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Mars: A Standard Crater Curve and Possible New Time Scale

Cratering links to lunar time suggest that Mars died long ago.

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One major goal in planetary science is to determine the chronology of development of the surfaces of the terrestrial planets, especially our neighbor Mars. Whereas for the moon we have rock specimens whose ages have been determined radiometrically, we will not have any way to analyze the ages of martian rocks in the near future. Nevertheless, the surface of Mars has been mapped extensively by the Mariner 9 and recent Viking missions. These pictures allow some qualitative classification of old or young features according to their stratigraphic relations and apparent degree of erosion. Fortunately—for the purpose of age determination from photographs—Mars is impact-cratered. Differences in impact crater frequencies at different sites reflect differences in age. Recently, two attempts have been made to determine absolute ages for Mars from its measured crater frequencies, based on extrapolations from the cratering chronology of the lunar surface (*1*, *2*). Unfortunately, a straightforward comparison of martian and lunar crater frequencies does not necessarily yield true ages: relative impact rates and the time dependence of the martian cratering rate are not known; and it is not certain whether the same meteoroid population bombarded both planets. Some of these questions are discussed by Hartmann (*1*) and Soderblom *et al.* (*2*).

No martian cratering time scale is better than the lunar-terrestrial one it refers to. Thus, before comparing the impact conditions on Mars with those in the earth-moon system, we will briefly review present knowledge of the cratering chronology in the earth-moon system.

Cratering Chronology in the Earth-Moon System

Four independent determinations of the cratering chronology in the earth-moon system may be found in the literature (*1–5*). We have compiled these data in Fig. 1, where crater frequencies per square kilometer are plotted against exposure ages of sites where the craters accumulated until today. The time dependence of crater frequency in the data sets of Baldwin (*3*), Hartmann (*1*, *4*), and Neukum *et al.* (*5*) in Fig. 1 appears similar. The absolute data agree within a factor of 2 to 3. In the first billion years after the formation of the lunar crust 4.4 to 4.5 billion years ago (*6*, *7*), the impact rate or number of craters as a function of time (dN/dt) dropped sharply. There are no crater frequency data for age-dated surfaces in the span 1 to 3 billion years. For the last 1 billion years, lunar crater frequencies have been measured (*8*) for structures whose ages have been very accurately determined (*9*). The terrestrial impact crater frequency data shown in Fig. 1 for the Canadian Shield area and other parts of North America are reduced to lunar impact conditions for gravitative acceleration and are compatible with the lunar data within a factor of 2 to 3. The terrestrial data are much more uncertain than the lunar data, as reflected by the large error bars. The data for the last 1 billion years together with the lunar measurements for an age of ≈ 3.2 billion years strongly suggest an impact rate varying at the most by a factor of 3 to 4 during that time. A nearly constant flux is indicated, especially in the last 1 billion years (*10*).

The crater frequency data of Soderblom *et al.* (*2*) in Fig. 1 do not seem to agree with those of the other authors for ages $\lesssim 3.5 \times 10^9$ years, differing by a factor of ≈ 5 from the data of Baldwin (*3*) and Hartmann (*1*, *4*) and a factor of ≈ 10 from those of Neukum *et al.* (*11*). In addition, there is a difference in radiometric ages for some of the same Apollo landing sites because of progress in age measurements and differences in interpretation of lunar rock ages (*12*).

The minor differences between the frequency data of Baldwin and Hartmann and those of Neukum *et al.* can be partly explained as follows. Crater frequency data are commonly obtained for different size ranges. To intercompare these data, it is necessary to apply a size distribution law. The lunar impact crater production size-frequency distribution (the undisturbed image of the meteoroid mass-velocity distribution) has been determined recently (*13*) and is displayed in Fig. 2 (*14–16*). All the data of Neukum *et al.* in Fig. 1 have been reduced by using this "calibration" or standard distribution to project the frequency measurements to the diameter D = 1 km intercept. Baldwin (*3*) and Hartmann and Wood (*16*) used $N \sim D^{-1.8}$ and $N \sim D^{-2}$, respectively, as calibration lines, which seem to be good approximations at larger sizes but are too flat in the 1-km size range. They usually reduced their frequency data to sizes larger than 3 km. For the 1-km size range they have included some data reported by others, especially for the

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younger Apollo sites. Applications of the slopes of −1.8 or −2 to those data in the kilometer size range or extrapolation from larger sizes ($D \geq 3$ km) would commonly result in values higher than those derived with the standard curve by a factor of about 2 or 3.

The overall picture we derive from Fig. 1 is the following. For ages of around 4 billion years all authors' data agree fairly well. For younger ages the discrepancies are as great as one order of magnitude. The data of Soderblom *et al.* differ the most, and we believe that this difference may reflect an error in the conversion (*11*) of their measurements to the published frequencies of craters 4 to 10 km in diameter. If the inconsistency between figures 1 and 14 in (*2*) is removed, their values fall close to those of the other authors.

On the grounds stated above we have elected to use the curves drawn as solid lines in Figs. 1 and 2 as the representation of lunar impact cratering. Choice of these curves has the added advantage for our martian correlations that they are derived in the same size range as the martian curves, by use of the same equipment and data reduction methods.

