Reports

Age of Craters on Mars

Abstract. *The rate of crater formation on Mars is calculated to be about 25 times higher than that on the Moon. The crater density observed by Mariner IV points to an age only one-sixth that of the lunar maria, or 300 to 800 million years. Hence no conclusions can presently be drawn from these photographs concerning the early Martian environment.*

Mariner IV has shown that the crater density on Mars is comparable to that on the Moon. Leighton *et al.* (*1*) have therefore proposed that the surface of Mars must be as ancient as that of the Moon—perhaps 2 to 5 $\times 10^9$ years old. From the absence of visible remnants of rivers and oceans, and from the low erosion rates implied, they argue that Mars cannot have had a dense atmosphere or liquid water in the form of streams or oceans since its surface formed. These conclusions appear to rest on the tacit assumption that cratering rates on Mars and the Moon are equal. Let us examine this assumption.

The moon is exposed to two types of large objects: comets and asteroids of the Apollo group, which cross the orbits of the Earth and Mars. The Apollo asteroids, having lifetimes against planetary capture as short as 10^8 years, are obviously replenished from some outside source. Some of them appear to be extinct nuclei of short-period comets, while others are asteroids deflected into terrestrial space during close encounters with Mars. Thus we can confine our discussion to the two primary sources: asteroids and comets.

Table 1. Impacts on Mars, Earth, and Moon by Mars asteroids. The fate of each asteroid was followed through 1000 sequences of repeated close encounters with the planets.

Family*	Impacts per 1000 runs (No.)		Ratio of impacts per unit area,
	Mars	Earth	Mars/Moon
5	169	33	30.2
29	86	30	21.7
30	92	22	24.1

* Asteroids representing each family were: 5, 1310 Villigeria; 29, 1134 Kepler; 30, 1036 Ganymede. Impacts on Venus and Mercury occurred with the following frequency: 1310 Villigeria, 31 and 8; 1134 Kepler, 29 and 7; 1036 Ganymede, 20 and 2. Nearly all remaining histories ended in ejection from the solar system by Jupiter.

Given the present distribution of asteroids, what will be the relative rate of capture by Mars and by the Moon? The bombardment rates have been estimated by Öpik in his classic papers on collision probabilities with the planets (*2, 3*). One of us has shown, however, that repeated deflections during close encounters with the planets can cause serious changes in the orbits and hence collision probabilities (*4*). The history of small bodies in interplanetary space is therefore best followed by a Monte Carlo calculation, in which a computer traces the fate of an object through a series of deflections to its final capture (*4*).

Two possible asteroidal origins have been considered: (i) the present Mars-crossing asteroids and (ii) objects ejected from the inner asteroid belt. Most Mars asteroids belong to three Hirayama families: groups with similar orbital elements that have resulted from the breakup of a single parent asteroid (*5*). Accordingly, one representative asteroid was chosen from each family, and 1000 sample histories were computed. Most of these histories ended in ejection from the solar system by Jupiter. Impacts on Mars and the Earth are listed in columns 3 and 4 of Table 1.

From these data the relative impact rates can be calculated. Let N be the number of impacts; F the impact rate per unit area; r the physical radius of the planet; and s its capture radius, enlarged by the effect of gravity. Using the subscripts M, E, and L for Mars, Earth, and Moon, we write for the impact rate on Mars relative to that on the Moon:

$$F_M/F_L = (N_M/N_E)\ (r_E/r_M)^2\ (s_E/r_E)^2$$

The term $(s_E/r_E)^2$ is the Earth's capture cross section, in units of its physical cross section. For the Moon, this factor is close to unity and therefore negligible. At a given flux, the Moon will have a lower impact rate than the Earth, by the factor $(s_E/r_E)^{-2}$.

For the Earth

$$(s/r)^2 = 1 + 0.1423/U^2$$

where U is the velocity of the impacting body in units of the Earth's orbital velocity (*3*, Eq. 8). The mean values of U_E for Earth impacts by the three asteroids in Table 1 are 0.480, 0.370, and 0.587, corresponding to capture cross sections of 1.59, 2.04, and 1.41, respectively. These values lead directly to the relative impact rates on Mars and the Moon in the last column of Table 1. All three rates are nearly the same. Since the masses, capture lifetimes, and capture probabilities of the three families are not very different from one another (*5*), the mean of the three rates, 25, should be representative of the entire class of Mars asteroids and the Apollo asteroids derived therefrom.

