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Late heavy bombardment of the moon and terrestrial planets

G. W. WETHERILL

Department of Planetary and Space Science, University of California, Los Angeles, California 90024*

Abstract—Photogeological data indicate many similarities between the cratering record of the moon and that of Mercury. Although the data are less conclusive, there is evidence that the cratering history of Mars has also been similar to that of these other bodies. This suggests the hypothesis that the impact flux on the terrestrial planets has been the same and that the plains units with ~ 100 craters/10^6 km^2 > 10 km in diameter from a ~3.9-b.y. "marker horizon" throughout the inner solar system. The present paper addresses the question of whether this hypothesis appears to be dynamically permissible. It is shown that it is. Monte Carlo calculations indicate that as a consequence of planetary perturbations a wide class of starting orbits evolve to produce a similar flux on all the terrestrial planets, and storage places with the necessary 100–200-m.y. lifetimes exist. Post-accretional mass requirements are not excessive and breakup of $\sim 10^{23}$-g bodies within the Roche limit (for a solid body) provides a dynamically probable mechanism for producing simultaneous episodes of bombardment on the moon and terrestrial planets. More specific models for the source of this bombarding material are examined. The most satisfactory of these are derivation of projectiles from Mars-crossing orbits and from residual planetesimals in the vicinity of Uranus and Neptune, possibly the proto-cometary cloud. The Mars-crossing source has the property that the impact rate per unit area on Mars will be about 10 times that of the moon and Mercury. As a consequence the cratering time scale for Mars will then be different from that of these other planetary bodies. If the hypothesis of simultaneous late heavy bombardment is correct, a small (~4-fold) increase in impact-related ages of achondritic and iron meteorites may be expected to occur at the time of this bombardment.

1. INTRODUCTION

PRIOR TO THE RECENT PROGRAM of manned and unmanned exploration of the moon and terrestrial planets, there was a tendency to separate earth history into two discrete and non-overlapping periods of time. These were the last $\sim 3.5 \times 10^9$ yr, revealed by the terrestrial geological record, and the primordial nebular and accretional periods, 4.6×10^9 yr ago. Evidence concerning the latter was inferred from theoretical considerations and observational and meteoritic data. It was commonly believed that the cratered surface of the moon represented bombardment during the terminal phase of this primordial period.

Following the Apollo 14 mission to the Fra Mauro region of the moon, the results of radiometric age determinations on this material (Papanastassiou and Wasserburg, 1971; Turner *et al.*, 1971) showed that the period of intensive lunar cratering and mare basin formation continued long after the completion of the $\sim 10^7$-yr formational period of the moon and planets. In addition to the "early heavy bombardment" which more or less accompanied the accretion of the

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*Present address: Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, N.W., Washington, D.C. 20015 planets, there was thus a "late heavy bombardment" which continued for hundreds of millions of years, and may well have been episodic in character (Tera and Wasserburg, 1974). The $3.9–4.0 \times 10^9$-yr ages found for the Apollo 14 impact-related rocks have been interpreted in various ways. One possibility is that these ages represent the time of excavation of the Imbrium Basin (Compston *et al.*, 1972). In this case, the Imbrium impact and subsequent events, such as the Orientale impact and the excess crater density on ejecta deposits of these basins, occurred rather late in lunar history, 600–700 m.y. after the formation of the solar system. Another possibility is that many of these ages are the result of impact metamorphism during pre-Imbrium cratering and they have become mixed with Imbrium materials by secondary cratering (Oberbeck *et al.*, 1974). In both of these cases extensive lunar bombardment must have occurred until ~3.9 b.y. ago. The only hypothesis which can avoid this conclusion is that the impact-related ages are the consequence of post-Imbrium (and Orientale) cratering. The gross difference between the abundance of impact breccias at the Apollo 14 and 16 sites and that of the mare surfaces is in marked contrast to the relatively small difference (factor of ~3) in the crater density observed between the Fra Mauro, Cayley, and Descartes formations and the mare surfaces. For this reason, any interpretation of the majority of the ~3.9-b.y. ages invoking significant post-Imbrium and Orientale cratering is untenable.