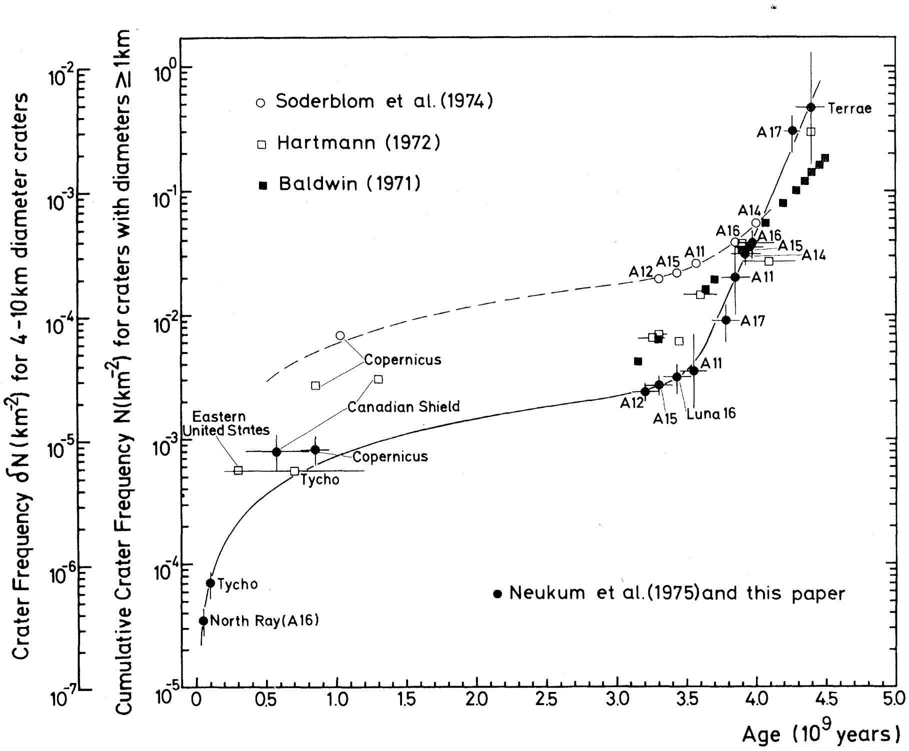
Martian and Lunar Production Size-Frequency Distributions

Before discussing the Mars models derived from different lunar data sets (*1–5*) and comparing them with a time scale derived from the lunar data (*17*), we will discuss the importance of a precise knowledge of the martian impact crater production size-frequency distribution in comparison to the lunar one shown in Fig. 2.

The lunar curve shows a characteristic steepening around a crater diameter of 2 km. This steepening was detected when the Surveyor and Lunar Orbiter photographs were investigated and was widely interpreted as due to an admixture of secondary craters produced by the larger primary ones (*2*). We do not agree with this interpretation. In our investigations (*8, 13*) we found that the lunar crater size distribution curve remained the same for crater counts on ejecta blankets, floors, or terrace deposits of younger (Eratosthenian and Copernican) lunar craters as well as on homogeneously cratered mare areas and a few light plains areas with ages ranging to more than 4 billion years. We excluded obvious secondary craters by applying criteria developed by Oberbeck and Morrison (*18*). The resulting general curve is the calibration distribution of Fig. 2.

The constancy in shape of the lunar curve regardless of distance to large craters (outside the discontinuous ejecta blanket) capable of producing secondary craters, and on the continuous ejecta blankets of large craters too young to have secondaries from other sources superimposed on them (such as Tycho), argues that the curve does not include significant numbers of secondary craters but represents the primary-production population. The constancy with time of the slope and inflection point of the standard lunar curve suggests that the size and velocity distribution of bodies impacting the lunar surface has not changed significantly over the last 4 billion years.

Whatever view is favored for the steep branch of the lunar crater size distribution, this part of the curve is very important for the derivation of a martian crater time scale based on the lunar one, because most of the lunar data have been obtained in this size range, for crater diameters between ≈ 500 m and ≈ 5



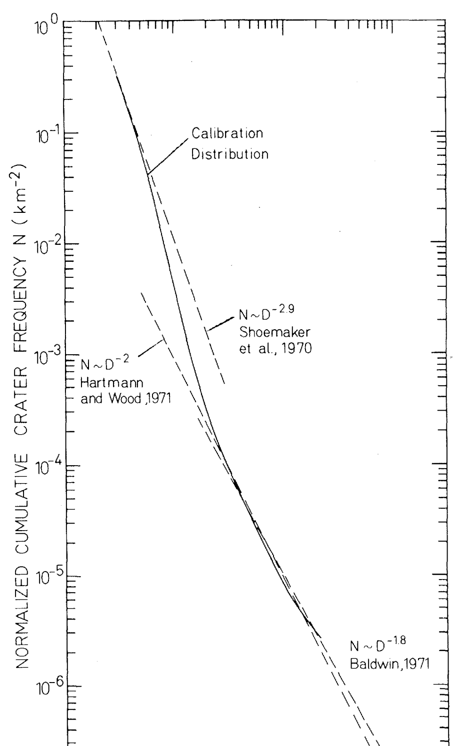


Fig. 1 (left). Lunar cratering chronology. Data are from Soderblom *et al.* (*2*), Hartmann (*4*), Baldwin (*3*), Neukum *et al.* (*5*), and this article. The two parallel scales on the ordinate are cumulative crater frequency [the number of craters equal to or larger than a certain diameter D (here D = 1 km) per unit area; compare Fig. 2] and frequency (the number of craters with diameters between 4 and 10 km per unit area). These scales are proportional (*35*). The lunar ages are those measured radiometrically for the Apollo lunar rocks (*12*), except ages > 4 billion years from Baldwin, which are inferred from morphological criteria. The terrestrial crater frequency data are reduced to lunar conditions, the ages from the terrestrial data (*4, 5*) are based on geologic estimates and radiometric measurements. Terrae are lunar highlands; the prefix A means Apollo. Fig. 2 (right). Lunar calibration curve, or production size–frequency distribution. These data (*13*) reconcile former linear distribution laws (also given) which partly contradicted each other. The steepening at small sizes (*15*) is confirmed and precisely determined.

