in planetary areas, the total meteoritic infall on Mars for large objects will be taken as 0.75 times the Earth infall.

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 200 μm in diameter, the dominant radiation effect in this radiation drag force [*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 causes a rapid decrease in the aphelion and a slower decrease in the perihelion, 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 toward the Sun under P-R drag. They would pass Mars, providing an opportunity for Mars collection, and later pass Earth. Thus the Earth flux can 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 category 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 relative to the center of mass of the planet, v_p, as

$$\sigma = \pi R_p^2 (1 + v_e^2/v_p^2) \tag{1}$$

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} g 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:

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

where $F(v)$ is the fraction of the particles having a velocity v. This distribution is shown in Figure 2. 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 for Mars is shown in Figure 2. The ratio of the area under the curve of Earth entry velocity, which was normalized to 1.0, to the area under the Mars entry 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 small particles, the ratio of the mass influx at Mars to that at Earth would be 0.17.

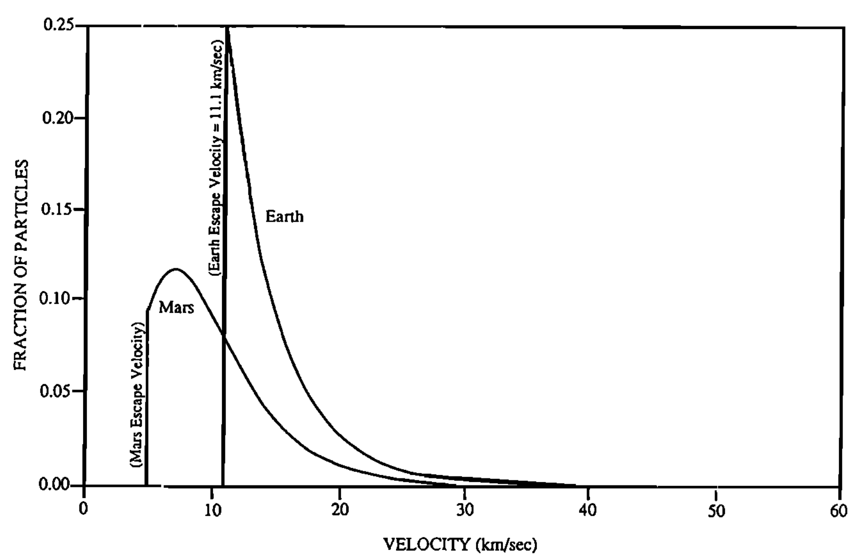

Fig. 2. Atmospheric entry velocity distributions measured at Earth [*Southworth and Sekanina*, [1973] and calculated at Mars using the method described in the text.

Flux Assessment

Since particles in the narrow mass range from 10^{-7} to 10^{-3} g contribute 80% of the continuous, planet-wide meteoritic flux at Earth, we have concentrated our attention on these particles. Interplanetary dust particles at the low end of this mass range (10^{-9} to 10^{-7} g) recovered from the stratosphere of the Earth have densities near 1 g/cm^3 [*Flynn and Sutton*, 1988]. Taking this as an appropriate density, the 10^{-7} to 10^{-3} g mass corresponds to particles from 58 to 1249 μm in diameter. Most of these particles are 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.

We estimate the meteoritic infall on Mars by combining the measured Earth flux with an estimate of the Mars/Earth impact rate ratio. A lower estimate of the infall rate of meteoritic material on Mars, obtained by combining the *Hughes* [1978] Earth flux with our P-R drag dominated flux ratio, is 2700 t/yr. An upper estimate of the Mars infall, obtained combining the *Kyte and Wasson* [1986] terrestrial flux and the *Shoemaker* [1977] flux ratio, is 59,000 t/yr. The large range in values reflects the uncertainties in the Earth flux and the Mars/Earth flux ratio.

CHEMICAL SIGNATURES

Our estimated meteoritic infall rates on Mars bracket the observed current terrestrial infall rate of 16,100 t/yr [*Hughes*, 1978]. The terrestrial infall rate is sufficient to produce detectable chemical perturbations in terrestrial sediments, particularly in Ir. Since the preservation of ancient craters on the surface of Mars must indicate that the erosion and soil production rates on Mars are significantly lower than on Earth, even greater chemical perturbations would be expected in the soils of Mars.