The Mariner 10 spacecraft photographed ~40% of the surface of Mercury to a resolution of 10 km and selected regions to a resolution of 200 m. Photogeological study of these data indicates a remarkable similarity between the cratering record on Mercury and the moon (Murray *et al.*, 1975). Both planets contain densely cratered regions containing >200 craters/10^6 km^2 more than 10 km in diameter. The lunar regions of this kind represent a steady-state crater population whereas Mercury contains both steady-state regions of this kind as well as poorly understood "intercrater" terrains in which a high density of craters >50 km in diameter appear to be superimposed on an older relatively uncratered surface (Trask and Guest, 1975). Both planets contain ringed impact basins and associated ejecta deposits ranging up to ~1000 km in diameter. In both cases post-basin surfaces have crater densities of ~120 craters/10^6 km^2 greater than 10 km in diameter. Finally, both planets contain younger basin-filling surfaces presumably of volcanic origin with lower crater frequencies of ~40 craters/10^6 km^2 greater than 10 km in diameter. Although the Martian crater record is obscured by erosional and depositional processes, photogeological studies suggest that but for modifications caused by these processes, a similar cratering record might be found for that planet (Wilhelms, 1973; Chapman, 1974; Soderblom *et al.*, 1974).

These similarities between the three planetary bodies could be coincidental, or could be the result of their experiencing a very similar impact flux history. If the latter is the case, the relatively lightly cratered post-basin surfaces with crater counts of ~120/10^6 km^2 represent a "marker horizon" throughout the inner solar system corresponding to a time of 3.9 ± 0.1 b.y. ago, as indicated by the lunar radiometric chronology.

Whether it is plausible to regard this similarity as significant or coincidental

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depends on the *a priori* probability of these various planets experiencing the same bombardment and to some extent a similar volcanic history. Although the similarity in crater densities is quite striking, if there were strong dynamical arguments precluding a similar bombardment history, it would be most plausible to regard the observations as coincidental. On the other hand, if there exist one or more natural and plausible ways which lead to a similar flux history, then it would be wise to take seriously the hypothesis that the lunar crater time scale can be extended to the terrestrial planets.

The purpose of this paper is to quantitatively explore alternative models for the interplanetary flux during the first $\sim 10^9$ yr of solar system history in order to evaluate whether any of these are compatible with the hypothesis of a uniform flux history for these planets. The other consequences of these models will also be examined, in order to undertand the extent to which they can be reconciled with other features of the solar system, its origin, and history.

This investigation must of necessity be preliminary. Interpretation of the photogeological data, particularly for Mercury and Mars is rudimentary. The present distribution of asteroidal and cometary matter is fairly well known. These data have been used to support the hypothesis that the recent flux on the moon and Mars has been similar (Wetherill, 1974a) but in this work it was necessary to point out a number of problems which make even this inference somewhat uncertain. The size, nature, and distribution of similar smaller bodies much earlier in solar system history involve greater uncertainties. Finally, theoretical techniques required to calculate the dynamic evolution of the orbits of these impacting bodies deserve considerably more development and critical attention than they have received to date. Therefore the treatment given here of the various models should be regarded as outlines of their principal features, and the "conclusions" given herein can be considered hypotheses which have survived a preliminary screening but require more detailed investigation.

2. SIZE DISTRIBUTION OF THE IMPACTING BODIES

Insofar as the crater density is not so high so as to represent a steady-state between crater production and destruction (Gault 1970) the size distribution of craters can be used to infer the size distribution of the impacting bodies. Although the most densely cratered regions of the lunar highlands are in such a steady-state, the more lightly cratered plains regions such as the Fra Mauro and Cayley Plains are well below a steady-state density.

Detailed investigations of lunar crater size distributions (Neukum *et al.*, 1975) show that except for a constant factor, pre-Imbrium, plains, and mare surfaces contain the same size distribution of craters. This distribution cannot be described by a single power law exponent over the entire range of crater sizes. For the largest craters (>10 km in diameter) the slope of the distribution is rather flat, and approximately corresponds to a cumulative distribution:

$$N = N_0 D^{-\alpha}, \tag{1}$$

where α is in the range 1.4–1.6. This is in agreement with the results of previous authors (Shoemaker *et al.*, 1962; Baldwin, 1963). The parameter α in the crater size distribution is related to the analogous parameter γ in the bombarding projectile mass distribution by

$$\gamma = \alpha/\beta, \tag{2}$$

where β is defined by the relationship between impact energy and crater diameter:

$$D = E^{1/\beta}. \tag{3}$$

The value of β varies from 3 (energy scaling) to 4 (gravity scaling) as discussed by Gault *et al.* (1975). A value of 3.4 is frequently recommended. Use of $\beta = 3$ together with $\alpha = 1.5$ in Eq. (2) gives $\gamma = 0.5$. This represents a projectile mass distribution in which the total mass is strongly concentrated in the largest projectiles. Use of $\beta > 3$ would give an even greater concentration of mass in the larger projectiles.

