Pre-Mare Cratering and Early Solar System History

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An evaluation of the application of the high extralunar flux in pre-mare times to more general problems of early solar system history is attempted by combining the results of dynamic studies with lunar chronological data.

There is a twofold to fourfold contrast in the integral impact flux between the Apollo 14 and 16 sites and the older mare surfaces. This is judged insufficient to account for the contrasting lithology between these two sites: basalts and soil breccias in the maria, annealed breccias and impact melts in the highlands. Therefore these rocks and their ages (3.9–4.0 b.y.) are thought to predate the surfaces in which they are found. Estimation of the flux needed to produce these lithologies, and difficulties associated with extrapolating this further back in lunar history give support to the "cataclysm" hypothesis of Tera, Papanastassiou, and Wasserburg.

Dynamical studies permit separate evaluation of the possible sources for both the "normal" flux during the first 600 million years of lunar history and the "peak" that apparently occurred 4.0 billion years ago. The most likely sources for the normal flux are comets from the vicinity of Uranus and Neptune. The most promising source for the peak is tidal disruption by Earth or Venus of a Ceres-size asteroid initially in a Mars-crossing orbit. Alternative possibilites are suggested.

Dynamical studies have been carried out in order to determine the extent to which a heliocentric flux could be confined to the Moon (and Earth). A Monte Carlo method, based on that of Arnold (ref. 1), has been used to calculate the relative impact rates of planet-crossing bodies with the Moon and the terrestrial planets. It is found that except for nearly circular initial orbits, the resulting impact density on these bodies is similar. Nearly circular initial orbits at the distance of Mercury greatly favor impact with that planet. In the case of Earth and Venus, they tend to share the material with one another.

It is concluded that the time variation of the flux on these planets is closely related to that on the Moon.

The Extralunar Flux in the Early History of the Moon

In order to understand the evolution of planetary interiors and surfaces, it is necessary to establish a time scale to which the major events in its history may be referred. Prior to obtaining samples of a planet it is possible to establish a relative time scale based on geological principles of superposition, in which contact relationships between units resulting from identifiable events are used to determine which of the events occurred first. Unless erosion processes are too severe, it is possible to go further and establish a planet-wide time scale based on crater frequencies and crater morphology. A time-related parameter

$$\tau = \int_0^t \phi(t')\,dt'$$

is thereby determined, where $\phi(t)$ is the flux of impacting bodies at time t in the past. Work in a number of laboratories is establishing the relationship between absolute time, t, and the flux time, τ, for the Moon by determination of Rb^{87}-Sr^{87}, K^{40}-Ar^{40}, and U, Th → Pb ages of suitable lunar rocks. Under fairly general circumstances, as will be explained later, establishment of this time scale for the Moon represents a major step in establishing a cratering time scale for all of the inner planets, as the extralunar flux forms a link connecting the history of the terrestrial planets.

An early result of the task of relating ϕ to t was the demonstration that ϕ was not a linear function of time. Although the integrated flux indicated by crater frequencies at the Apollo 11 site in Mare Tranquillitatis was $\ll .1$ that of the lunar highlands (ref. 2), the age of the basalts flooding this region was found to be 3.6×10^9 yrs, the greater part of the entire age (4.6×10^9 years) of the Moon (refs. 3 and 4). More detailed information on the relationship between ϕ and t has been provided by subsequent lunar missions (refs. 5, 6, and 7).

Particularly striking is the rapid decline in flux between the time of filling of the oldest mare surfaces, and the younger premare surfaces (Cayley and Fra Mauro). As will be discussed in somewhat greater detail subsequently, there is some uncertainty as to the exact time interval over which this decrease took place. It is clear, however, that the decrease in flux during a few hundred million years about 4×10^9 years ago was greater than the decrease in flux during all of subsequent lunar history. This has been interpreted by Tera et al. (refs. 8 and 9) as indicating a lunar "cataclysm," a peak of extralunar bombardment about 3.9×10^9 years ago.

Both the Fra Mauro (Apollo 14) and Descartes Highlands (Apollo 16) sites are relatively lightly cratered terra surfaces which have received two to four times the impact flux of the older mare surfaces in Mare Tranquillitatis and Mare Serenitatis. At both these sites igneous rocks (including probable impact melts) and shock-metamorphosed breccias have yielded ages of 3.84 to 4.01×10^9 years by the Rb-Sr and K-Ar methods (refs. 10–16), and U-Pb measurements indicate that this was also a time of U-Pb fractionation, presumably associated with volatilization of Pb (refs. 17, 18, and 19). Most, if not all, of these ages are best interpreted as impact-related. Post-mare impact-melted rocks and well-annealed breccias are notably absent from the mare sites sampled. Although such rocks are undoubtedly produced by the same flux that has produced melted rocks on the earth (e.g., the Ries basin), the overall effect of this flux for the past 3.6 b.y. has caused a negligible resetting of ages on the mare surfaces. A few post-mare breccias have been investigated from the Apollo 15 site (refs. 15 and 20) and the age of the mare basalts in these rocks has not been noticeably affected by their later brecciation. Therefore it is thought unlikely that increasing this integrated flux by a factor of only two to four would result in the impact metamorphism dated by the Apollo 14 and 16 rocks. Consequently, it is believed that these ages of 3.84 to 4.01×10^9 years *predate* the surfaces on which they have been collected. On the other hand, Rb-Sr ages of 3.77 to 3.82×10^9 years are obtained on Mare Serenitatis basalts at the Apollo 17 site (refs. 9 and 21). These mare ages nearly overlap those found at the terra sites. This small difference in ages makes it difficult to calculate precisely the rate of decrease of the flux of impacting bodies, as the difference between the mare and terra ages is comparable to differences found for the same rock in different laboratories by the same method, and also comparable to the uncertainty introduced by half-life errors in comparing ages measured by different methods. Probably the most consistent way of calculating the change in flux is to use four Rb-Sr ages measured at the California Institute of Technology: Fra Mauro rocks 14073 and 14310 ($3.88 \pm .03$ b.y.), Descartes Highlands rock 68415 ($3.84 \pm .01$ b.y.) and Mare Serenitatis basalt 75055 ($3.77 \pm .06$ b.y.). Use of Rb-Sr ages on the same or related rocks from other laboratories will shift the absolute ages somewhat but will not change the differences appreciably. Fitting the measured integral flux to these ages, as well as to those of the Apollo 11, 12, and 15 mare basalts, and the present measured flux requires a component of flux decaying with a half-life of 40 ± 10 m.y., joined to at least two longer lived components.

