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 $P\{\text{i}\}$, 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 $P\{\text{c}|\text{i}\}_{\text{M}}$. 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:

$$\frac{S_{\text{M}}}{S_{\text{m}}} \approx \frac{(2/T_{\text{M}})\, N_{\text{M}}\, P\{\text{i}\}_{\text{M}}\, P\{\text{c}|\text{i}\}_{\text{M}}}{(2/T_{\text{m}})\, N_{\text{m}}\, P\{\text{i}\}_{\text{m}}\, P\{\text{c}|\text{i}\}_{\text{m}}} \quad (1)$$

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 $P\{\text{i}\}_{\text{M,m}}$ 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:

$$\frac{P\{\text{i}\}_{\text{M}}}{P\{\text{i}\}_{\text{m}}} = \frac{r_{\text{M}}/R_{\text{M}}}{r_{\text{m}}/R_{\text{m}}} \quad (2)$$

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

The term $P\{\text{c}|\text{i}\}_{\text{M}}$ 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 $P\{\text{c}|\text{i}\}$ can be shown to be less than 10 percent. Neglecting this angle dependence, the ratio is:

$$\frac{P\{\text{c}|\text{i}\}_{\text{M}}}{P\{\text{c}|\text{i}\}_{\text{m}}} = \frac{\sigma_{\text{M}}/r_{\text{M}}R_{\text{M}}}{\sigma_{\text{m}}/r_{\text{m}}R_{\text{m}}} \quad (3)$$

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:

$$\frac{\sigma_{\text{M}}}{\pi r_{\text{M}}^2} = 1 + \frac{G m_{\text{M}}/r_{\text{M}}}{(v_{\text{M,a}})^2} \quad (4)$$

where $v_{\text{M,a}}$ is the magnitude of the relative velocity between the asteroid and Mars and m is mass. Neglecting Earth-scattered lunar collisions, a like formula holds for the lunar cross section.

For Mars, $Gm_M/r_M = 12.8$ km^2/sec^2; for the Moon, $Gm_m/r_m = 2.9$ km^2/sec^2. The majority of asteroids which pass the orbits of Mars or the Moon do so near perihelion and have semimajor axes of the order of 2.4 AU. The minimum relative velocity such bodies can have relative to Mars and the Moon is:

$$(v_{M,a})_{min} = 4 \text{ km/sec}$$
$$(v_{m,a})_{min} = 8 \text{ km/sec}$$

Clearly, the term in Eq. 4 involving velocity is negligible for the Moon, and is smaller than unity for Mars, even under the most favorable conditions of asteroidal inclination and other orbital parameters. It is reasonable to drop this term, then, noting that the actual Martian cross section may be somewhat larger than the approximation.

By eliminating the velocity dependence in the cross sections it is possible to set down the ratio of collision rates per unit area $S/4\pi r^2$:

$$\frac{S_M/4\pi r_M^2}{S_m/4\pi r_m^2} \simeq \frac{N_M}{N_m}\,\frac{T_m}{T_M}\,\frac{R_m^2}{R_M^2} \qquad (5)$$

In order to evaluate the ratio N_M/N_m, a plot of the number of catalogued asteroids with distances of perihelion in a fixed range Δr_p versus r_p has been prepared and is shown in Fig. 1. Two asteroidal samples were chosen. For the circles a sample consisting of the first 1563 numbered asteroids is used; the data were compiled by Cincinnati Observatory (*5*). For the crosses the first 1563 numbered asteroids plus about 2000 unnumbered asteroids, given by Cincinnati Observatory (*6*), plus a few others (Adonis, Apollo, Hermes, Geographos, Betulia) constitute the sample.

We consider the points lying below $r_p = 1.3$ AU as not representative because of strong observational bias (smaller asteroids having low perihelia can be more easily observed). This bias can be shown to be especially strong for asteroids having perihelia less that 1.1 AU. For example, in published data (*6, 7*) no g-value (normalized magnitude) is catalogued for such asteroids less than magnitude 17.0 except Geographos ($g = 15.9$), while near Mars—for example, $1.5 < r_p < 1.6$ AU—the catalogue average of the numbered asteroids is $g = 13.4$.

Therefore, to obtain the ratio $(N_M/N_m)_{observed}$, the points below $r_p = 1.3$ AU are ignored, and straight lines are drawn through the points from $r_p = 1.8$ to 1.3 AU and extrapolated to $r_p = 0$.

Total numbers of catalogued asteroids having perihelia within the Martian or the lunar orbit are then found from integration. Using assumption 3, that the ratios of the numbers of crater-making asteroids are the same as the ratios of the numbers of catalogued asteroids, we obtain estimates for N_M/N_m for each sample. For the numbered sample,

$$N_M/N_m = 120 \qquad (6a)$$

For the larger sample,

$$N_M/N_m = 36 \qquad (6b)$$

The next ratio appearing in Eq. 5 is T_m/T_M. Most asteroids have periods between 3.0 and 4.5 years, and no significant trend toward changes in period with distance of perihelion below $r_p = 1.8$ AU is seen, though statistics are poor. Therefore we take the ratio T_m/T_M to be unity.