Description of a mass distribution by use of a mass-distribution law breaks down when the number of bodies greater than a given mass becomes less than one. In any real situation there will be a single largest body, and by definition the number of greater mass will be exactly zero. A reasonable expectation value for this largest mass which is compatible with a given mass-distribution law can be found by considering an ensemble of planets of the same size. If $N = 0.5$ in the cumulative power law,

$$N = CM^{-\gamma}, \tag{4}$$

half of these planets will have been impacted by a body of mass greater than M, whereas for the remaining half the largest impacting body will be smaller than M. The value of M for which $N = 0.5$ in Eq. (4) will therefore be used as the value M_1 of the largest impacting body. Adopting this convention leads to the result that the ratio of the total projectile mass less than M_1 to the mass of the largest projectile will be

$$R = 0.5\frac{\gamma}{1-\gamma} = 0.5 \qquad \text{for} \quad \gamma = 0.5. \tag{5}$$

In other words, the mass of the single largest projectile is greater than the combined mass of all the smaller projectiles. This may be contrasted with the value $R = 2.5$ corresponding to $\gamma = \frac{5}{6}$, the collisional steady state derived by Dohnanyi (1969).

If the size range of bombarding projectiles is continued to include the Imbrium planetesimal, this concentration of mass in the largest bodies is at least equally pronounced. The projectile mass required to produce the large mass craters can be estimated by combining mare crater counts (Shoemaker *et al.*, 1962) with a reasonable energy scaling law, based on nuclear explosions and, which relates diameter to impacting mass:

$$D = .115M^{1/3}, \tag{6}$$

where D is the crater diameter in meters and M is the impacting mass in grams, and an impact velocity of 15 km/sec is used. This calculation gives 3×10^{19} g as the total post mare-filling impacting mass. All but a few percent of this mass is associated with the production of craters >10 km in diameter. The integral flux on the Fra Mauro and Cayley Plains formations is about 3 times as great, corresponding to an impacting mass of $\sim 10^{20}$ g. A similar calculation for the mass of the Imbrium planetesimal gives a mass of $\sim 10^{21}$ g. In the same way, the mass of the Orientale projectile comes out to be $\sim 2 \times 10^{20}$ g. Therefore, up to and including projectiles of Imbrium size (~ 50 km in radius), the large projectiles are characterized by the fact that the largest body has a mass greater than that of the remaining objects.

As pointed out before, this is not the kind of a size distribution expected for objects which are in a steady-state resulting from mutual collisional comminution. Rather, it more resembles the end product of an accretional process in which larger bodies have grown at the expense of smaller ones. In the subsequent treatment of specific models for the sources of the late heavy bombardment, one relevant consideration will be whether or not a collisional mass spectrum should be expected under the conditions assumed for the model.

Insofar as there is some proportionality between the quantity of impact breccias and extent of impact resetting of measured ages, an impact history dominated by the last few large impacts will produce an episodic age distribution. Therefore the ~ 30-fold decrease in mass flux between the time of the Imbrium impact and the older mare surfaces need not be entirely explained in terms of a uniformly decaying mass flux, but will be in a major way a consequence of a statistical fluctuation in this flux. Therefore to a certain extent episodicity will result simply from the "lumpiness" of the size distribution. This effect in itself is insufficient to produce *simultaneous* episodes on several planets. However approximate simultaneity of the cessation of the late heavy bombardment could result from a flux decreasing with a characteristic half-life of ~ 50 m.y.

3. RELATIVE BOMBARDMENT RATES ON THE MOON AND TERRESTRIAL PLANETS

The hypothesis that the lunar crater density time scale can be extended to the other terrestrial planets requires that there has existed one or more populations of bodies in the inner solar system which had a nearly equal probability of impacting a given area on any of the planets. Candidate populations will be characterized by their orbital element and mass distributions and by their total mass.