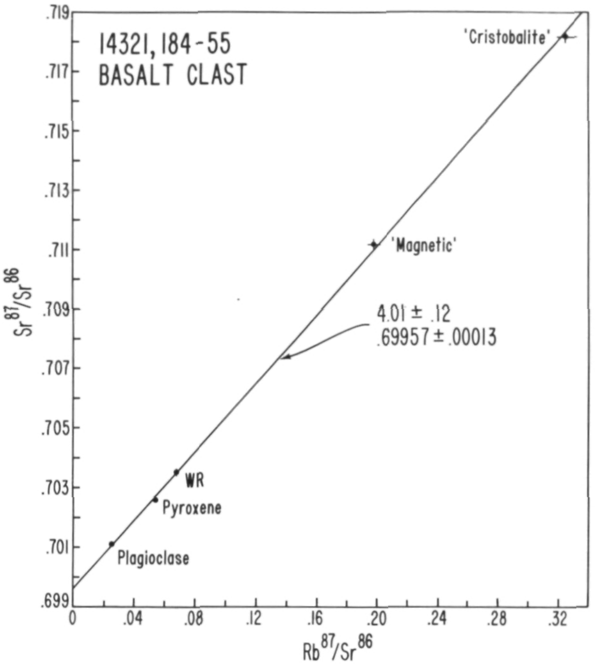

Figure 1.—*Mineral isochron for basaltic clast from breccia 14321.*

The gap between the youngest terra rocks and the oldest mare basalts becomes even smaller if the mare age of 3.9 b.y. found by Stettler et al. (ref 22) is included. However, it is possible that these older mare samples somewhat predate the surface on which they are now found.

The half-life of the short-lived component will be lengthened to about 60 m.y. if 14310, 14073, and 68415 are not interpreted as being impact melts, but as minor extrusive or intrusive rocks, postdating the surface on which they are found. The meteoritic component found in these rocks (ref. 23) argues against this interpretation.

The foregoing discussion made no assumptions regarding the relationship of the rocks studied to basin-forming events, e.g., the relationships of the Apollo 14 samples, the Fra Mauro formation, and Imbrium ejecta. Such a discussion is not necessary in order to demonstrate the rapid decay of the extralunar bombardment. However, these results are entirely consistent with the view that the Fra Mauro formation is an Imbrium ejecta blanket and that the rocks collected near the rim of Cone Crater are derived from the Fra Mauro formation. As discussed above, the age of the Fra Mauro surface is known to be less than 3.88 b.y., if 14310 and 14073 are impact melts, and less than 3.95 to 4.01 b.y., if they are small-scale igneous rocks of internal origin. Compston et al. (ref. 13) have presented reasons for believing that the mineral ages of 3.95 to 4.01 × 10^9 years found for basaltic clasts in 14321 are metamorphic ages, their resetting resulting from metamorphism in a hot Imbrium ejecta blanket. Although the difference is not far outside of experimental error, this conclusion is at least nominally inconsistent with the view that the age (3.88 b.y.) of 14073 and 14310 is Pre-Imbrium.

We have carried out some Rb-Sr measurements which show it to be unlikely that these ages are metamorphic. We have determined a mineral isochron for a basaltic clast in 14321 (fig. 1) as well as for a microbreccia clast in the same rock (fig. 2). The ages calculated from these isochrons are equal, well within experimental error. However, the initial Sr^{87}/Sr^{86} ratios are entirely different, showing that the basaltic clast and microbreccia clast were not in isotopic equilibrium at that time. This result, however, did not exclude the possibility that the basalt did not equilibrate internally, even though such equilibration did not extend between clasts. In order to check this possibility we have obtained Rb-Sr data at the contact between a basalt clast and adjacent microbreccia clasts, all within 1 mm of one another (fig. 3). If the surface region of the basalt clast had equilibrated with the adjacent microbreccia clasts, all three would lie along an isochron of slope 4.0 b.y. This is not the case. The basaltic material does not deviate at all from the previously determined internal basalt isochron, and there is no suggestion that any of the more radiogenic strontium from the microbreccia has entered into the basalt. Therefore it seems unlikely that reequilibration of the basalt has been completely internal, if this rock represents a fragment of, or a clast within, the Fra Mauro