If distributed uniformly over the planet, the meteoritic mass accretion rates range from 18 to 400 g m^{-2} m.y.$^{-1}$. For density 1 g/cm^3 material, these correspond to the addition of between 1.8 and 40 cm/b.y. of meteoritic material to the Martian surface. Even the lower estimate would be expected to produce some detectable perturbations in the soil composition, unless the indigenous materials are very similar to meteoritic composition or the indigenous soil production rate far exceeds that on Earth.

The soil production rate on Mars is not yet 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 have been 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 m [*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 m. 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 1-2 m. *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 few billion years of meteoritic material may be concentrated could be only a few meters deep.

To illustrate the expected meteoritic concentration in the soil of Mars, we take a soil production rate of 1 m/b.y. With this soil production rate our meteoritic accretion rates would give rise to meteoritic concentrations ranging from 2% to 29% in the average Martian soil. Since the actual soil production rate on Mars is unknown, a much wider range of meteoritic concentrations is possible.

Constraints From The Viking Measurements

Our inferred meteoritic concentration range is not inconsistent with the Mars soil chemical analyses from the Viking landers. In comparing the Martian soil elemental abundances to typical terrestrial and lunar basalts, *Clark and Baird* [1979] noted the Mars soils were enriched in S and Fe but depleted in Al and Ca relative to the basalts. *Clark and Baird* [1979] and *Boslough* [1988] suggested the Mars soil composition could be fit by a mixture of 40% CI meteorite and 60% basaltic planetary rock fragments. *Boslough* [1988] suggests the meteoritic component on Mars is ancient, but it could equally well be the more recent micrometeorite component, which dominates the ancient component in lunar mare soils.

In the lunar case the composition of the nonindigenous material was taken as the residual after subtracting rock composition from soil composition. Two distinct meteoritic components were detected. In mare 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]. Highland soils also show a second meteoritic component characterized by a fractionated siderophile content and low volatiles. This second component is attributed to ancient bombardment [*Anders et al.*, 1973].

The resurfacing of major areas on Mars may trap the ancient component within the lavas, allowing the modern micrometeorite component to dominate the soils. Presumably, a similar mechanism operating on the Moon results in the ancient component being detected only in the highland region which have not been resurfaced.

The mixing model of *Boslough* [1988] and *Clark and Baird* [1979] is 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 our micrometeorite influx provided the rate of production of soil on Mars is no more than a few meters per billion years.

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 3-5% 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 chromatograph mass spectrometer, they detected 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 and if the napthalene were not altered by Martian surface processes, 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. However, as discussed by *Banin* [1988], the high redox potential of the Martian soil may have caused the decomposition of any organic matter from meteoritic infall.

Laboratory simulations of organic degradation under ultraviolet conditions simulating those on the surface of Mars give an organic decomposition rate of 3.1×10^{-1} g $m^{-2} yr^{-1}$ [*Stoker et al.*, 1989]. This exceeds our upper limit on the meteoritic infall rate of 4×10^{-4} g $m^{-2} yr^{-1}$. Thus, even if organic compounds were the major constituent of the infalling micrometeorites, it is likely that it would be destroyed by ultraviolet breakdown as rapidly as it was being added.

In addition, the organic content of the micrometeorites in the 10^{-6} to 10^{-2} g mass range has never been established, since particles in this mass range collected on Earth are melted on atmospheric entry. Analysis of larger, melted micrometeorites, recovered from the ocean floor on Earth, suggests that three of the nine particles show chemical similarities to ordinary chondrites rather than the carbon-rich carbonaceous chondrites [*Sutton et al.*, 1988]. Thus the carbon content of the micrometeorites contributing to the Mars soil is not known. As a result, the Viking gas chromatograph mass spectrometer results do not provide a meaningful constraint on the present micrometeorite influx at Mars.

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 abundant in CI meteorites but depleted in crustal materials. The observed low Ni abundance in the SNC meteorites, thought to be samples of the surface of Mars [*McSween*, 1985], suggests the addition of a meteoritic component would perturb the Ni concentration of the Mars soil. Direct spacecraft measurement of the Ni and/or Ir abundances in the Mars regolith should help constrain the meteoritic content of the soil of Mars.