The classes of orbits which can be considered are those in interstellar or heliocentric orbits, or those orbiting as satellites of a planet. It is conceivable that interstellar or even intergalactic bodies may play a role in bombardment. However observational data on comet, fireball, and meteor orbits indicate that at present the importance of these sources is so small that no firm evidence exists for even a single event from an extra-solar system source in the size range $>10^{-6}$ g. Very near to the time of formation of the solar system it is probable that such sources were of at least somewhat greater significance, as it is likely that the sun was formed as part of cluster of stars in a region of anomalously high density of gas and dust. However on the time scale under consideration here, 10^8–10^9 yr, typical interstellar velocities of ~ 20 km/sec will permit such projectiles to traverse distances comparable to the dimensions of the galaxy, and any primordial concentration of these projectiles will have been dissipated.

Because it is so unlikely that interstellar sources were significant, bodies in heliocentric or planetocentric orbits should be considered as the principal candidates.

Apart from the possibility that a constant crater density may arise by coincidence, the latter class must evolve into heliocentric orbits in order to impact planets other than the one they are initially orbiting. No detailed discussion of this evolution from planetocentric to heliocentric orbits exists as yet, although treatments of tidal evolution of satellites (reviewed by Kaula, 1971) and geocentric swarms (Ruskol, 1960, 1963, 1972; Ruskol *et al.* 1975; Kaula and Harris, 1975) are relevant to this problem. This class of initial orbits will not be discussed here in any detail. However this possibility should not be forgotten. The most commonly encountered version of a planetocentric source for the lunar late heavy bombardment involves geocentric planetesimals colliding with the moon as a consequence of tidal evolution. The moon was probably near to its present geocentric radius at the time of this bombardment, and lunar perturbation of these fairly weakly bound planetesimals into heliocentric orbits should have occurred. However a comparable flux on the moon and Mercury requires that all but a fraction of one percent of the bodies be ejected from geocentric to heliocentric orbits which seems unlikely. Another possibility which is more difficult to evaluate involves the tidal escape of a satellite of Venus of .01 to .1 lunar mass as suggested by Harris (private communication). Subsequent close encounters with Venus and earth could have disrupted this body into a number of heliocentric projectiles, along the lines discussed in Section 5. There is at present no observational or theoretical evidence for or against this speculation.

The evolution of various classes of heliocentric interplanetary orbits has been discussed previously (Wetherill, 1975). This treatment included a discussion of the modifications made in the Monte Carlo techniques which permitted an adequate statistical sample of impacts on small bodies such as the moon and Mercury. The results of these calculations are given in Table 1.

The first two entries in this table represent bodies evolving from initial orbits similar to those required to explain the orbital distribution of the Prairie Network fireballs, and the observed time of fall and radiants of chondritic meteorites (Wetherill, 1968, 1971). Such orbits can evolve from those of short period comets. The second entry in Table 1 is such an object, Comet Temple 2. These data are normalized so that the lunar impact probability per unit area is assigned the value of unity. The impact probability per unit area on the four terrestrial planets is seen to agree with the lunar value within a factor of about three. This result is largely independent of the large differences in the efficiency with which these bodies impact the planets. This can be calculated from the relative impact efficiencies and

Table 1. Relativity impact probability/unit area (normalized to moon = 1.0).

	Initial orbit		Earth impacts				
	perihelion	aphelion	(%)	Mercury	Venus	Earth	Mars
1.	1.01	4.00	24.0	0.30	0.94	2.26	1.15
2.	1.36	4.67	0.11	0.69	1.26	1.78	0.71
3.	0.34	4.18	6.0	4.21	2.37	1.23	0.37
4.	0.19	1.97	18.5	7.50	1.97	1.08	0.45
5.	0.70	3.61	5.2	1.60	2.34	1.34	0.27
6.	1.27	1.89	27.8	1.08	2.58	2.82	11.9
7.	0.98	0.99	45.0	1.05	3.02	3.99	0.96
8.	0.67	0.82	29.6	1.08	2.44	1.36	0.18
9.	0.33	0.41	$<.01$	$>1.5\times10^4$	—	—	—

that for the absolute efficiency for impacting any single planet; e.g. the earth, as shown in the third column. Objects initially in orbits similar to those of the first entry will very frequently strike an inner planet, 24% of them will hit the earth. In contrast, those in orbits similar to that of the second entry will more often be perturbed into Jupiter-crossing and ejected by that planet into interstellar orbits. Only a fraction of one percent of these bodies will impact a terrestrial planet.