In addition, a number of shorter runs have been made, using all the Mars asteroids except Eros and the Apollo group. The mean values of $(s/r)^2$ are larger (U is smaller), in the region of 2 to 3. The calculated relative impact rates, however, are about the same.

A number of runs have also been made using asteroidal orbits derived by ejection from belt asteroids (*2*). The value of $(s/r)^2$ is again larger, around 3, and the relative impact rates are larger also, about 30.

Finally, the many runs made in the earlier work (*4*), using a wide variety of asteroidal starting conditions, have been examined. The range of calculated relative impact rates is from 15 to 40.

Obviously, asteroidal impacts on Mars are far more frequent than those on the Earth and Moon. Öpik made this point 14 years ago (*2*). A reasonable mean ratio is 25.

We now consider cometary impacts. Impacts on inner planets by comets crossing the orbit of Jupiter are exceedingly improbable. Virtually all short-period comet orbits cross Jupiter's orbit initially. They are far more likely to be captured or ejected by Jupiter or Saturn, on a time scale of about 10^6 years, than to strike one of the inner planets. Earlier Monte Carlo calculations gave only one impact on an inner planet in 1000 cases (*4*). The long-period comets have still higher probabilities of ejection. However, we know little about the total flux of comets.

Short-period comets with aphelia inside Jupiter's orbit have a better chance of being captured by the inner planets. Typically, they may spend 10^7 to 10^8 years in the inner solar system before being captured or ejected, though they remain luminous for only a small fraction of this time. Those dead comets that do not disintegrate into meteor streams (an unknown and possibly large fraction) contribute to the population of the Apollo group.

It is possible to distinguish cometary from asteroidal members of the Apollo group. A plot of their velocities with respect to Mars and the Earth shows a clear division into two groups. Of the eight known Apollo asteroids, six lie within the range of meteorites, asteroidal meteors, and "computed meteorites" derived from Mars asteroids. The remaining two, Adonis and Icarus, are highly eccentric, high-velocity objects lying in the range of cometary meteors, well outside the preceding group. Although the velocity does not remain strictly invariant in repeated encounters with the planets (particularly if more than one planet is involved), Monte Carlo calculations show that transfers to and from the high-velocity group are rare. Hence it seems safe to classify Adonis and Icarus as cometary objects, and most or all of the remaining six as asteroidal ones.

A third cometary object is Encke's comet, the only live comet not crossing the orbit of Jupiter. Though it is disintegrating into a meteor stream (Taurids) and may not last long enough to strike a planet, it is nonetheless included to improve statistics on the cometary component.

Numerically, cometary objects thus comprise one-third of the Apollo group. They will not necessarily contribute to the lunar cratering rate in the same proportion, however, since the cratering rate depends on capture probability, lifetime against capture, impact velocity, and mass. The first three parameters were again determined by a Monte Carlo calculation, in which 200 histories were computed for each object (Table 2). The potential contribution of each Apollo asteroid to the crater density on the Moon can be expressed as crater area produced per unit time R:

$$R = \frac{N_E A\, r_L^2}{200(s_E^2/r_E^2)\, r_E^2 t_E}\ \text{km}^2/10^6\ \text{years}$$

Here N_E is the number of Earth impacts and t_E is the harmonic mean life against Earth capture, both from Table 2. A is the crater area produced in a lunar impact; it was calculated from Öpik's eq. 5 (*6*). Densities of 3.6 and 0.3 g/cm^3 were assumed for asteroidal and cometary members of the Apollo group. Velocities were taken from Table 2.