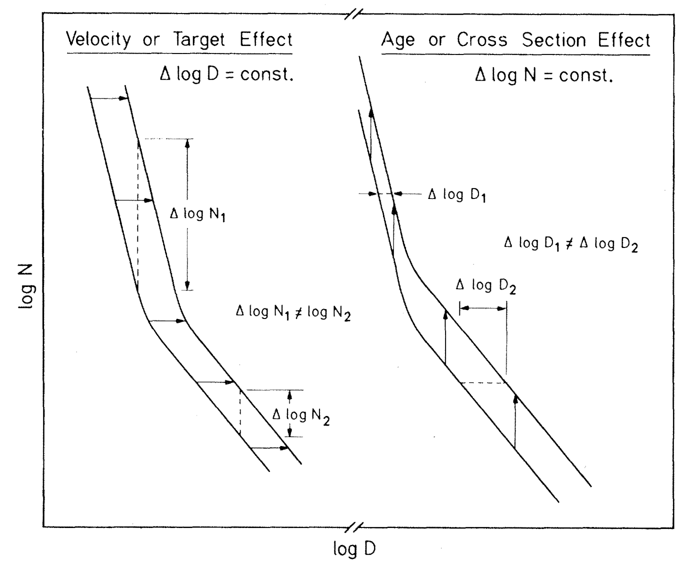
km. To compare martian with lunar crater frequency data, we have to know about the shape of the martian impact crater size distribution in this size range.

The martian crater size distribution is known to follow power law $N \sim D^{-2}$ in the size range from several kilometers to about 100 km (*1, 2, 19*), practically identical with the lunar case. At a diameter of about 2 km a steepening similar to that in the lunar case was detected (*2, 20*). These measurements were not sufficient to determine the martian production size distribution in this size range, although they indicated that it was not too dissimilar from the lunar one.

Before reporting new measurements, we wish to state what we can learn from an exact knowledge of the martian distribution curve in the size range where it steepens. Figure 3 shows such a steepening distribution in a somewhat simplified and exaggerated form. Different impact conditions on different planets will result in characteristic effects on a distribution of this form. Age effects—that is, similar ratios of exposure times of the surfaces to cratering—will result in similar ratios of crater frequencies at any diameter ($\Delta \log N$ = constant for the right half of Fig. 3). The same is true for different cross-section effects, in which slower meteorites are more easily deflected by a planet's gravity. This is equivalent to a difference in flux. These effects do not change the shape of the curve—that is, the crater frequency at some diameter in the steep part of the curve relative to the value at some diameter in the flat part of the curve. In other words, age differences and cross-section effects are such that the curves can be shifted vertically and should coincide. The shape of the curve, in terms of the diameter at which the inflection point occurs in Fig. 3, does not remain constant if the impact velocity is different on different planets, or if target properties have an effect on the sizes of the craters produced. Thus, even with the same meteoroid mass distribution, different (average) impact velocities on Mars and on the moon or different target properties will result in different crater sizes for the same projectile mass, and the shapes or inflection points of the curves for the moon and Mars will differ. The ratio of crater frequencies at two fixed diameter values in the steep and flat parts of the curve will be different, as seen in the left half of Fig. 3 ($\Delta \log N_1 \neq \Delta \log N_2$ for a diameter shift by a constant factor).

To derive a martian time scale by comparing martian crater frequencies with lunar ones, we have investigated the shape of the martian production size frequency curve in comparison with the lunar calibration distribution of Fig. 2 (*17*). The ideal conditions for measuring a standard curve are: a homogeneously cratered area of a large enough extent; adequate resolution of imagery; a single, well-defined time of surface origin; and the absence of resurfacing by processes other than impact cratering. In that this ideal cannot be met with the Mariner 9 imagery, the curve has been pieced together from a variety of areas and imagery scales.

Fig. 3. Effects of different impact conditions on a size distribution curve whose slope is different at different crater sizes; N is the cumulative number of craters with diameters greater than a given diameter D. Velocity or target effects cause the curve to shift left or right while maintaining a constant change in log D. The bend in the curve produces an inconstant ΔN for different diameters. For age or cross-section effects the curve shifts vertically and the reverse relations obtain.



The most homogeneous areas of high-resolution Mariner 9 imagery (B frames) were selected, and the corresponding lower-resolution A frames covering a large area surrounding the B frames were checked for quality of imagery and homogeneity of larger craters. Most areas proved to be inadequate for our purpose because they had experienced extensive resurfacing resulting in irregularities (bumps) in the distributions. These resurfacing processes have been extensively documented (*19, 21*). Details of our own measurements are given in (*17*).

The most homogeneous "test" areas we found with both high-resolution and low-resolution Mariner 9 coverage are Elysium Planitia (240°W, 30°N) and the Alba Patera volcano central cone area (110°W, 40°N). These measurements are displayed in Fig. 4, a and b, where the solid lines through the data represent a computer least-squares fit. This curve (*22*) through the Alba and Elysium points is the one we consider the best derivable