The next three entries represent initial orbits which penetrate more deeply into the inner solar system, penetrating the perihelia of Venus or Mercury. The orbits calculated are those of actual bodies in the present solar system, but this is done only for an illustrative purpose, rather than suggesting that these modern objects have any relation to the late heavy bombardment. The objects with the smaller perihelia will cause a greater crater density on Mercury than on the moon and Mars. Strictly speaking, these initial orbits are not consistent with a uniform flux history. However an admixture of such orbits with others with perihelia nearer to that of the earth (the first two entries) would lead to an approximately uniform flux history as an average result.

The last four entries represent initial orbits of sufficiently low eccentricity to cross the orbit of only one planet. It might be thought that this would greatly favor impacts on that planet. To some extent this is true. The Mars-crossers are about 10 times more likely to strike Mars (per unit area) than the moon. Mercury-crossers only very rarely evolve into even Venus-crossing before they strike Mercury. The results for these two planets are largely a consequence of these small planets having insufficient mass to readily "pump" the eccentricity to sufficiently high values to cross another planetary orbit. In contrast the larger terrestrial planets, Venus and the earth, perturb bodies into highly eccentric orbits which have a good chance of striking the moon or any of the terrestrial planets.

The general result of these calculations is that planetary perturbations tend to spread interplanetary bodies throughout the inner solar system, resulting in a comparable flux on the moon and terrestrial planets. There are exceptions to this; those which initially cross only Mercury are a particularly striking exception. Nevertheless it will usually be difficult to confine an interplanetary population

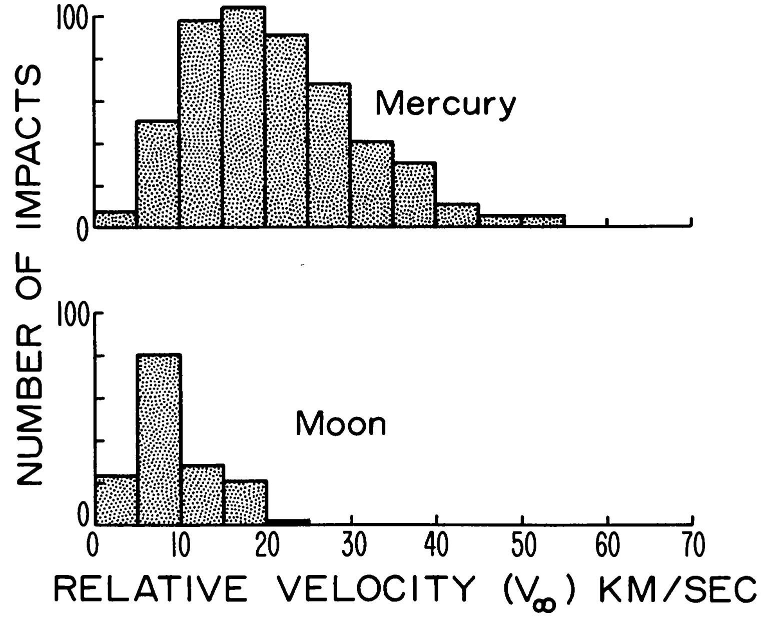

Fig. 1. Distribution of impact velocities on the moon and Mercury for a swarm of bodies initially in Mars-crossing orbit (aphelion = 1.90 a.u., perihelion = 1.27 a.u., inclination = 6°). The velocity is given as V_∞, i.e. prior to the additional acceleration resulting from the gravitational field of the planet. For small planets such as these this effect is small.

primarily to a particular planet, and many distributions of initial orbits will lead to a similar flux on the moon and Mercury.