MICROMETEORITE SURVIVAL

On entering the Earth's atmosphere, most particles in the 10^{-7} g to 10^{-3} g mass range are volatilized, producing ionized trails detectable by radar. Some particles at the lowest end of this mass range are decelerated sufficiently slowly to survive entry unmelted [*Brownlee*, 1985]. Particles near the lower end of this mass range, up to about 100 um in diameter, have been collected from the Earth's stratosphere, after atmospheric deceleration [*Brownlee*, 1985]. Taking 1 g/cm^3 as a representative density for the particles, the 10^{-7} g to 10^{-3} g mass range corresponds to particles from 60 to 1200 μm in diameter.

A typical, unmelted micrometeorite collected from the stratosphere of the Earth is shown in Figure 3. These particles generally exhibit solar flare tracks, proving their extraterrestrial nature [*Bradley et al.*, 1984]. The major element abundances are consistent with the CI meteorites [*Brownlee*, 1985], with minor and trace element abundances generally within a factor of 2 of the CI value, though there are some indications of volatile enrichments [*van der Stap et al.*, 1986; *Sutton and Flynn*, 1988]. The properties of these micrometeorites, collected in the NASA Cosmic Dust Collection Program, are described in more detail by *Brownlee* [1985].

Most of the material in the 100-3000 μm size range incident on the top of the Earth's atmosphere would be expected to melt or volatilize during atmospheric deceleration [*Brownlee*, 1985]. 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 100 μm in diameter has been recovered unmelted, and intact in the NASA Cosmic Dust Collection Program [M. E. Zolensky, personal communication, 1989].