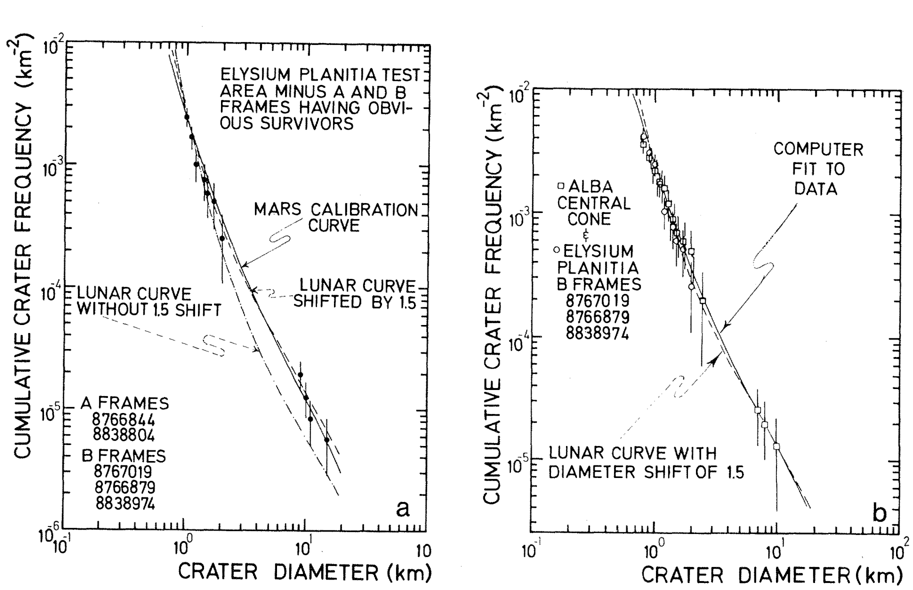


Fig. 4. (a) Test plot for Elysium Planitia after frames showing obvious survivor craters were eliminated. The lunar standard curve is included with and without a diameter shift by a factor of 1.5. In the latter case, the curve is vertically "age-shifted" to fit approximately at small crater sizes. (b) Standard curve for Alba central cone. Thin edges of the cone were excluded from the counting area. Included are B-frame counts from the second-best test area, Elysium Planitia.

from the Mariner 9 imagery and the one having the best fit to our other Mars crater frequency measurements (17). It is considered the best approximation of the Mars standard curve—that is, the production crater size-frequency distribution (23) derivable from Mariner 9 imagery.

The projection of the standard curve to larger craters and older surfaces is explored in Fig. 5 for the older Lunae Planum and the ancient cratered highlands of Mars. The highland curve shows a break at 15 to 20 km, indicating resurfacing and obliteration of many craters below that size. Above that size, the data seem to fall nicely onto the projection of the standard curve.

In the size range between 3 and 7 km the statistical limitations of the Mariner data are severe. It is possible that the curve has a slight bump in this region, but this seems unlikely because (i) a few exceptionally homogeneous areas show no or almost no bump, (ii) the size of the bump is variable and related to numbers of obvious survivor craters (those not extinguished by resurfacing), and (iii) by analogy, the lunar curve shows no obvious bump near this size range. Detailed work on the Viking imagery, when it becomes generally available, should resolve the issue.

As seen in Fig. 4, simple superposition of the lunar and martian standard curves (taking out age or cross-section differences by shifting vertically, as discussed in connection with Fig. 3) shows that they are not identical. If the ratio of martian and lunar crater frequencies at $D = 10$ km is compared with that at $D = 1$ km, a difference of a factor of 2.5 is found. In other words, if the martian standard curve is normalized to the lunar one at $D = 1$ km (by vertical shift), the flat branch of the lunar curve (around $D = 10$ km) lies below the martian curve by a factor of 2.5. Does this mean that the meteoroid population that cratered the moon is different in this size range from the one that cratered Mars? Not necessarily, because, as we discussed before (Fig. 3), meteoroid impact velocity or target differences between the moon and Mars could shift the curves horizontally and be responsible for this effect in the shape of the curve. In fact, the impact velocities on Mars should be lower than those on the moon, because the aphelia and perihelia of meteoroids crossing the orbit of the earth-moon system are judged to be smaller on the average than those of meteoroids crossing the orbit of Mars. Lower velocities on Mars would result in smaller crater diameters for bodies with the same masses. Observations of the velocities of Apollo-Amor and Mars-crossing asteroids are in agreement with this: the average impact velocity of objects hitting the moon is 15 km/sec and that of bodies hitting Mars is between 8 and 12 km/sec (24).

In accord with this velocity argument, the lunar curve was shifted horizontally to smaller crater diameters to test whether a better fit to the Mars curve could be obtained. The best fit of the two curves is with a diameter shift by a factor of 1.5, corresponding to a Mars velocity of about 8 km/sec (25). Because of the slope of the curve, this diameter shift would reduce the 1-km intercept of the crater density plot for a Mars surface by a factor of 4.8 with respect to an identically aged lunar surface. If the cross-sectional effect for more effective gravitational capture of slower bodies is included, the factor is reduced to 4.5.

A lunar curve with a diameter shift of a factor of 1.5 is contrasted with the standard Mars curves in Fig. 4, a and b, to show the high degree of similarity between them and to illustrate the need for a diameter shift if coincidence is to be obtained. Whether the best value of the diameter shift is precisely 1.5 awaits refinement of the standard curve with Viking imagery.

A diameter shift could also be produced by target effects (Fig. 3). At present, we have no detailed information on martian surface composition and its effect on possible differences in crater sizes. Such an effect is considered small though, since martian surface rock composition is supposed to be not too different from the lunar one.

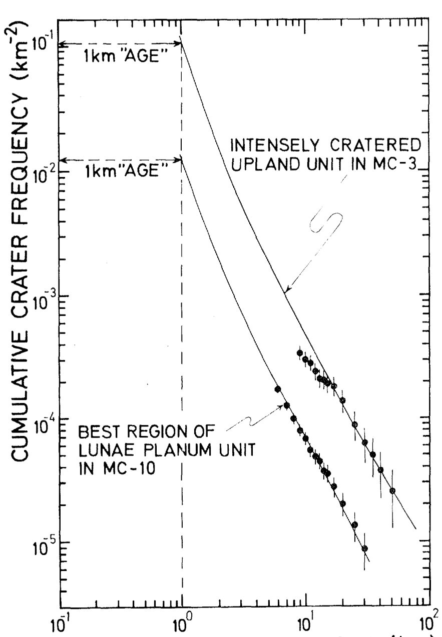


Fig. 5. Comparison of the projection of the standard Mars curve (slope ~ −1.8 at $D \geq 10$ km) with two older cratered areas. MC-3 and MC-10 are map quadrangle numbers.