To compare crater densities on the various planets it is necessary to consider the impact velocity as well. These have been calculated by the same techniques

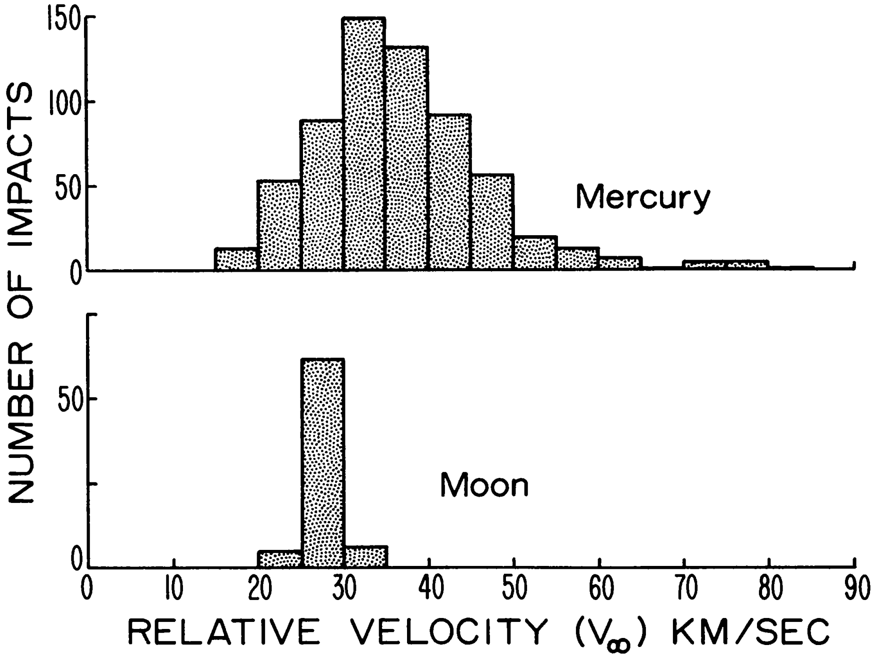

Fig. 2. Distribution of impact velocities for bodies initially in orbits equal to that of periodic comet Encke (aphelion = 4.18 a.u., perihelion = 0.34 a.u., inclination = 12°).

used to obtain the data of Table 1. Examples of these calculated velocity distributions are given in Figs. 1 and 2. Those orbits with initial perihelia well beyond Mercury, will impact Mercury with about 2–3 times the velocity they impact the moon. When this result is combined with the size distribution discussed in the previous section, it turns out that the effect of velocity is to increase the crater density by a factor of about 2.5. For objects such as those given in the first two entries of Table 1, this effect offsets the factor of 2–3 lower impact probability on Mercury relative to the moon, which arises from the rather ineffectual "earth and Venus barrier" which these bodies must surmount. This velocity effect is less pronounced for orbits which are initially Mercury-crossing, as shown in Fig. 2. These bodies are those which produce a greater flux on Mercury than on the moon. The effect of velocity is thus seen to partially offset the effect of the initial perihelia, tending to result in more uniform crater densities.

4. STORAGE PLACES

Some of the earlier discussion of this problem has centered on the question of whether there exist places in the solar system in which large bodies can be "stored" for hundreds of millions prior to their impacting the moon or planets. This concept of "storage places" has been used in two senses. In the first sense, the bodies are thought of as constrained from impact for a long period of time, after which they become available. Opportunities for storage of this kind are rather limited. Bodies must be formed in a fairly stable orbit which then evolves slowly toward a much more unstable condition containing the possibility of planetary impact. An example of this, mentioned in the previous section, would be satellites of a planet escaping into heliocentric orbits as a consequence of tidal increase of eccentricity (Goldreich, 1963). Another example could be the evolution of Mars-crossing asteroids (such as 512 Taurinensis) with initial perihelia near Mars and aphelion far into the asteroid belt. Perturbations following close approaches to Mars will not be sufficiently great to place the object directly into earth-crossing, but the random walk arising from multiple close encounters can eventually cause the perihelion to cross the orbit of the earth. In the case of an initial swarm of such bodies in nearly identical orbits, no members of the swarm will become earth-crossing until after a fairly distinct time interval of 500–1500 m.y. has elapsed. A similar case, discussed more fully in Section 6, is that of objects in the outer solar system initially crossing the orbits of Uranus and/or Neptune. Perturbations by these planets will cause many bodies to become Saturn-crossing. Perturbations by Saturn will lead to Jupiter-crossing. All this takes time and the first Jupiter-crossers will appear after about 20 m.y. This contrasts with an initial distribution of Mars-crossers in which the perihelia are distributed at random. In this latter case some bodies will cross the earth's orbit almost immediately, and the residual population of Mars-crossers will decrease approximately exponentially. The other sense of the term "storage place" refers to the more usual situation in which there is no special constraint preventing impact with a terrestrial planet, and the delay in striking the planet is simply a

Table 2. Typical lifetimes of planet crossing orbits.