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

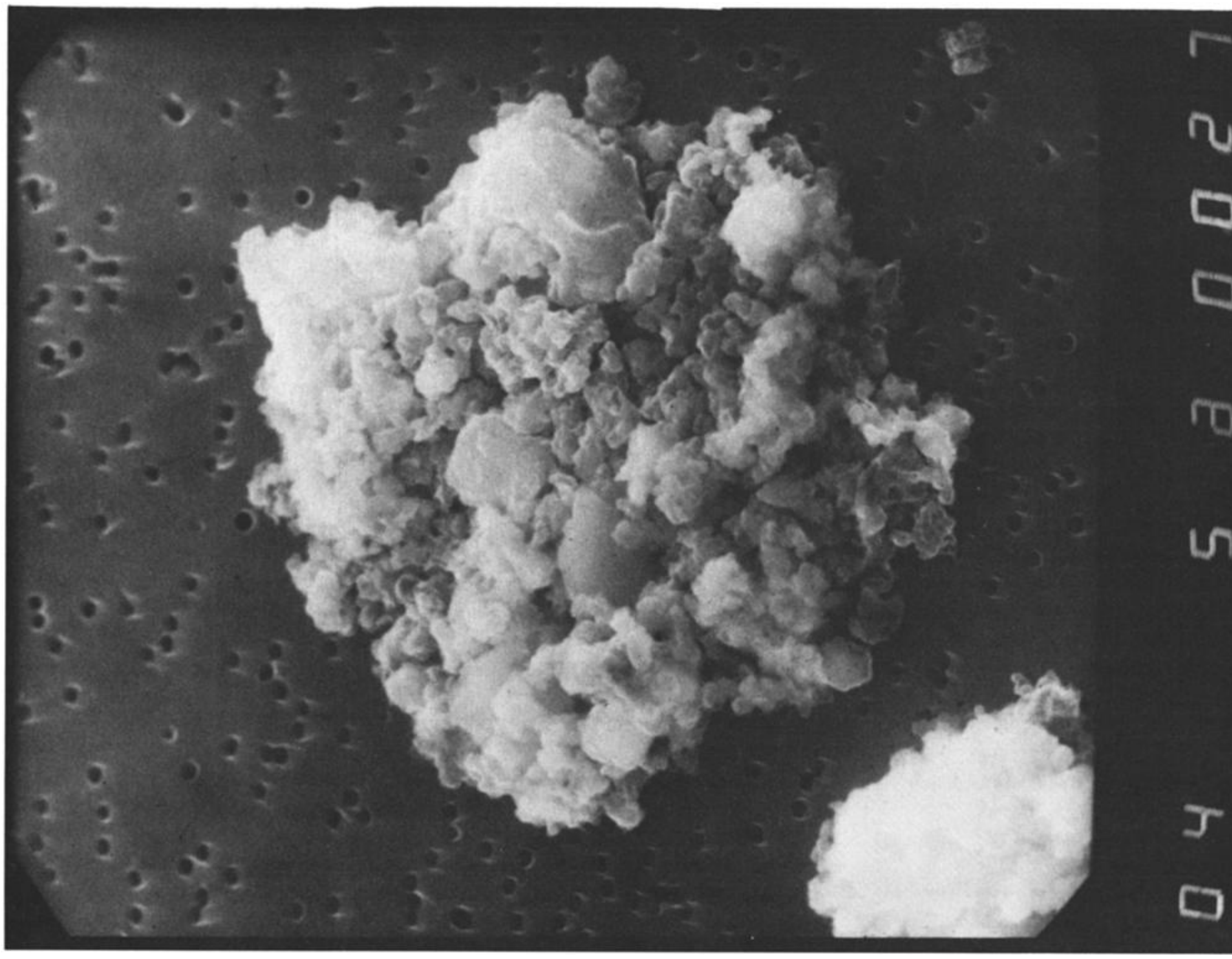

Fig. 3. A typical cosmic dust particle of chondritic composition collected from the stratosphere of the Earth in the NASA Johnson Space Center collection program.

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.

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 4, the calculated fraction of incident particles of diameter 10 µm, 100 µm, and 1000 µm, 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 characterizing drag, kinetic energy transfer, and emissivity. The reasons for this latter assumption are examined in *Flynn* [1989].

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 micrometer particles, about half of the 100 micrometer particles, and essentially none of the 1000 micrometer 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 micrometeorites entering 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 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 2) was used, and the particle size, density, and interation parameters were the same as for the Earth atmospheric entry calculations.

Unlike the Earth case, we calculate that almost 90% of the 100-um diameter particles would be expected to survive Mars atmospheric entry without melting. For the 1000-µm