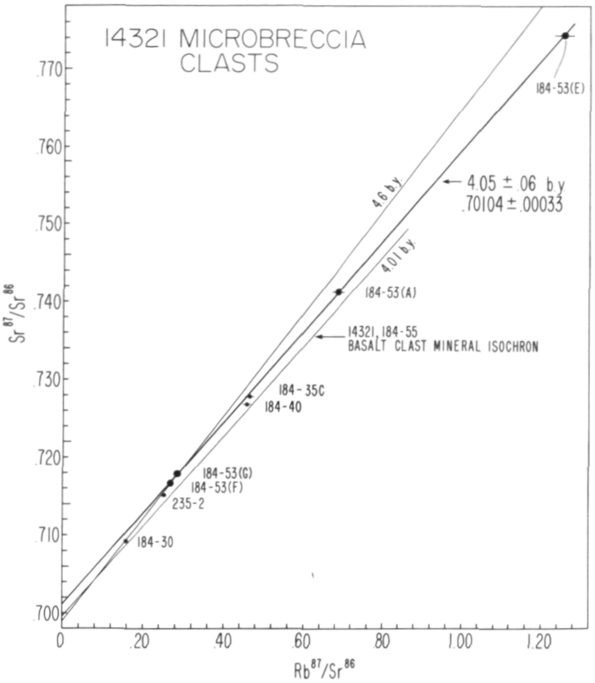

Figure 2.—*Mineral isochron for microbreccia clasts from breccia 14321. The line marked 4.05 ± .06 b.y. is the isochron drawn through density fractions of clast 184-53. The others are "whole-rock" microbreccia clasts.*

formation. However, as discussed by Chao (ref. 24) it is by no means necessary to believe that the Fra Mauro formation at the Apollo 14 site was ever very hot, and is more likely to represent a debris blanket more analogous to the Bunte breccia of the Ries basin. In this case, the age of 4.0 b.y. found for the basalt and microbreccia represents a Pre-Imbrium age, consistent with the previous interpretation that such ages, as well as those slightly younger, predate the cratered surface at this site.

Following this line of thought, the ubiquitous ages (~ 4.0 b.y.) found in the highlands must represent the effect of an integrated flux considerably greater than the fairly moderate twofold to fourfold increase found at the Apollo 14 and 16 sites. In order for these ages to dominate in the manner they do, a much greater integrated flux, e.g., a further tenfold increase, is required in the interval 3.95 to 4.05 b.y. Alternatively, or

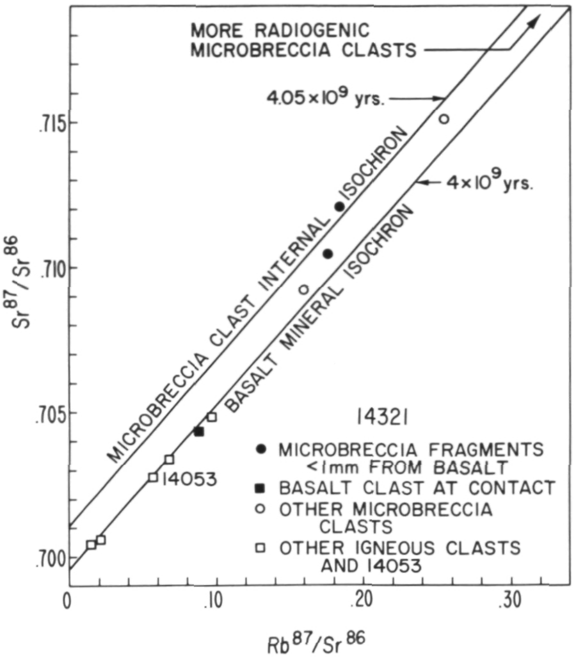

Figure 3.—*Rb-Sr evolution diagram showing lack of isotopic equilibrium at the contact between a basalt clast and adjacent microbreccia clasts.*

possibly equivalently, this could represent a period of major basin formation. In this case it is necessary to assign at least the Imbrium and Orientale impacts, and possibly that of Crisium and Nectaris as well, to this short interval of time. If this rapid decline in bombardment by basin and/or crater-forming bodies is extrapolated back in time, an integrated flux more than 1000 times that found on the oldest mare surfaces would be expected on a surface of 4.4 b.y. Such a rapid increase would greatly reduce the probability of finding ages of 4.2 to 4.3 b.y. still preserved, as found in several laboratories (refs. 25, 26, and 27). In addition, it would seem difficult to confine the radioactive KREEP material to the Procellarum-Imbrium region, as found by the orbiting γ-spectrometer experiments. Rb-Sr data on KREEP-rich rocks show that the original Rb enrichment of this material took place about 4.4 b.y. ago, and a continued increase in bombardment beyond that found at 4.0 b.y. would be expected to result in more uniform distribution of this material.

In view of the foregoing, the most plausible interpretation of the data is that given by Tera et al., that the lunar bombardment went through a peak about 4.0 b.y. ago, and the rapid decline in flux following that time was not merely the "tail" of a continually declining flux beginning 4.6 b.y. ago.

Possible Sources of the Early Extralunar Flux

Regardless of whether the actual lunar flux history was the late-peaking "cataclysmic" one outlined above, or the more frequently stated one of continually declining bombardment, some source which decays with a short lifetime, i.e., ~ 40–80 m.y., is required to be still present 600 m.y. after the formation of the solar system.

A fundamental but incompletely resolved problem is whether or not the bodies constituting this source were in geocentric or in heliocentric orbit. The time delay of 600 m.y. in the decay of the flux is much too long for randomly oriented crossing geocentric orbits. However, the lifetime does not rule out special geocentric orbits, such as bodies in circular orbits intersected by the Moon as it moves out to greater geocentric distance as a result of tidal friction. There is no special reason to believe that clusters of bodies in such circular orbits were likely to have ever formed. In fact, current theories of the evolution of a geocentric swarm (refs. 28–31) involve formation of "geocentric planetesimals" much closer to the Earth. Also, if objects of $\sim 10^{22}$ g were in Earth orbit at ~ 50 Earth radii for 600 m.y. it seems surprising that no much smaller bodies exist at somewhat greater geocentric distances today. Nevertheless, understanding of the formative stages of the solar system is insufficient to preclude this possibility.

The principal difference between impact by bodies in geocentric or heliocentric orbit will be their impact velocity: ~ 3 km/s for geocentric bodies and $\gtrsim 15$ km/s for heliocentric bodies of sufficient lifetime. The kinetic energy of the impacting geocentric bodies is barely sufficient to melt the impacting body itself. At the velocities stated above, the kinetic energy per gram will be about 25 times as great for the heliocentric bodies, and much more extensive shock-melting would be anticipated.