Substituting these values of T_m/T_M and N_M/N_m into Eq. 5, we obtain two values for the ratio of collision rates of crater-making asteroids per unit surface area. For the numbered sample,

$$\frac{S_M/4\pi r_M^2}{S_m/4\pi r_m^2} \simeq 50 \qquad (7a)$$

For the larger sample,

$$\frac{S_M/4\pi r_M^2}{S_m/4\pi r_m^2} \simeq 15 \qquad (7b)$$

The larger collision rate on Mars indicates that more craters were made during a given time interval than on the Moon. Since average impact velocities on Mars are less by only a factor of about 2 than average impact velocities on the Moon, and since crater diameter is only weakly dependent on impact velocity ($d \propto v^{0.6}$), the rate of

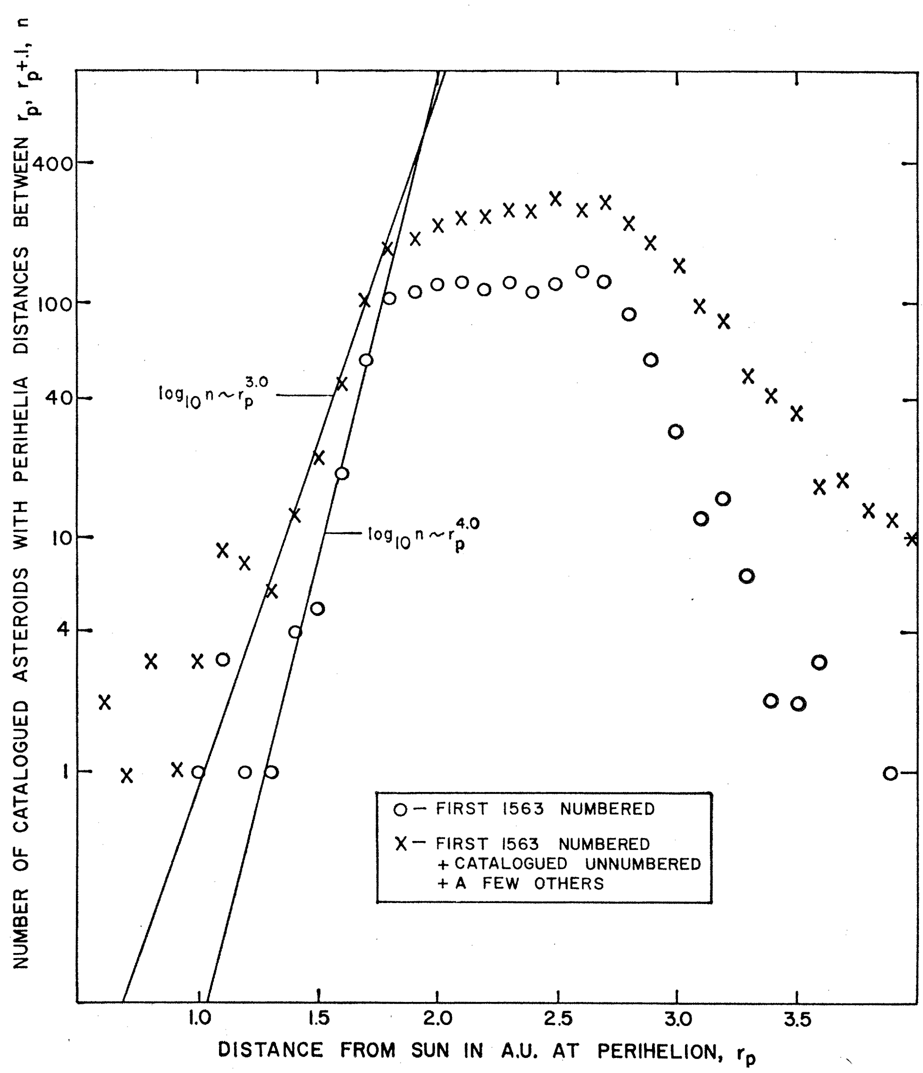

Fig. 1. Distribution of asteroids in perihelia distances. One straight line is fitted to the x's between $r_p = 1.3$ and $r_p = 1.8$ AU; the other is fitted to the o's in the same range.

crater formation can be taken to be directly proportional to the collision rates.