The combined cratering rate for the asteroidal members of the Apollo group is 4.65; for the cometary members, 0.39 km^2/10^6 years. Obviously, the cometary contribution is small and would remain so even if a higher value for the density were used. It must be recognized, of course, that the present census of Apollo asteroids is incomplete (*3, 7*) and that cometary objects may be more prominent among the undiscovered members of this group. To shift the balance appreciably, several cometary objects of diameter equal to or greater than 10 km would be required. But such objects, if present, should have been detected. In Öpik's estimate, the search for Apollo asteroids was done to a completeness of more than 80 percent for objects larger than 3.4 km in diameter (*3*). It does not seem likely that the contribution of comets to the lunar craters exceeds 25 percent at the most.

The crater distribution plot of Leighton *et al.* was linear down to a diameter of 20 km. Accordingly, only craters of this size or greater will be considered. On Mars, there were 25 such craters in an area of 0.67 × 10^6 km^2, or 37 craters per 10^6 km^2. Corresponding figures for the maria and uplands of the Moon are given in Table 3. If we take 25 for the relative impact rate of asteroidal objects, and if 25 percent of the lunar craters are assumed to be cometary, as a generous upper limit, the overall rate drops to 20. Accordingly, if the Martian surface were as old as the lunar maria, there ought to be 11 × 20, or 220, craters per 10^6 km^2, as opposed to the observed value of 37. This discrepancy points to an age only one-sixth as great. If the age of the lunar maria is taken to lie between n and 4.5 × 10^9 years, then, if the impact rate was constant during this time, the Martian craters are on the order of 300 to 800 million years old.

Such a low age implies a significant erosion rate. Possibly dust storms at the present level can account for it. If not, other processes of crater oblit-

Table 2. Impacts by Apollo asteroids.

Name of object	Diameter (km)	Impacts per 200 histories (No.)*				Mean life† (10^6 yr)	Mean velocity‡ (km/sec)	Cratering rate on Moon (km^2/10^6 yr)
		Mars	Earth	Venus	Mercury			
Asteroidal objects								
Apollo	1.0		24	31	2	3.45	13.6	0.122
Hermes	0.4	1	30	49	4	2.34	13.0	.032
Geographos	3.2	1	32	30	6	3.83	11.9	1.123
1948EA	6.3		13	11	1	11.4	15.0	0.945
1948OA	4.8	3	33	36	4	5.01	12.6	2.251
1950DA	1.8	4	28	19	4	8.92	13.6	0.180
Cometary objects								
Adonis	1.3		18	21	3	1.76	24.9	.305
Comet Encke	1.7	1	10	9	5	16.3	29.1	.041
Icarus	1.4	4	30	45	20	27.9	28.9	.048

* Most of the remaining histories terminated in ejection from the solar system, or capture by the Jovian planets. Vaporization due to passage within 0.02 astronomical units of the sun occurred mainly in the cometary objects: Adonis, 4; Encke, 3; Icarus, 24. † Harmonic mean life for Earth captures. ‡ Mean velocity for impacts on Earth or Moon, not including gravitational attraction of either body.

Table 3. Frequency of craters greater than 20 km in diameter on Moon and Mars.

Region	Craters per 10^6km^2 (No.)	Reference
Moon (maria)	11	(*7*)
Moon (uplands)	193	(*7*)
Mars (observed)	37	(*1*)
Mars (expected since formation of lunar maria)	220	

eration must be postulated, such as isostatic adjustment or tectonic processes. Alternatively, the surface may be effectively "saturated" for craters of this size range by multiple, overlapping impacts. In any event, the crater density on Mars no longer precludes the possibility that liquid water and a denser atmosphere were present on Mars during the first 3.5 billion years of its history.

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Mars: Age of Its Craters

Abstract. *If the craters on Mars were formed by asteroidal particles having spatial distributions independent of asteroid size, and if both spatial distributions and total numbers are independent of time, the average age of the craters may be less than 300 million years.*

The Mariner IV photographs of Mars show a large number of craters similar in number density to lunar craters (*1*). Mainly on the basis of this similarity, Leighton *et al.* suggested that these features of the Martian surface are very old—2 to 5 × 10^9 years (*1*). They further suggested that Mars might be the "best—perhaps the only—place in the solar system still preserving clues to primitive organic development . . . "(*1*).

We now suggest that the crater density is possibly much too low for Mars to be "primitive" and that the age of the craters may be more of order of 300 million years or less.