The arguments presented in the preceding section implicitly assumed that the energy of the impacting bodies in early lunar history was the same as that in more recent times (at present ~ 30 km/s). If the earlier bodies were less energetic, the increase in flux necessary to explain the widespread shock metamorphism 4 b.y. ago would be much greater. However, in view of the special orbital circumstances already required for the geocentric source, it does not seem too much of an additional burden to require the bodies to be 100 times larger.

An even lower energy source of lunar impacts, Moon-orbiting bodies $\sim 10^{23}$ g in mass, has been proposed by Reid (ref. 32).

It seems difficult to believe that there is no way to distinguish between the highland breccias and craters being produced by very large slow bodies on the one hand, or by smaller bodies with ~ 100 times as much energy per unit mass on the other. However, this seems to be the case at present, and it would represent a major contribution to lunar science if this uncertainty could be eliminated.

With regard to bodies in heliocentric orbits, there are a number of classes of bodies in various kinds of orbits which have undoubtedly played a role in bombarding the Moon. It would be a mistake to seek to explain all lunar impact phenomena in terms of a single source, even though such interpretations may appear more simple.

In discussing the contributions of various sources, it has been conventional to speak of various "components" of the flux which began to decay 4.6×10^9 years ago with various half-lives. This approach is acceptable, provided it is not taken too seriously. Although an exponential decay is a fair approximation for some classes of initial orbits, there are others that provide a flux with a more complex time history. An example of this is offered by Mars-crossing bodies with perihelion near Mars. For such bodies, a discrete interval of .5 to 1.0 b.y. is required for any members of an initial ensemble or "swarm" of such bodies to become Earth-crossing. Therefore the rate of Earth and Moon impacts from such a source will remain zero for a long time, increase to a maximum, and then decay with a half-life of $\sim 10^9$ yrs.

The orbital evolution of a number of classes of initial heliocentric orbits has been studied by Monte Carlo iteration of Öpik's (ref. 33) collision theory (refs. 1 and 34–37). These results will be used in the subsequent discussion. Although there are special cases to which this theory is not applicable, particularly where commensurabilities in period occur, the general lifetime and history of most planet-crossing initial orbits are treated sufficiently well by this method. In any case these calculations are to be preferred over those in which Öpik's collision theory is used without iteration. This is particularly true when more than one planet's orbit is crossed.

Except for the problem of the probable "cataclysm" at 4 b.y., to be discussed later, there is no special difficulty in describing plausible sources for the generally declining flux over most of lunar history. During the earliest accretionary phase of the Moon, low-velocity heliocentric (or geocentric) orbits would be required. After the Moon grew to nearly its present size, the bulk of any residual Earth-crossing bodies would be swept up on a time scale of $\sim 10^7$ years. A similar time scale would apply to bodies with aphelion near Jupiter in orbits similar to those providing the source of most of the large meteoroid flux at the Earth today. Bombardment by these bodies probably played a major role in establishing the present size distribution in the asteroid belt, and may have been important in supplying material for the final stages of the Earth and Moon. However, it is doubtful if any record remains of the impact of these transient sources.

On the more relevant time scale of $\sim 10^8$ years, there are several sources that need to be considered. Some members of the short-lived initial Earth-crossing population will be perturbed into orbits of high inclination, and their lifetime will be lengthened to $\sim 2 \times 10^8$ years. On this same time scale, Mars' perturbations will transfer into Earth-crossing orbit Mars crossers in initial orbits similar to Eros, i.e., those with initial perihelion near Earth. At the present time both of these sources are of such minor importance that it is very difficult to estimate their initial strength. The total flux required to impact the Moon during the first ~ 500 m.y. after the end of terminal accretion may be estimated at $\sim 10^{22}$ to 10^{23} g. Even for bodies with a high probability of terminating their heliocentric history by planetary impact, rather than by ejection from the solar system, the efficiency of the Moon for capturing such bodies is small because of its small cross section relative to Earth and Venus. An adequate source will therefore require an initial mass of $\sim 10^{24}$ to 10^{25} g in the proper orbits. This is similar to or greater than the present mass of the entire asteroid belt. There is no evidence that such a mass of material was not present in these orbits in the early solar system. With regard to the "Eros-type" orbits, a somewhat special distribution of initial orbits is required to avoid a residue of very long-lived ($\sim 2 \times 10^9$ years) Mars crossers greater than the number actually observed at present.

As mentioned before, data from the Prairie Network (ref. 38) shows that most of the present flux of large meteoroids at the Earth is of cometary origin (ref. 39), primarily nonvolatile residues of short-period comets with aphelion near Jupiter. Therefore, it is appropriate to inquire as to the role of this source in the early solar system. At the present time it is believed that comets are perturbed by passing stars into the inner solar system from the Oort cloud of comets at distances of 10^4 to 10^5 AU. It is usually thought that the Oort cloud was initially generated in the region of the major planets and perturbed into its present position by perturbations of the major planets and later by nearby stars. This process of populating the Oort cloud is roughly the inverse of the process by which they are captured into "Jupiter's

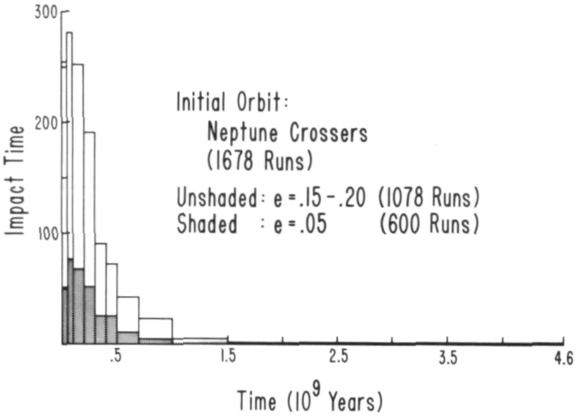

Figure 4.—*Histogram showing the time distribution of lunar impacts resulting from comets initially in Neptune-crossing orbits.*

family" at the present time. Those cometary bodies which were originally in the vicinity of Jupiter will be lost from the solar system proper on a very short time scale ($\sim 10^6$ years) and will contribute only to the terminal bombardment. However, those comets formed in the vicinity of Neptune and Uranus will evolve more slowly. First, perturbations by Neptune and/or Uranus will cause their perihelion to cross Saturn. In turn, Saturn perturbations will lead to Jupiter-crossing. Once in Jupiter-crossing, the further evolution will be similar to that of a modern short-period comet, and a similar fraction will be brought into Earth-crossing orbits.