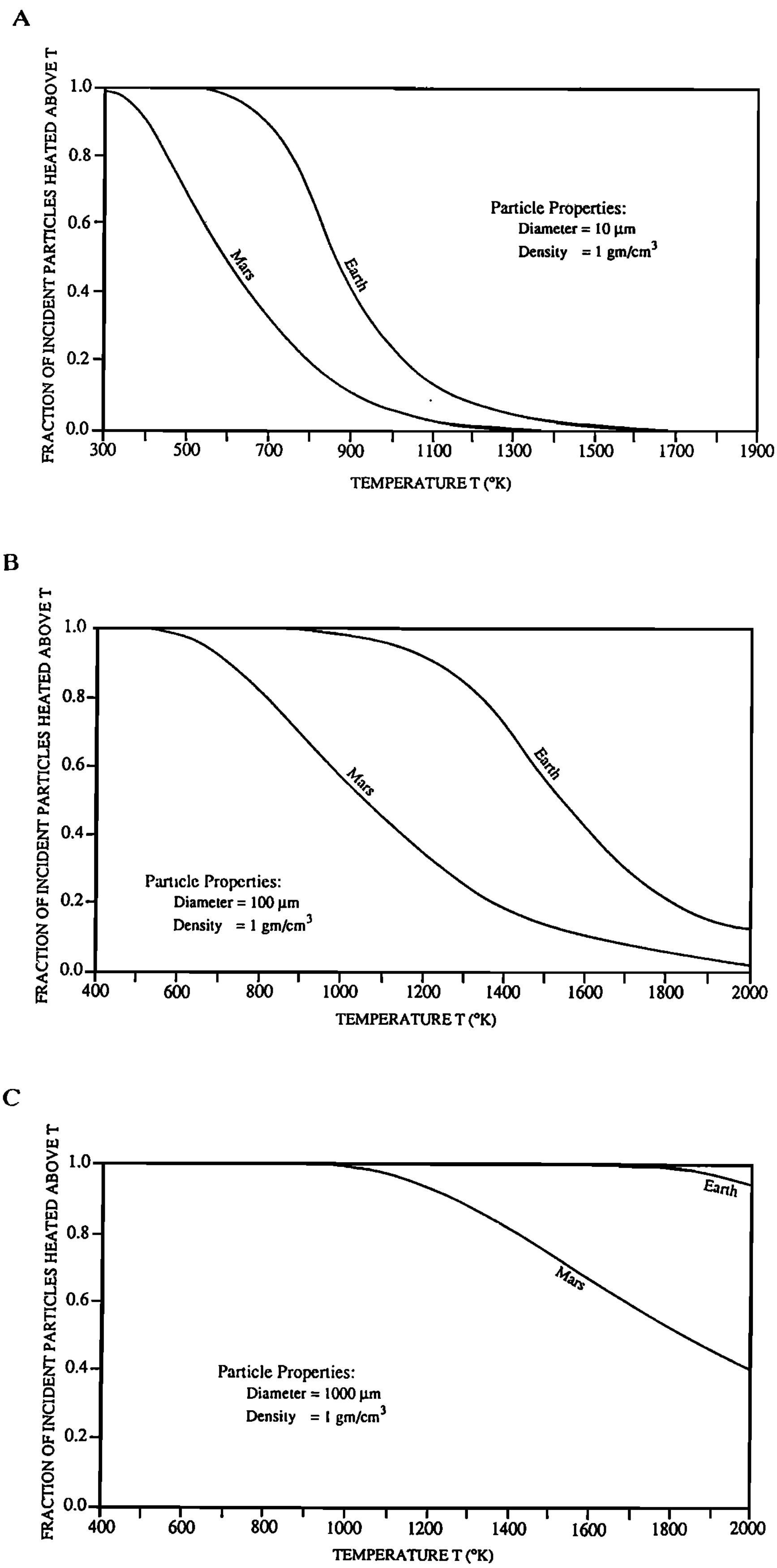

Fig. 4. Fraction of entering particles heated above temperature T on atmospheric deceleration for Earth and Mars for three particle diameters: (a) 10 μm, (b) 100 μm, and (c) 1000 μm.

diameter particles, 30% would be expected to survive Mars atmospheric entry unmelted. Micrometeorites in this size range which have survived atmospheric entry unmelted are rare in the Earth collections. A comparison of the fraction of micrometeorites surviving atmospheric entry at Earth and at Mars for 10-, 100-, and 1000-μm-diameter particles is shown in Figure 4. Since these larger particles are more likely to sample different sources [*Flynn*, 1989; *Zook and McKay*, 1986] than the smaller micrometeorites collected at Earth in the cosmic dust sampling program, 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 μm in Figure 5. 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 g/cm^3, consistent with the range of 0.7-2.2 g/cm^3 measured for the smaller micrometeorites recovered from the Earth's stratosphere [*Fraundorf et al.*, 1982]. The results of these calculations are reported in Table 2. 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.

Atmospheric entry simulations, using the method described by *Flynn* [1989], indicate that for all entry angles and for Mars atmospheric entry velocities below the solar system escape velocity particles from 10 to 1000 μm in diameter are all slowed below 1 km/s long before hitting the surface of the planet. Thus all particles in the peak of the micrometeorite mass distribution will be at their settling terminal velocities when striking the surface. These velocities are slow enough to insure their immediate survival. The possibility that micrometeorites or 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. However, on Earth, millimeter size fragments of meteoritic material, both unmelted and melted, have been recovered from late Pliocene deep-sea sediments [*Brownlee et al.*, 1982], demonstrating that survival is possible on Earth for at least several million years.