This estimate is based on the following assumptions:

1) The primary process leading to the formation of craters of the appropriate size (4 to 120 km) both on the Moon and Mars is collision with asteroidal bodies.

2) The spatial distribution of asteroids, including their total number, has been fairly constant over time comparable to the lifetime of a lunar crater.

3) The spatial distribution of asteroids is the same for crater-making asteroids as for the larger, catalogued asteroids, though the total numbers may differ.

Facts relating to these assumptions have been reviewed by Shoemaker *et al.* (*2*).

The distribution of catalogued asteroids, plus assumption 3, indicates that crater-making asteroids are much more numerous near Mars than near the Moon. Using assumption 2, we conclude that the observed Martian craters are younger by a factor of 15 or more.

Shoemaker (*3*) is reported to have reached similar conclusions (age ratio of about 1/10).

A first step in calculating collision rates is the determination of the probability that a given asteroid having perihelion distance less than, and aphelion distance greater than, the mean solar distance of Mars, 1.52 astronomical units (AU), will collide with Mars (for our purposes the Martian orbit can be taken to be circular and lying in the ecliptic).

No knowledge of the other orbital parameters is assumed, except that the individual asteroid is a member of a sample of asteroids having a distribution function for these other orbital parameters, and that most asteroid orbits have low (<20°) inclination to the ecliptic.

Mars sweeps out a torus in space. The collision probability per crossing of a sphere containing Mars's orbit is the product of the probability that the unperturbed asteroid orbit will pass through the torus swept out by Mars, $P\{\text{intersection}\}$ or $P\{i\}$, and the probability that, given this intersection, Mars will be in the proper location in its orbit to ensure a collision, $P\{\text{collision} \mid \text{intersection}\}$ or $P\{c|i\}_M$. A similar relation holds for the Moon.

The ratio between the collision rate of crater-making asteroids with Mars (S_M) and the collision rate of such asteroids with the Moon (S_m) can be put in the following (approximate) form:

$$\frac{S_M}{S_m} \approx \frac{(2/T_M)\, N_M\, P\{i\}_M\, P\{c|i\}_M}{(2/T_m)\, N_m\, P\{i\}_m\, P\{c|i\}_m} \quad (1)$$

where T is some average period of the asteroids, N is the total number of crater-making asteroids having distances of perihelia less than the mean distance of Mars (N_M) or the Moon (N_m) from the Sun, and the terms containing P are suitable averages over the asteroid distribution.

The factor $2/T$ comes from the fact that almost all known asteroids having perihelia at less than 1.52 (or 1.00) AU have aphelia greater than 1.52 (or 1.00) AU, and so cross a sphere at 1.52 (or 1.00) AU exactly twice per orbit.

The term $P\{i\}_{M,m}$ is dependent on the distribution of asteroids in inclination at Mars and the Moon. There is evidence that, where statistics are good ($r > 1.8$ AU), the asteroidal distribution in inclination is independent of distance from the Sun (*4*). We assume that this independence extends down to 1.0 AU. Then it can be shown that:

$$\frac{P\{i\}_M}{P\{i\}_m} = \frac{r_M/R_M}{r_m/R_m} \quad (2)$$

where R is the orbital radius and r is the radius of the body.

The term $P\{c|i\}_M$ is a complicated function of the angles between the velocity vectors of Mars and the asteroids at intersection, and the collision cross section. We assume that distributions of asteroid-orbit angles are comparable at Mars and the Moon. Then the angle-dependence of the ratio of $P\{c|i\}$ can be shown to be less than 10 percent. Neglecting this angle dependence, the ratio is:

$$\frac{P\{c|i\}_M}{P\{c|i\}_m} = \frac{\sigma_M/r_M R_M}{\sigma_m/r_m R_m} \quad (3)$$

where σ is the collision cross section.

The cross sections can easily be calculated. Conservation of energy and angular momentum for the collision yields the cross section for Mars:

$$\frac{\sigma_M}{\pi r_M^2} = 1 + \frac{G m_M/r_M}{(v_{M,a})^2} \quad (4)$$

where $v_{M,a}$ is the magnitude of the