The orbital evolution of bodies initially in Neptune-crossing or Uranus-crossing has been calculated by the Monte Carlo technique of Arnold. The initial orbits chosen are

	a	e	i
Neptune-crossing:	36.0 AU	0.2	6°
	28.0 AU	0.15	6°
	30.2 AU	0.05	4°
Uranus-crossing:	23.5 AU	0.2	6°
	18.0 AU	0.2	6°
	19.0 AU	0.05	4.5°

These calculations were made with the original Arnold procedure, rather than that I have used more recently, wherein the effect of the free oscillations of the secular perturbations was included. At present there are no adequate data on this phenomenon for orbits in the outer solar system.

Histograms showing the time at which the body first becomes Jupiter-crossing are presented in figures 4 through 6. Following Jupiter-crossing, the orbital evolution will follow the course previously calculated for short-period comets. The time scale for this subsequent evolution will be $\sim 10^6$ years,

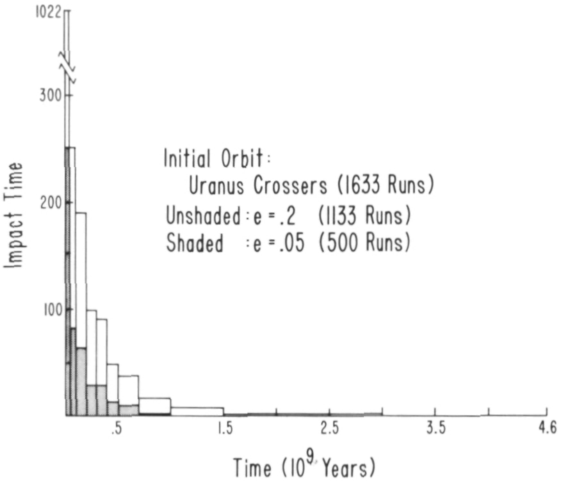

Figure 5.—*Histogram showing the time distribution of lunar impacts resulting from comets initially in Uranus-crossing orbits.*

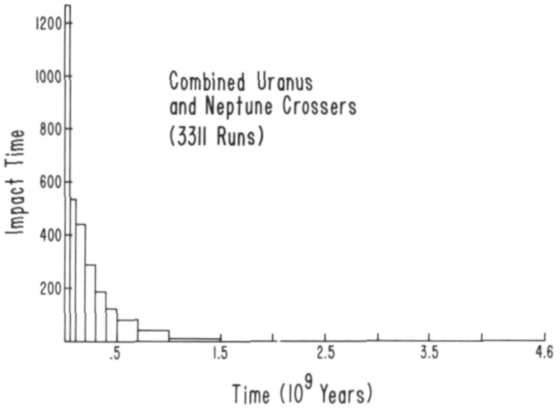

Figure 6.—*The time distribution of lunar impacts from the combined effect of Neptune- and Uranus-crossing comets.*

usually culminating in ejection by Jupiter into hyperbolic heliocentric orbits. If Earth or Moon impact occurs, it will be within 10^7 years of initial crossing. Therefore, on the time scale of 10^8 to 10^9 years, the time distribution of Jupiter-crossing is equivalent to the time distribution of Earth or Moon impacts.

The shaded portion of the histograms shown in figures 4 and 5 represents those initial orbits with low eccentricity. The general similarity of the low- and moderate-eccentricity results shows that the results are not strongly dependent on details of the initial orbits.

The cumulative impact flux from these sources is shown (on a logarithmic scale) in figure 7. There is considerable similarity between this curve and the lunar impact rate inferred by various authors on the basis of crater investigations (e.g., ref. 7).

The fact that no increase is found at 4 b.y. corresponds to the "cataclysm" of Tera and Wasserburg. The flux of these bodies on the Earth may be estimated to be

$$\frac{\text{present cometary flux}}{\text{primordial cometary flux}} = \frac{\text{lifetime near Neptune}}{\text{lifetime in Oort cloud}} \times \frac{\text{Number in Oort cloud}}{\text{Number in Neptune region}}$$

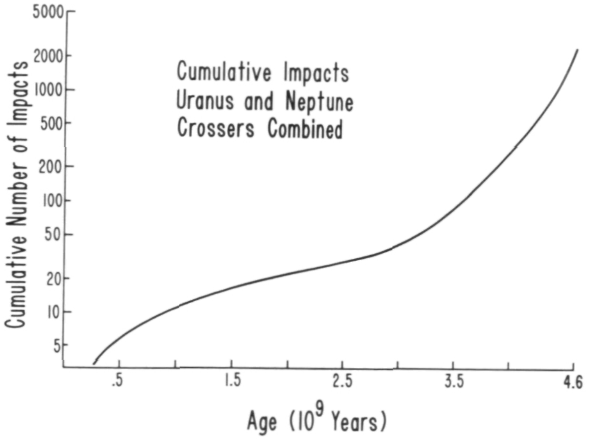

Figure 7.—*Cumulative lunar impact flux from Neptune and Uranus sources.*

The lifetimes are $\sim 10^8$ and $\sim 10^{10}$ years, respectively, and the ratio of the number of comets in the Oort cloud to the number in the vicinity of Neptune is the efficiency for population of the cloud which may be estimated to be ~ 1 percent. Therefore, it is estimated that the early cometary flux was $\sim 10^4$ times the present flux. This is adequate to provide the integrated early cratering of the lunar terra, and it is quite possible that cometary bodies and their inactive cores have been the primary source of lunar bombardment over almost all of solar system history.