TABLE 2. Particles Surviving Mars Atmospheric Entry Unmelted

Diameter Range, μm	Upper Estimate, particles m^{-2} yr^{-1}	Lower Estimate, particles m^{-2}yr^{-1}
16-12	2.3×10^4	1.1×10^3
12-27	7.8×10^3	3.7×10^2
27-58	1.8×10^3	8.4×10^1
58-124	4.6×10^2	2.1×10^1
125-268	9.3×10^1	4.3
269-576	7.8	3.6×10^{-1}
577-1240	4.2×10^{-1}	1.6×10^{-2}
1241-2680	9.0×10^{-3}	4.1×10^{-4}
2681-5760	9.6×10^{-5}	4.5×10^{-6}

Direct Collection

To illustrate the collection possibilities, we calculate the expected concentration of micrometeorites in a soil whose planetary average production rate is 1 m/b.y. The concentrations obtained can then be scaled to other assumed soil production rates by multiplying by (1 m/b.y.)/(production rate). Table 3 shows the number of unmelted micrometeorites in each size range expected in an average 10-g Mars soil sample. Since these micrometeorites may sample a different parent population than the smaller particles recovered from the Earth's stratosphere, the returned Mars soil samples may offer a significant new resource for the study of micrometeorites.

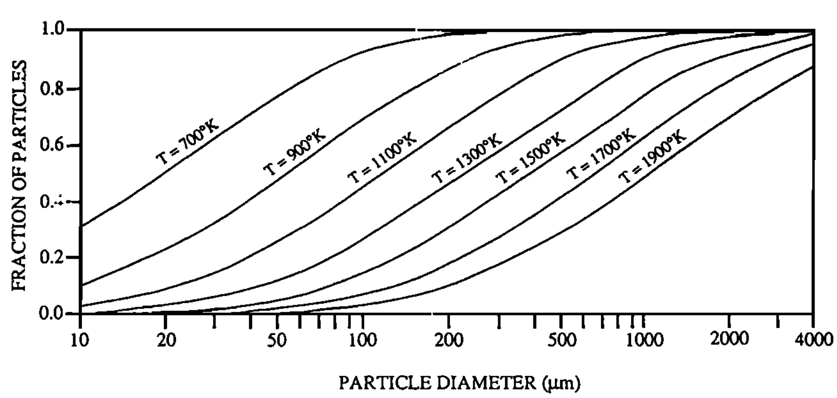

Fig. 5. Mars atmospheric entry temperature distribution for particles having the Mars entry velocity distribution shown in Figure 2. Particles have a density of 1 g/cm^3 and a thermal emissivity of 1.

TABLE 3. Number of Unmelted Micrometeorites Expected in 10-g Average Soil Sample

Diameter Range, µm	Upper Estimate	Lower Estimate
6-12	4.0×10^8	1.1×10^7
12-2	1.3×10^8	3.7×10^6
27-58	3.1×10^7	8.4×10^5
58-124	8.0×10^6	2.1×10^5
125-268	1.6×10^6	4.3×10^4
269-576	1.3×10^5	3.6×10^3
577-1240	6.0×10^3	1.6×10^2
1241-2680	1.5×10^2	4
2681-5760	1.6	< 1

Assumes an planet-wide average soil production rate of 1 m/b.y.

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, particularly magnetite, on atmospheric entry [*Brownlee*, 1985]. The extent to which magnitite would be produced on atmospheric entry into the oxygen-poor atmosphere is unknown, as is the abundance of indigenous magnetic minerals in the Mars soil. However, 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.

Magnetic particles were separated from the Martian soil and airborne dust by the Viking landers. Results from Viking 1 and Viking 2 are consistent with about 1-7% of the soil at each site being strongly magnetic, with spectral indications that the magnetic mineral might be magnetite [*Hargraves et al.*, 1976]. The fraction of this magnetic material which is meteoritic is unknown.

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.

Noble Gases and Hydrogen

The micrometeorites collected at Earth, because of their small size, contain large concentrations of solar wind implanted ions, particularly the noble gases [*Hudson et al.*, 1981; *Rajan et al.*, 1977] and likely hydrogen. These solar wind species, carried into the Martian regolith by the micrometeorites, may also perturb the bulk chemical abundances.

The ratio of cosmic ray induced tracks to spallogenic noble gasses in soil samples from Mars has been proposed by *Arvidson et al.* [1981] as a sensitive indicator of the average atmospheric shielding experienced by the crystal fragments in the soil. They suggest that in layered soil samples the tracks and spallogenic noble gases would serve as an indicator of temporal variations in the atmospheric density. Their calculations assume the noble gas inventory in the Martian regolith is limited to adsorbed Martian atmospheric gases and in situ derived cosmogenic gases [*Arvidson et al.*, 1981]. However, the cosmic dust particles collected from the stratosphere of the Earth contain large abundances of solar wind implanted gases [*Rajan et al.*, 1977; *Hudson et al.*, 1981] and solar flare tracks [*Bradley et al.*, 1984]. Care will need to be taken to distinguish indigenous Martian crystals from those added by micrometeorites. In addition, solar wind could complicate the measurements proposed by *Arvidson et al.* [1981]. We have used our cosmic dust accretion rates to infer the addition rates of the noble gases to the surface of Mars.