Type of orbit	Approximate half-life (10^6 yr)
Earth-crosser, aphelion ~ 3 a.u.	40
Earth-crosser, aphelion ~ 4.50 a.u.	10
Mars-crosser, perihelion ~ 1.2 a.u.	200
Mars-crosser, perihelion ~ 1.5 a.u.	1200
Jupiter-crosser	1
Saturn-crosser	2
Uranus-crosser	100
Neptune-crosser	200

geometric consequence of close encounters being more probable than impacts. In this case the population decreases more or less exponentially, and the "storage time" is comparable to the characteristic mean life or e-folding time of the exponential decay. It was stated that the decrease is only "more or less exponential," because there is a tendency for the population to evolve into longer-lived orbits by a process of natural selection. The initial earth-crossing orbits used in the calculations given in Table 1 are of this continually decreasing type. Their mean life is typically 10–40 m.y., as given by Monte Carlo calculations (Arnold, 1965; Anders and Arnold, 1965; Wetherill and Williams, 1968; Wetherill, 1974b). Earlier calculations by Öpik (1951) yielded longer lifetimes of ~100 m.y. However these lifetimes are actually only the partial lifetime for planetary impact, and do not include the usually more probable effect of perturbation by earth or Venus to Jupiter-crossing, followed by ejection from the solar system. While it is possible that future more exact treatment of this problem will lead to somewhat longer lifetimes than those given by the Monte Carlo calculations, there is at present no justification for using a 100-m.y. earth-crossing lifetime. Typical lifetimes, given by Monte Carlo calculations, characterizing the stability of various types of initial orbits, are given in Table 2.

In considering impacts by a population in which most of the mass is in a few large objects, from the point of view of mass flux it is not very consequential which of the two types of "storage places" are envisaged, as long as the characteristic times are similar in length. However the flux history of a swarm of smaller bodies can be quite different for the two cases. In the former case there will be a peak in the flux following the finite delay interval, whereas in the latter case the highest flux will occur immediately.

5. BREAKUP WITHIN THE ROCHE LIMIT

There are no known storage places which lead to a simultaneous sharp peak in the flux on the moon and terrestrial planets. The possibility of delayed appearance of bodies in highly unstable orbits was discussed in the previous section. While this can lead to a fairly sharp onset of the flux, the decay of the flux will subsequently be determined by the decay time of the long-lived source, which is comparable in duration to the delay interval.

If one wishes to interpret the photogeological and radiometric age data to indicate a peak flux or "cataclysm" at ~3.9 b.y. and possibly at other discrete earlier times, some other explanation must be found. Several authors have proposed the breakup of a large body in the asteroid belt at that time. This is possible, but very improbable. Combining the impact rates per unit area (Table 1) with the surface area of the planets, and the $\sim 10^{21}$-g mass of the Imbrium projectile leads to the conclusion that $\sim 10^{23}$-g needs to impact the terrestrial planets in order to explain the lunar crater density. A 10^{23}-g body will have a radius of about 200 km. There are at present three asteroids of this size or larger.

The density of matter in the asteroid belt was probably somewhat greater at 4 b.y. than at present, but there is no reason to believe that densities orders of higher magnitudes persisted this late in solar system history. The collision lifetime of 200-km bodies can be calculated from a treatment given elsewhere (Wetherill, 1967) to be $\sim 10^{11}$ yr or longer. The probability of such a collision occurring while the body is in an earth-crossing orbit with a $\sim 10^{7}$-yr lifetime is about 10^{-4}. Therefore the effect of direct impacts will be dominant in comparison with impacts of collision fragments.