The Lunar Cataclysm

Plausible natural sources have been found for the principal features of the time-dependent lunar meteoroid flux, with the exception of the peak in this flux which appears to have occurred 4 b.y. ago.

Some suggestions can be made as to how this missing peak can be supplied from a heliocentric source in as natural a way as possible.

The interval of 600 m.y. between the origin of the solar system and the appearance of this peak suggests that it be associated with the disruption of a large body belonging to one of the populations previously identified as having a characteristic lifetime of hundreds of millions of years. The rapid decay of the disrupted material must occur from orbits with characteristically short lifetimes of $< 10^8$ years, such as Earth-crossing orbits or those with aphelion near Jupiter.

The mass of material impacting the Moon in this event must be $\sim 10^{22}$ g. As in the case of the integrated "normal" flux, the small cross section of the Moon requires that the total mass disrupted in the inner solar system be much greater, $\sim 10^{24}$ g for bodies with a high (~ 50 percent) probability of impacting a terrestrial planet, and even larger for bodies with a high probability of being deflected into Jupiter-crossing and, from there, into hyperbolic ejection orbits.

Three heliocentric sources of the necessary lifetime have been identified:

1. High-inclination (e.g., 45°) Earth-crossing orbit
2. Mars-crossing with perihelion well within the orbit of Mars (e.g., Eros)
3. "Comets" in Uranus or Jupiter orbits

The latter two sources have the characteristic that although the lifetime of the source region is maintained in the $\sim 10^8$-year range by its initial conditions, disruption can occur in low-inclination Earth-crossing orbit, leading to a short residual lifetime for the fragments

The only portion of the solar system definitely known to contain objects anywhere near the proper mass is the asteroid belt. However the required mass of $\sim 10^{24}$ g is about equal to the mass of the largest asteroid, Ceres. There is no special reason why a similar body should or should not have been in a suitable Mars-crossing orbit after the formation of the planets. On a time scale appropriate to the observed interval of 600 m.y. this body will be deflected by Mars into Earth-crossing. Earth perturbations will usually cause it to become Venus-crossing as well, within $\sim 10^6$ years. It is necessary that this body have a high probability of being disrupted while in Earth-crossing orbit rather than of impacting a planet prior to disruption. The reason for this is that in the latter case it would have only a small probability of hitting the Moon. In order to avoid an ad hoc assumption that the one such body surviving until a point in time 4 b.y. ago took the improbable course of hitting the Moon rather than Earth or Venus, it would be necessary to assume there were many such bodies. This would then lead to the problem that the record of their subsequent impact cannot be found on the Earth. In order to produce more than one mare basin, the even more difficult problem of requiring more than one Moon-impacting body would be incurred. A breakup avoids these difficulties by spreading the product of a single impact among the various terrestrial planets and the Moon at a single time.

The most obvious way to cause a disruption is for the body of 10^{24} g to impact a smaller asteroid (e.g., 10^{20} g) while traversing the asteroid belt. The difficulty with this is that again an improbable event will have been invoked. Calculations of the lifetimes of asteroids (e.g., ref. 40) show that the lifetimes of asteroids of this size are $\sim 10^{11}$ years, and the probability of being destroyed by collision during the $\sim 10^7$ years an asteroid is in Earth-crossing orbit is very small ($\sim 10^{-4}$). The somewhat greater density of bodies in the asteroid belt 4 b.y. ago may increase this probability slightly. However, by this time most of the short-lived bodies would have been removed and the effect would be small.

There exists a much more probable cause of disruption. The Earth- or Venus-impacting probability of an Earth- or Venus-crossing body in an orbit derived from Mars-crossing is about 30 percent. For small bodies, about this fraction will end their course by hitting the Earth or Venus; the remainder will strike Mars or Mercury, make a very close approach to the Sun, or be perturbed by Earth or Venus into Jupiter-crossing and subsequent ejection. However, *prior* to impacting Earth or Venus, there is a high probability that the body will come within ~ 3 planetary radii of one of these planets, i.e., within the Roche limit. This is more probable than actually impacting the planet in the ratio R_R^2/R_P^2 where R_R is the Roche distance and R_p is the planetary radius. Therefore, for bodies of sufficiently low strength relative to the force of tidal disruption, a much more probable event is tidal fragmentation. Most of the remaining fragments will continue in heliocentric orbits. Their slightly different velocities following disruption will result in different subsequent planetary approaches and in divergent orbital evolution. A portion of the fragments will hit the Moon, in accordance with the relative impact probabilities described in the next section.

This is a probable course of events leading to a lunar cataclysm, provided a sufficiently large Mars-crossing body were initially present.

An identical disruption history could be described for an unusually large comet derived from Neptune- or Uranus-crossing. In contrast to the asteroidal situation, no comets of sufficient size are known. The cometary contribution will be dominated by those few bodies which chance to evolve into Earth-crossing orbits with aphelion $\lesssim$ 4.2 AU. Such bodies will have about a 5 percent probability of impacting Earth or Venus, and about a .15 percent probability of hitting the Moon. Therefore, a comet with the apparently improbable mass of $\sim 10^{25}$ g is required. This may be compared with the mass of $\sim 10^{18}$ g usually assumed for comets. However, comets have been observed for only a few thousand years, and a comet this large would not necessarily be a conspicuous object if its perihelion were beyond 2 AU. There is at present one body with a mass of $\sim 10^{27}$ g in a Neptune-crossing orbit (Pluto) and the possibility of there being many objects of $\sim 10^{25}$ g early in the history of the solar system cannot be ruled out a priori. The high inclination of Uranus' rotation axis may be a further indication of the former presence of large bodies in this region.