In any case, we have found that the meteoroid populations cratering Mars and the moon in their middle to late history are probably not two populations with different mass distributions, but the same family of objects in the size range investigated. A simple diameter shift by a factor of 1.5 removes all differences in the shapes of the two standard curves within the error limitation. It is not necessary to assume an additional target effect, because the diameter shift corresponds to a reasonable impact velocity difference of 15 km/sec on the moon and 8 km/sec on Mars (25).

The correlation by diameter shift strengthens our interpretation that the steep parts of the standard curves at $D \lesssim 2$ km are not due to an admixture of secondary craters but represent the original primary production size–frequency distribution.

Absolute Age Correlations

The reasonably good fit of the lunar standard crater curve to cratered lunar surfaces less than 4 billion years old implies that the production population of lunar impacting bodies has not changed significantly in that time. Similarly, the close fit of the standard Mars curve to a wide range of ages of martian surfaces (17) suggests that the bodies impacting Mars also have not changed over a very long (but not radiometrically determined) period of time. The likelihood that one family of objects is involved argues for the same or at least a very similar time dependence of impact flux on both Mars and the moon. This is important, because at present we have no other means to determine the time dependence for Mars.

Hartmann (1) and Soderblom *et al.* (2) have also considered some of the problems in linking the martian and lunar cratering histories. They assumed that the time dependence of lunar and martian impact flux was the same. Hartmann also took into account the velocity effect by considering the present-day asteroid velocities but assumed a constant martian size distribution with a slope of −2 for all sizes. In this way he arrived at a crater frequency difference of a factor of 1.5 for all sizes, which is in accord with our calculation for the flat part of the standard curves ($D \gtrsim 5$ km) but different from our values at smaller sizes. Soderblom did not account for impact velocity differences on Mars and the moon.

Both Hartmann and Soderblom *et al.* considered a possible difference in impact flux at Mars because of its greater proximity to the asteroid belt. Soderblom *et al.* made the ad hoc assumption that the cratering flux at Mars was about the same as that at the moon (*26*), and Hartmann presented various arguments in favor of an impact flux at Mars ten times higher than that at the moon, which gives a six times higher cratering rate on Mars (because of the velocity effect). Both assumptions have been criticized (*19, 21*). Our work discussed above and in (*17*) places some additional constraints on these assumptions about the relative lunar and martian impact fluxes.

As pointed out by Soderblom *et al.* (*2*), the highlands of Mars and the moon were cratered at the time of the early intense bombardment, between 4.5 and 4 billion years ago. We assume that the martian highlands, like the lunar highlands, show the cratering record from about 4.4 billion years until the present. A frequency of 1-km craters of 480,000 per 10^6 km^2 has been determined for the 4.4-billion-year-old (*6, 7*) lunar highlands by using the craters in the 100-km size class and the lunar calibration curve to project to the 1-km size (Fig. 1). For the martian highlands the frequency of 1-km craters, from Fig. 5 and from a second area in quadrangle MC-3 (*17*), is 100,000 per 10^6 km^2. This result would argue for about the same flux at Mars as at the moon because martian crater frequencies at $D = 1$ km should be a factor of 4.5 lower than lunar ones for identically aged surfaces because of the velocity effect.

Lunar highland crater populations have commonly been interpreted (*16, 27*) to be in saturation (or a state of equilibrium) with respect to the crater frequencies (that is, preexisting craters are so densely packed that they are extinguished by subsequent impacts, keeping the crater densities constant at all times). We agree with this for craters smaller than ≈ 50 km but not for those larger than 50 to 70 km (for the moon), since the slope of the crater size distribution for this range is not −2 as expected for saturated surfaces. Instead, the slope has been measured as −2.4 to −2.6 (*5, 19, 28*). The martian highlands are clearly undersaturated (*1, 4*) at all sizes visible at Mariner 9 A-frame resolution; that is, we deal with production populations to which our martian standard curve can be directly applied.

There is some uncertainty in the lunar highland point in Fig. 1. Considering the Terrae point together with the Apollo 17 point at 4.3 billion years, and taking the average behavior of crater frequency as a function of age (solid line in Fig. 1), we regard this uncertainty to be smaller than a factor of 2.

Finding similar lunar and martian absolute fluxes could be coincidental. If the martian highlands were 100 million years younger than 4.4 billion years the martian flux could be about a factor of 2 higher. However, another correlation between crater frequency and age can be derived from measurements of crater densities on Mars' satellite Phobos (*29*). Using the crater densities on Phobos and the standard Mars curve for craters 2 to 5 km in diameter, we obtain a 1-km crater frequency of 350,000 per 10^6 km^2. [Since the craters have no ejecta blankets they can be measured without significant superposition even for these small sizes (*29*).] This crater frequency value would be expected for the surface of Phobos if it was exposed for 4.5 to 4.6 billion years and experienced approximately the same flux as the moon, with the velocity effect taken into account. An age of 4.5 to 4.6 billion years for the solidification of Phobos is cosmologically very likely (*30*). This supports our assumption of an age of about 4.4 billion years for the solidification of the martian crust. We conclude that the flux at Mars was the same as that at the moon early in the histories of these planets, with an uncertainty of about a factor of 2. This result disagrees with Hartmann's assumption (*1*) that the martian flux is ten times higher than the lunar one, but roughly agrees with the assumption by Soderblom *et al.* (*2*) of about the same cratering rate (*26*), which would correspond to about the same flux (a factor of 2 higher) for objects forming craters in the size range 4 to 10 km.

These considerations have given the constraints necessary to derive a martian time scale on the basis of our lunar results in Fig. 1.

1) The flux at Mars is the same as that at the moon.

2) The 1-km crater frequency values for Mars are a factor of 4.5 lower than the lunar ones for identically aged surfaces.

3) The time dependence of impact flux is the same for both planets.