We estimate ^{20}Ne, ^{36}Ar, and ^{132}Xe addition rates as well as an upper limit of the ^{84}Kr addition rate by taking the gas concentrations determined for cosmic dust collected from Earth's stratosphere [*Hudson et al.*, 1981] as representative of 10-um-diameter particles at Mars. The gas concentrations in particles of other sizes are scaled with the reciprocal of particle radius, as appropriate for a surface correlated component. The ^{4}He addition rate was obtained in the same manner, using the ^{4}He mean concentration in stratospheric cosmic dust from *Rajan et al.* [1977]. The release temperature of noble gases and hydrogen from these particles is unknown, but the gas is retained by 10-µm particles on Earth atmospheric entry. We have assumed that all gas is retained in those particles which we have calculated to survive entry. The expected noble gas additions to the Mars soil from infalling micrometeorites are given in Table 4.

Hydrogen has been discussed as an important resource for space development. We use our cosmic dust accretion calculations to infer the addition rate of ^{1}H to the Martian

TABLE 4. Hydrogen and Noble Gas Addition to Martian Soil

	High Estimate	Low Estimate
^{1}H	1×10^{-5}	8×10^{-7}
^{4}He	3×10^{-6}	2×10^{-7}
^{20}Ne	2×10^{-8}	8×10^{-10}
^{36}Ar	2×10^{-9}	1×10^{-10}
^{84}Kr	$< 2 \times 10^{-11}$	$< 8 \times 10^{-13}$
^{132}Xe	3×10^{-12}	2×10^{-13}

Values in cm^3 STP m^{-2} yr^{-1}.

surface. Since the noble gases in these particles exhibits an elemental abundance pattern characteristic of solar wind [*Hudson et al.*, 1981], we have used the solar wind ratio of $^{1}H/^{4}He \sim 4$ to infer the ^{1}H addition rate.

Martian Agglutinates

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. Significant agglutinate production could only have occurred on Mars in an era in which the Martian atmosphere was considerably less dense that in the present era. No evidence exists for such an era. However, many types of impact glasses would be expected from larger impacts, and some of these glasses may resemble lunar agglutinates in some respects.

Martian Soil Maturity

Gault and Baldwin [1970] have estimated a minimum impact crater size of 50 m, 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 m 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 g 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-m 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. In the event that there were major impacts, dispersing a planet- wide layer of meteorite material, such as the impact associated with the K-T event on Earth [*Alverez et al.*, 1980], marker layers may also be present on Mars which could help establish a chronology of soil deposition.

CONCLUSIONS

Micrometeorites in the 10^{-7} to 10^{-3} g mass range should be a major contributor to the meteoritic input on Mars. 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 in the 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 *Clark and Baird* [1979] and *Boslough* [1988] that the Mars soils analyzed by Viking could be 40% meteoritic. Mars lander measurements of the Ni and/or Ir abundances in the soils should constrain the meteoritic component of those soils.

A direct spacecraft measurement of the flux of micrometeorites at Mars, preferably in the 50-μm and above size range, would provide a calibration of the meteoritic mass infall rate. This coupled with a measurement of the mean meteoritic concentration in the soils would provide a strong constraint on the soil production rate on Mars.

Unlike the Earth, where most particles above 10^{-6} g 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 first returned soil samples from Mars should provide the opportunity for recovery and analysis of unaltered micrometeorites larger than any sampled on earth. Since 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, micrometeorites recovered from soil of Mars may provide a new resource for understanding the origin and evolution of the solar system.

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G. J. Flynn, Department of Physics, State University of New York at Plattsburgh, Plattsburgh, NY 12901.

D. S. McKay, SN14, NASA Johnson Space Center, Houston, TX 77058.

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