A conceivable way to produce the "cataclysm" without invoking an unusually large comet would be to assume that the formation of Uranus and Neptune were delayed by 600 m.y. Such a delay, owing to their slow rate of accretion, is in itself plausible, as discussed by Levin (ref. 41). In this case the "cataclysm" would correspond to the initial "spike" produced from Uranus-crossers during the first 10^8 years. This alternative is not very attractive. The effect is not large enough. Furthermore, if Uranus were delayed 600 m.y., it is natural to suppose Neptune would be delayed much longer. This would lead to a second "Neptune cataclysm" late in solar system history, which is not observed on either Earth or Moon.

Undoubtedly there are other possibilities, but those I have thought of present more difficulties than those mentioned above. For example, the mechanisms involving asteroid-Jupiter resonances proposed by Williams (ref. 42) and Zimmerman and Wetherill (ref. 43) almost certainly contribute to the lunar meteoroid flux. However, in order to provide the peak in flux 4 b.y. ago, an asteroid of $\sim 10^{25}$ g would have to be totally disrupted in the asteroid belt. As discussed earlier, this is an unlikely event.

Of those processes considered, the most plausible to produce this peak is probably tidal disruption of a large asteroid perturbed by Mars into an Earth-crossing orbit. The similar process with a cometary source, as well as those involving geocentric bodies, may be considered as possible alternatives.

Cratering on the Terrestrial Planets

Now that a reasonable understanding exists concerning the absolute cratering time scale of the Moon, it is of interest to learn what this can tell us about the cratering time scale of the other terrestrial planets. This possibility is largely confined to the heliocentric component of the cratering flux, again emphasizing the importance of finding some way to separate the effect of these two sources.

An object in Earth-crossing (and Moon-crossing) orbit will make close approaches to the Earth much more often than it will strike the Earth. These close approaches will change the orbital elements of the body. As a result of these changes the body can, for example, become Venus-crossing, after which close approaches and impacts with Venus become possible also. Continuation of this process can lead to the possibility of the body's striking any of the terrestrial planets. The relative probability of striking the various planets will depend upon the initial orbit of the body.

The orbital evolution of various initial orbits has been calculated by use of the development of Arnolds' Monte Carlo method described previously (ref. 44). Some modifications in the calculations were made in order that a statistically significant number of impacts with the smaller bodies, i.e., Moon and Mercury, could be obtained. This was done in two ways:

1. As described by Arnold (ref. 1) (1965), the close approaches are considered as random impacts on a target circle centered on the planet and having an orientation perpendicular to the velocity of the passing body. The radius of the target circle is chosen to be a specified number of planetary radii, K. Impacts on the outer half of this target circle, i.e., approaches at distances greater than $K/2$ planetary radii, are weighted differently from those on the inner half, in order to include the effect of more distant approaches within the sphere of influence of the perturbing planet, but beyond the radius of the target circle. This causes the perturbing effect of a particular planet to be independent of the radius chosen for the target circle associated with that planet, provided it is chosen to be large enough to eliminate large statistical fluctuations. In order to increase the number of interactions with the smaller planets (Moon, Mars, and Mercury) a larger target radius, K, is chosen for these planets. This in itself does not increase the probability of impacting the planet at all, nor does it increase the perturbing effect of the planet. It merely smoothes out statistical fluctuations that would otherwise occur if a small planet had to compete on an even basis with large planets in the choice of the next planet to be approached.
2. For intersections on the inner half of the target circle, the only difference between an impact and a close approach is that for an impact a random number is found to have a value between 0 and $4/K^2$, whereas a close approach occurs when the number is between $4/K^2$ and 1.0. For example, for $K = 10$ planetary radii, the area of the inner half of the circle is 25 square planetary radii. The probability of impact is $^1/_{25}$, which corresponds to the random number's being between 0 and .04. However, this choice of the range of the random number designated as "impact" rather than "close approach" is arbitrary. Therefore, close approaches resulting from the number's being between .04 and .08 would have been impacts if impacts had been assigned to random numbers in this interval. In this way close approaches, in the inner half of the target circle, may be "scored" as impacts, and the evolution calculation permitted to continue. In order to do this properly, it is necessary to permit each range of .04 to be counted as an impact only once, and also to continue the orbital evolution when the random number is between 0 and .04. When this procedure of scoring close approaches as impacts is combined with the procedure described in 1., above, of augmenting K for the smaller planets, the apparent relative impact rate on the smaller planets increases, thereby providing a more statistically significant number of impacts. Effectively, the number of runs has been increased by a factor $(K/2)^2$ as each run is now equivalent to $(K/2)^2$ runs with different choices of the random number region designated as impact for each run. At the end, the effect of obtaining more impacts on the smaller planets is corrected for exactly by dividing the number of impacts on each planet by the value of K^2 used for that planet. Without these modifications, the cost of obtaining statistically significant data for lunar impacts would be prohibitive.

The results of these calculations are shown in table 1. All these probabilities are relative to the Moon, which is assigned the value of unity.