Following these arguments, we have shifted the lunar cratering chronology curve of Fig. 1 to 1-km crater frequency values, a factor of 4.5 smaller, to reduce them to martian conditions. This curve is displayed in Fig. 6, together with Soderblom's and Hartmann's relationships, which differ markedly from ours. This difference reflects several factors:

1) In shifting their lunar curve, Soderblom *et al.* made the reasonable but ad hoc assumption of a higher cratering

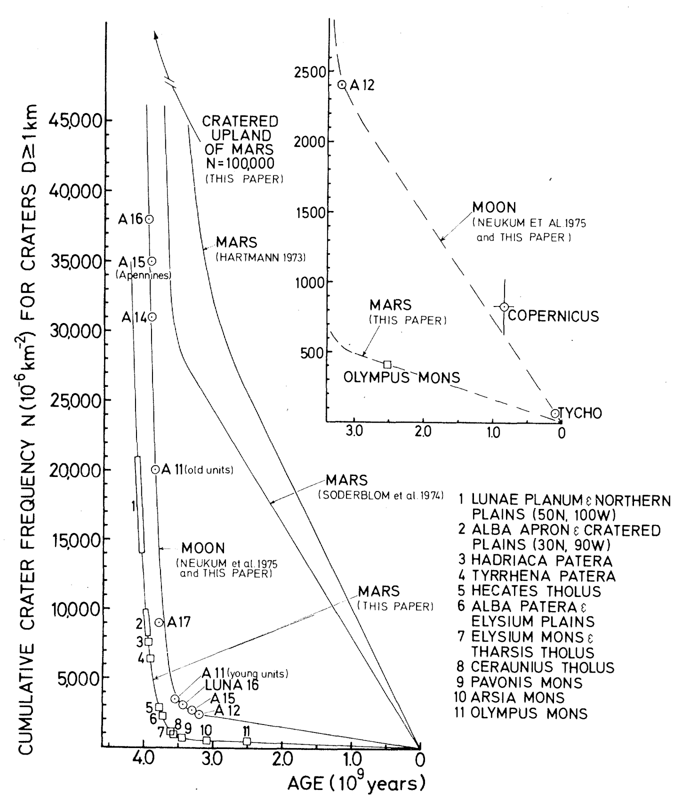


Fig. 6. Cumulative crater frequencies plotted against age for the moon and Mars. The older Mars curves of Hartmann (*1*) and Soderblom *et al.* (*2*) are given for contrast to indicate the radical shift backward in time of martian events. The prefix A means Apollo.

rate on Mars (factor of $\approx$ 1.5) and did not include the velocity effect. Thus, their curve is shifted with respect to the lunar curve in the opposite direction from ours.

2) The lunar counts on which the martian cratering chronology of Soderblom *et al.* is based lie much higher than any other values (Fig. 1) for ages < 4 billion years.

3) Although Hartmann's lunar crater frequency–time curve is higher than ours by only a factor of 2 to 3 (Fig. 1) but is lower than Soderblom's by a factor of 5 for ages $\lesssim$ 3.5 billion years, their Mars curves appear similar in Fig. 6. This is a coincidental agreement, due to Hartmann's assumption of a higher impact flux at Mars (*31*). If Hartmann had assumed equal martian and lunar fluxes, his martian curve would fall near our lunar curve.

The new curve leads to greatly increased estimates of the ages of martian events. The Lunae Planum lava flows are now 3.9 billion years old, the older cratered plains near 30°N, 90°W 3.8 billion years old, and Alba and the Elysium volcanics about 3.7 billion years old. The various volcanic landforms have been interpreted to be as young as 100 to 500 million years (*1, 2*), but are now estimated to be 2.5 to 3.9 billion years old [based on Carr's crater counts (*20*)]. The bulk of the volcanic cone activity was in the time span 3.4 to 3.8 billion years. Olympus Mons, the last great volcanic construct, is 2.5 billion years old.

Uncertainties

Another way of describing the relation between the lunar and martian curves is to say that the frequency ratio of small to large craters is lower for Mars than the moon. The observed velocity differences of asteroids indicate that some kind of diameter shift in the crater size distributions is probably required, but other causes of the differences between the curves might be suggested.

1) The crater counts for Mars may show fewer small secondary craters than the counts for the moon because of lower primary impact energy, later burial, atmospheric slowing, or poorer quality of imagery. The extent to which secondaries have been included in our Mars curves is open to question, but it is encouraging that the factors cited above argue as follows for no more secondaries on Mars than on the moon. The steeper portion of the lunar curve near D = 1 km (Fig. 2) must represent primary impacts where measured, for example, on the apron and terraces of the extremely young ($\approx$ 100 million years) Tycho (*9*), where secondary overprints from other large impacts are highly unlikely. If the primary bodies impacting Mars are not from a markedly different family of objects, we would expect a similar steeping for the small sizes in the martian crater distribution, and any secondaries would make the curve steeper rather than shallower.

2) A higher proportion of very large bodies may be included in the family of objects impacting Mars. We know of no way to evaluate this factor quantitatively at present.

3) Differences between Mars and the moon in target characteristics (strength and shock-wave velocity) and in gravity effects could affect the ability of impacting bodies to lift out material or influence crater enlargement by slumping (*32*). These factors, like the velocity differences, could lead to diameter shifts, but in an unknown direction. We suspect that these are relatively modest effects, but await the general availability of the Viking data for better information on target behavior. Our use of Phobos, with its essentially zero gravity, is debatable. Experiments by Johnson *et al.* (*33*) indicate that gravity is a significant factor in determining crater size for small explosion craters in cohesionless sand. However, these authors caution against using this result for cohesive materials and for higher explosive energies. Since the gravitational stresses in kilometer-sized craters are small compared to the tensile strength of most rocks, we think the gravity effect on crater diameter would be small for a cohesive rock mass like Phobos.