The observed craters of comparable size are equally dense on Mars and the Moon (*1*). The observed craters on Mars are, therefore, only the last few percent to be formed during the lifetime of a lunar crater. If the rate of formation has been constant over this time interval (assumption 2), then the ratio of the age of an observed Martian crater to that of an observed lunar crater is inversely proportional to the ratio of collision rates per unit area. With the most conservative number for this ratio from Eq. 7, 15, the average age of the Martian craters is only about 1/15 that of lunar craters. Since the lunar craters are certainly no more than 5 billion years old, this places an upper limit to the age of Martian craters of about 300,000,000 years, which is considerably less than the 2 to 5 $\times$ 10^9 years suggested by Leighton *et al.* (*1*).

Aside from difficulties in extrapolating asteroidal data to lunar distances, which can lead to substantial errors, the whole case for concluding that the Martian craters are relatively young hinges on the three assumptions we have stated. Since the validity of these assumptions (especially the second) seems unlikely to be checked in the near future, this study must be looked on as merely an alternative to the earlier suggestions, and not regarded as a definite prediction of the age of Martian craters.

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Mars: An Estimate of the Age of Its Surface

Abstract. *Intercomparisons of crater counts on Mars and the Moon suggest that the age of the visible Martian surface is approximately 340 to 680 million years.*

The recent Mariner IV pictures show that Mars has a remarkably moonlike surface, as was predicted in 1949 (*1*). It is pitted with numerous craters which appear to duplicate the familiar lunar structures and which probably were produced by meteorite impact.

The craters vary from 3 to 120 kilometers in diameter in the small area of Mars photographed. (The area of Mars covered by the photographs is 0.67 $\times$ 10^6 km^2.) Crater counts (*2*) show that, over most of the range of diameters, the plot of cumulative numbers of craters N_c larger than a given diameter versus diameter D may be represented by a straight line on a log-log scale (Fig. 1). The equation of this line is

$$\log N_c = 4.000 - 2 \log D_{\mathrm{km}} \quad (1)$$

If Mars is like the Moon, the tailing off of the plot in the small-crater end is not real but measures the difficulty of identifying small craters.

The slope of the line, -2, is almost exactly the same as that found from counts of lunar craters.

The counts of lunar craters have been interpreted to suggest that the lunar maria are about 2 $\times$ 10^9 years old (*3*). An intercomparison of crater frequencies may yield some information about the age of the Martian surface. The equation for the cumulative frequency of craters on the terrae portion of the Moon is

$$\log N_c = 3.604 - 2.120 \log D_{\mathrm{mi}} \quad (2)$$

and that for the lunar maria is

$$\log N_c = 1.903 - 1.707 \log D_{\mathrm{mi}} \quad (3)$$

The crater diameter is given in miles in Eqs. 2 and 3, and the area considered is 10^5 km^2.

The lower slope in Eq. 3 may be simply statistical. Two or three fewer large craters on the maria would permit the line to have about the same slope.

From the present rate at which objects of different masses are striking Earth, the correction factor to the Moon, the size of crater which a given meteorite can produce if it strikes at a typical velocity, and the observed numbers of craters on terrae and maria, we may derive an approximate probable age for the maria (*3*). The essence of the argument is as follows.

Hawkins has given the highest estimate of the frequencies with which large iron and stone meteorites are now striking Earth (*4*). These data were converted into the numbers of meteorites which would strike the Moon in 10^9 years and within an area of 10^5 km^2. If these results are divided into the counted lunar crater abundances from Eqs. 2 and 3, we find a ratio of about 180 for the terrae areas and 10 for the maria.

If the rate of infall of such objects has fluctuated wildly in the past, we can draw no conclusions about the age of the lunar maria, but if the rate has continually declined, as seems probable, from the Moon's beginning to the present, like a sort of compound interest problem in reverse, we may use the equation

$$A = P(1 + r)^n \quad (4)$$

where A is the relative number of objects originally (181 approximately), P is the remaining number of particles ($=1$), n is the number of billion years before the present, and r is -0.685.

If A is 10, as determined from the maria, then the age of the maria is 2 $\times$ 10^9 years.

Unless the average rate of infall on the Moon over the last 10^9 years has been at least 10 times higher than the highest estimate we can now give, the maria cannot be as young as 10^9 years. According to many lines of argument (*3, 5*), they cannot approach the age of the Moon.

With this background, we may now return to Mars. Equation 1 may be converted from kilometers to miles and to an area of 10^5 km^2:

$$\log N_c = 2.761 - 2 \log D_{\mathrm{mi}} \quad (5)$$

Intercomparison of Eqs. 2 and 5 shows that the Martian craters are less abundant than the craters on the lunar terrae, per unit area, by a factor of 7. If we divide 180 by 7, we get approximately 26. With $A = 26$, we may solve Eq. 4 for n, which becomes -2.8. This process implies that if the fluxes of large masses which have struck Mars and the Moon in the past are the same and the age of the lunar maria is