The first group (A) of initial orbits correspond to initial orbits which penetrate deeply into the inner solar system. All have aphelia in the asteroid belt. The first two have perihelia within the orbit of Mercury, while the third has perihelion within the orbit of Venus. It is seen that the probabilities per unit area of impacting Mercury,

Table 1.—*Relative Impact Probability per Unit Area (Moon = 1.0)*

Object	Perihelion	Aphelion	Earth Impact Effectiveness (Percent)	Mercury	Venus	Earth	Mars
A. At Least Mars-, Earth-, or Venus-Crossing							
P/Encke	0.34	4.18	6.0	4.21	2.37	1.23	0.37
Icarus	0.19	1.97	18.5	7.50	1.97	1.08	0.45
1959LM	0.70	3.61	5.2	1.60	2.34	1.34	0.27
B. Aphelion Near 4 AU; Earth- or Mars-Crossing							
	1.01	4.00	24.0	0.30	0.94	2.26	1.15
	1.36	4.67	0.11	0.69	1.26	1.78	0.71
C. Nearly Circular Initial Orbits							
Near:							
Mars	1.27	1.89	27.8	1.08	2.58	2.82	11.9
Earth	0.98	0.99	45.0	1.05	3.02	3.99	0.96
Venus	0.67	0.82	29.6	1.08	2.44	1.36	0.18
Mercury	0.33	0.41	$<.01$	$>1.5 \times 10^4$	—	—	—

Venus, Earth, or Moon are comparable, whereas that of hitting Mars is somewhat less. The Mercury-crossing bodies have a higher probability per unit area of striking Mercury than the other planets. The statistical uncertainty in these numbers is about 10 percent.

The first entry in Set B corresponds to initial orbits similar to those from which most meteoroids become Earth-crossing at present (ref. 36). Initially the Earth is at its perihelion, and the geocentric velocity is low. This causes the gravitational radius of the Earth to be large, increasing its impact rate relative to the Moon. Further orbital evolution results in frequent Venus impacts and an appreciable rate of Mercury impact. To some extent, Mercury is shielded by Earth and Venus and the rate of Mercury impact is about an order of magnitude lower than that found for the Mercury-crossers in Set A. The rate of impact on the Moon and Mars is comparable, as discussed elsewhere (ref. 39). The second entry in Set B represents an initial orbit beyond the orbit of Earth and with aphelion near Jupiter. Jupiter perturbations will frequently bring such bodies into Earth-crossing. Again, the impact rate per unit area on all the terrestrial planets is the same order of magnitude.

A more extreme situation is illustrated by the orbits of Set C. Here the initial orbits crossed only one planet. If the planets were in perfectly circular orbits no other planet would be crossed, because of the conservation of relative velocity in subsequent encounters. This is equivalent to the constancy of the Jacobi integral in the restricted 3-body problem. In spite of this tendency for the orbits to remain in the vicinity of one planet, they nevertheless evolve in such a way as to have a comparable probability of impacting all the terrestrial planets, again per unit area. A marked exception is the Mercury-crossing case, which never becomes Venus-crossing. The small mass of Mercury and the large energy change necessary to become Venus-crossing preclude this occurring at a significant rate.

These results do not include the effect of

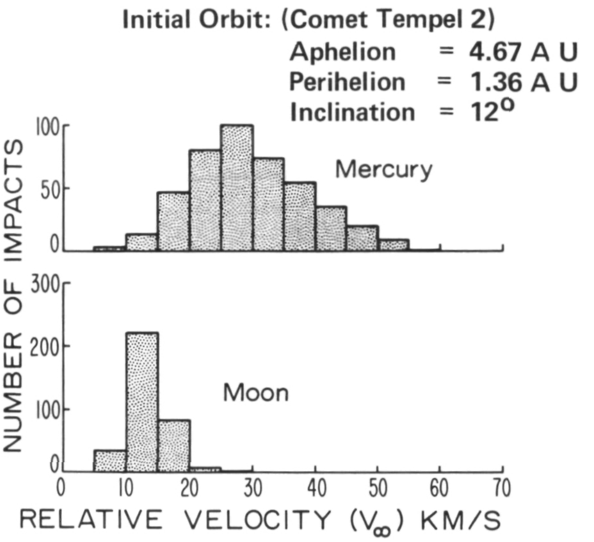

Figure 8.—*Calculated impact velocities on Mercury and Moon for a body initially in an orbit similar to that from which meteorites are being derived at present. Although the absolute values of the velocities are somewhat dependent on the initial orbit, the ratio of velocities remains within a factor of ~ 2 for most initial orbits.*

the mean energy of the impacts varying from planet to planet. The energy of each impact was also computed. This effect will be particularly important for Mercury, because typical impact velocities on that planet are about twice those on the Moon. Therefore a smaller mass will produce a crater of the same size. The results of a typical calculation of the velocity distribution are shown in figure 8. Depending on the exact size distribution of the impacting bodies, this will increase the integral number of craters greater than a given diameter by a factor of 2 to 3.

It can be concluded that the heliocentric flux producing lunar craters will also produce a similar number of craters per unit area on all the terrestrial planets. If such a flux causes a "cataclysm" at 3.9 b.y. on the Moon, it will cause a "cataclysm" on all the planets. Therefore, a reasonable first approximation might be to assume that, except for a constant factor $\phi(t)$ is the same for all the terrestrial planets. There is still a serious uncertainty in the constant factor. At the present time the meteoroid flux in the range of 100 g to 10^6 g, as given by McCrosky (ref. 38), is dominated by orbits similar to the earth-grazing orbit A1 and the Venus-crossing orbit B3. Including the velocity effect at Mercury, it is probably most reasonable to use the same proportionality factor for Mercury and the Moon. Mars is a somewhat different case. In addition to the sources prevailing at Earth's orbit, Mars will receive impacts from asteroids on the inner edge of the asteroid belt. In addition, there is significant transport of dust and associated erosion on Mars. Considering these problems, as discussed elsewhere (ref. 39), it is probably best to use a Mars flux/Moon flux factor of 1 to 2 rather than the value of 10 frequently used.

There is still much to be done before an entirely satisfactory time scale exists for the terrestrial planets other than the Earth. It may be expected, however, that present lunar and planetary studies will be a very significant aid in this endeavor.

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