The question of relative fluxes between the moon and Mars has not been finally resolved, but relatively narrow constraints have been given. The data from Phobos, to the extent that its crater density can be linked to the conditions on the martian surface, suggest that the lunar and martian highlands are of essentially the same age. Uncertainties in crater densities by factors of more than 2 or 3 are unlikely. Hence, age differences greater than 100 to 200 million years or flux differences between the moon and Mars of more than a factor of 2 or 3 are unlikely. Most previous workers have assumed a much higher flux at Mars than at the moon. Recent work by Shoemaker (*34*) on the present-day Apollo-Amor and Mars-crossing asteroids suggests essentially the same cratering rate at Mars and the moon (for crater diameters > 10 km) in fair accord with the conclusions from our work.

Conclusions

At Mariner 9 resolution, the impact crater production size-frequency distribution of Mars is generally similar to that of the moon for crater diameters in the range 0.8 to 50 km, and it appears to have been relatively stable through time. The lunar and martian crater curves can be brought into near coincidence by a diameter shift appropriate to reasonable impact velocity differences between bodies hitting Mars and the moon. This indicates that a common population of bodies impacted both planets and suggests the same or a very similar time dependence of impact flux. Constraints on relative lunar and martian fluxes can be obtained by comparing crater frequency data for the lunar and martian highlands and for Mars' satellite Phobos.

These cratering constraints provide the basis for a tentative martian time scale derived from lunar data. Previous time scales have painted a picture of a disorderly planetary evolution of Mars, punctuated by a strange pulse of Tharsis Ridge tectonic and volcanic activity late in geologic history. The new scale suggests a much more orderly evolution, with Mars, like the moon, winding down most of its major planetary tectonic and volcanic disturbances in the first 1.5 billion years of its history. By 2.5 billion years ago the volcanic-tectonic circus on Mars had folded.

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6. The probable date of $\approx$ 4.4 billion years ago for the final differentiation of the lunar crust and the ability to have recorded the early cratering has been discussed [for example, see D. A. Papanastassiou and G. J. Wasserburg, *Lunar Sci.* **7**, 665 (1976); Baldwin (*7*)]. The early lunar age determinations yielded a strong age peak around 4 billion years and only few greater ages; this was interpreted as due to an extraordinary peak in cratering rate at that time ("lunar cataclysm") [F. Tera, D. A. Papanastassiou, G. J. Wasserburg, *Earth Planet. Sci. Lett.* **22**, 1 (1974)]. Such a peak in cratering rate is not supported by studies of the lunar crater populations and is probably a misconception [Baldwin (*7*); W. K. Hartmann, *Icarus* **24**, 181 (1975); Neukum *et al.* (*5*)].
7. R. B. Baldwin, *Icarus* **23**, 157 (1974).
8. G. Neukum and B. König, *Proc. 7th Lunar Sci. Conf.*, in press.
9. R. Arvidson, G. Crozaz, R. J. Drozd, C. M. Hohenberg, C. J. Morgan, *Moon* **13**, 259 (1975); R. Arvidson, R. J. Drozd, E. Guinness, C. M. Hohenberg, C. Morgan, R. Morrison, V. Oberbeck, *Lunar Sci.* **7**, 25 (1976).
10. On the basis of the terrestrial Canadian Shield impact crater data, Baldwin (*3*) and Neukum *et al.* (*5*) suggested a peak in cratering rate 400 to 600 million years ago. Recent lunar data (*8*) indicate that a great fluctuation is unlikely. At the most, the recent flux rate has varied within a factor of 2.
11. The crater frequency data of Soderblom *et al.* were not in terms of crater numbers originally.

They determined the erosional state of craters in the size range 100 m to kilometers and converted the erosion data to crater frequencies, possibly erroneously [figures 1 and 14 in (*2*) are inconsistent]. This is discussed by G. Neukum (*Moon*, in press).
12. The meaning of the Apollo and Luna radiometric ages for the lunar cratering record and of terrestrial age data for the North American cratering record is discussed by Neukum *et al.* (*5*) and G. Neukum and P. Horn (*Moon*, in press).
13. G. Neukum, B. König, J. Arkani-Hamed, *Moon* **12**, 201 (1975).
14. The constant power law distributions also shown in Fig. 2 for comparison are taken from Baldwin (*3*), Hartmann and Wood (*16*), and Shoemaker *et al.* (*15*).
15. E. M. Shoemaker *et al.*, *NASA Spec. Publ. SP-325* (1970).
16. W. K. Hartmann and C. A. Wood, *Moon* **3**, 3 (1971).
17. G. Neukum and D. W. Wise, *NASA Tech. Memo. TM X 74316* (1976).
18. V. R. Oberbeck and R. H. Morrison, *Moon* **9**, 415 (1974).
19. C. R. Chapman, *Icarus* **22**, 272 (1974).
20. M. H. Carr, *NASA Tech. Memo. TM X 3364* (1976), p. 152.
21. K. L. Jones, *J. Geophys. Res.* **79**, 3917 (1974).
22. The polynomial fit of the standard curve is (for the age of the Alba cone)

$$[\log N = a_0 + a_1 \log D + a_2(\log D)^2 + a_3(\log D)^3 + a_4(\log D)^4]$$

with $a_0 = -2.605$, $a_1 = -2.998$, $a_2 = 0.578$, $a_3 = 0.637$, $a_4 = -0.498$, N = cumulative crater frequency per square kilometer, and D = crater diameter in kilometers.
23. We have not distinguished in our counts between single impacts and crater doublets produced by broken-up projectiles [V. R. Overbeck and M. Aoyagi, *J. Geophys. Res.* **77**, 2419 (1972)]. The effect of doublets on the size-frequency curve is considered minor because of their relative rarity (*19*).
24. The asteroids with perihelions inside the earth's orbit are called Apollo asteroids, and those with perihelions between 1 and 1.3 A.U. Amor asteroids. Those with perihelions (crossing Mars' orbit) greater than 1.3 A.U. are called Mars crossers. The relative impact velocities have been given (*9*).
25. Shock theory would suggest the law $D \propto v^{2/3}$ for constant mass, where D is the crater diameter and v is the impact velocity. Chemical explosion data [M. D. Nordyke, *J. Geophys. Res.* **66**, 3439 (1961)] show a variation of crater diameter as the 1/3.4 power of energy expended. Use of this relationship gives essentially the same results as use of the 1/3 power.
26. Soderblom *et al.* use impact flux (mass-related) as synonymous with cratering rate (diameter-related), and thus do not account for any velocity differences. In fact, they do not set the cratering rate at Mars equal to that at the moon over the whole past. In their crater chronology diagram, the martian crater frequency (time integral of impact rate) is about a factor of 1.5 higher than the lunar frequency for ages > 2 billion years and about the same as the lunar frequency for ages < 1 billion years.
27. D. E. Gault, *Radio Sci.* **5**, 272 (1970).
28. C. R. Chapman and R. R. Haefner, *J. Geophys. Res.* **72**, 549 (1967).
29. J. B. Pollack *et al.*, *Icarus* **17**, 394 (1972). These authors considered the Phobos crater population saturated. We do not agree with respect to the larger craters (D > 2 km) because they lie far apart from each other.
30. The crystallization ages of meteorites also fall in this age span. It is quite possible that some of the meteorites stem from asteroid-type bodies that are similar in size to Phobos. The meteorite ages reflect the time of solidification of these bodies. This is a corroborating argument for solidification of Phobos 4.5 to 4.6 billion years ago.
31. We have not corrected Hartmann's original martian cratering frequency data given for a crater size distribution law to the −2 power in our reduction to D = 1 km. The velocity effect in going from large crater sizes to 1 km would lower Hartmann's values by a factor of about 2.
32. H. J. Moore, *U.S. Geol. Surv. Prof. Pap. 812-B* (1976).
33. S. W. Johnson, J. A. Smith, E. G. Franklin, L. K. Moraski, D. J. Teal, *J. Geophys. Res.* **74**, 4838 (1969).
34. E. M. Shoemaker, paper presented at the Planetary Program Principal Investigators meeting, Flagstaff, Ariz. (1976).
35. For a distribution law $N = f(D)$, $N \propto \delta N$. The data of Soderblom *et al.* in Fig. 1 are the original data in terms of δN, and those of Neukum *et al.* are the original data in terms of N. The relation between N and δN used here is derived from the calibration distribution of Fig. 2 (*13*): $N(D$ = 1 km) = 96 δN. Baldwin originally gave his data as cumulative crater frequencies N for craters ≥ 161 km in diameter. We used his distribution law $N \propto D^{-1.8}$ for reduction to $N(D$ = 5 km) and the calibration distribution for reduction to $N(D$ = 1 km). Hartmann gave his crater frequency data originally "in arbitrary units relative to an average mare frequency." We used his Apollo 14 (Fra Mauro) counts for absolute reduction to $N(D$ = 1 km) in applying our calibration distribution. In this way, all data have been reduced by application of a consistent method and are directly comparable.
36. This work was supported by the Deutsche Forschungsgemeinschaft, and the Planetology Office of the National Aeronautics and Space Administration, and was completed while D. U. Wise was a guest scientist at the Max-Planck-Institut für Kernphysik, Heidelberg. B. König was most helpful in the data reduction. Discussions with R. Arvidson, K. Blasius, M. Carr, J. Cutts, R. Greeley, J. Guest, H. Moore, R. W. Shorthill, and J. Veverka helped clarify our ideas.

The Enigma of Radiation Effects in *Drosophila*

Linear relation between induced mutation and x-ray dose and related inconsistencies are discussed.

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It is very well known that the frequency of radiation-induced mutation in *Drosophila* is essentially linear with dose, from very low doses up to at least 5000 or 6000 roentgens (r units). What is not so widely appreciated is that there exists a number of inconsistencies in the theory of radiation-induced mutation and chromosome breakage in *Drosophila*. For instance, the apparently simple and almost self-evident linear relationship of mutation with dose is considered both perplexing and unsolved. A simple solution to some of these problems is proposed in this article.

Even the earliest radiation studies with *Drosophila* indicated that induced sex-linked recessive lethals may be associated with chromosome rearrangements (*1*) and that the percentage of such lethals increases with dose (*2–4*). From these findings it has been concluded that such lethals are produced predominantly, if not entirely, as a result of chromosome breakage (*3, 5–7*). The most precise formulation of the relation between breaks and lethal mutations was proposed by Lea and his colleagues (*5–7*). However, at that time, Fano pointed out (*8*) a serious and inexplicable flaw in their reasoning, which, in essence, is the following. For every viable rearrangement of the simplest two-break type, there should exist an inviable, dicentric type which should be lethal. These nonrecoverable rearrangements should cause a loss of the induced sex-linked lethals, leading to a depression from linearity of about 20 to 30 percent at 3000 r units. Furthermore, with increasing dosage the frequency of inviable types should go up markedly, not only because of the increase of two-break arrangements with a power of the dose greater than 1, but also because of the appearance of three-break and higher order events, of which a smaller proportion form viable rearrangements. Thus, the depression at higher doses should be even more extreme. Such a departure from linearity is not at all borne out by the existing data. In fact, if anything, the data obtained by Edington (*9*) in a carefully controlled experiment over a wide dose range shows a slight but significant excess of induced lethals at the higher doses.

Herskowitz (*10*) demonstrated that no simple combination of hypotheses of le-

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