There is another way in which ~200-km bodies in earth-crossing orbits may be fragmented which is much more probable. As discussed by Öpik (1951) secular perturbation of the argument of perihelion will cause planet-crossing orbits to evolve on a time scale of $\sim 10^{4}$ yr into orbits which intersect those of the crossed planets. Collisions with the planets can occur during the time interval for which this intersecting condition exists. Quantitative evaluation of this problem leads to the well-known collision formula of Öpik which forms the basis for subsequent Monte Carlo calculations of orbital evolution. The same formula can be used to calculate the probability of close encounter within a given distance of a planet simply by use of the encounter radius rather than the planetary radius. It does not matter that the planet's gravitational field results in an effective "gravitational radius" which is greater than the actual physical radius by a factor of $\sqrt{1 - V_\infty^2/V_g^2}$, where V_∞ is the relative velocity of the small body and the planet (prior to the local gravitational acceleration) and V_g is the planetary escape velocity, since for close encounters, the encounter radius is increased by the same factor. Therefore the probability of encounter within a distance of R_e planetary radii is simply R_e^2 times the probability of impact. A consequence of this is that close planetary encounters do not in any sense constitute an improbable or *ad hoc* assumption, but are a natural consequence of the same dynamical processes which have produced the observed craters on the moon and planets.

When a small body passes sufficiently close to a planet differential gravitational attraction by the planet will generate a stress field within the body which, if sufficiently strong, can lead to its disruption. Roche (1847) considered this problem for the case of a self-gravitating liquid satellite and obtained the result:

$$R_e = 2.44(\rho_0/\rho)^{1/3}. \tag{7}$$

When the encounter distance (in planetary radii) is less than R_e, disruption will occur; ρ_0 and ρ are the densities of the planet and the small body respectively. This expression must be modified in the case of a solid body with non-zero rigidity. The rigid solid body problem has been treated by Jeffreys (1947), Öpik (1950, 1966), and Sekiguchi (1970). This earlier work has been reviewed and extended to elastic bodies by Aggarwal and Oberbeck (1974). The latter authors show that a 200-km radius heliocentric body with a reasonable tensile strength of 10^7 dynes/cm^2, will undergo tensile failure along a complete plane passing through the center of the body within an encounter distance of $1.18(\rho_0/\rho)^{1/3}$ planetary radii. For a "rocky" body with $\rho = 3$ encountering the earth ($\rho_0 = 5.5$) this distance is 1.44 planetary radii, whereas for a predominantly "icy" body with $\rho = 1$, the corresponding encounter distance will be 2.08 planetary radii. Somewhat smaller distances will be found for Venus encounters.

The deformation and rupture has been treated as a static problem, whereas the actual physical problem requires a dynamic analysis of the motion of the fragments during and following disruptions. To my knowledge this has not been done, and is required before this theory can be considered entirely satisfactory. The results above lead to the result that very close approaches are required for disruption. Under these circumstances the number of disruptive encounters will be similar to the number of earth or Venus impacts. Because of the greater surface area of earth or Venus, impacts with these planets are much more frequent than lunar or Mercury impacts (Table 1). Consequently a large body is more likely to undergo a disruptive encounter with earth and Venus and distribute fragments to the moon and Mercury than it is to impact these smaller planetary bodies directly. For the projectile mass-distribution law $\gamma = 0.5$ (Section 2), and disruption into ~ 100 fragments of more or less equal mass, lunar impacts of $\sim 10^{21}$-g fragments of a 10^{23}-g body will outnumber direct impacts of 10^{21}-g bodies by a factor of about 5. Therefore even in this extreme case, disruption can be expected to produce episodes of heavy bombardment distributed throughout the inner solar system.

The possibility that disruption may occur much more easily cannot be excluded. For bodies of this size, tensile failure will occur near the surface at much greater encounter distances. These surface cracks could connect with preexisting surfaces of low strength caused by prior impacts. Bodies of this size which survived the early heavy bombardment accompanying planetary formation (Wetherill, 1972; Kaula and Bigeleisen, 1974) would very likely be highly fragmented. This results from the fact that complete fragmentation following a single impact is the dominant mode of destruction of an asteroidal body up to a radius of ~ 10 km. This is a consequence of the low energy of $\sim 10^6$ ergs/g required to disrupt a finite target (Gault and Wedekind, 1969). However this low energy also limits the average velocity of the escaping fragments to ~ 10 m/sec, which will be below the velocity of escape from a 200-km body. Consequently larger bodies are likely to consist of an assemblage of broken pieces which were unable to escape because of their mutual gravitational attraction. The additional compressive as well as tensile stresses near the surfaces present during the close encounter are likely to impart motions to these surficial fragments and cause a progressive spalling or crumbling from the surface inward. The effect of rotation of the body will also be to facilitate disruption.

It is possible that large bodies of cometary composition will not have experienced an early heavy bombardment sufficiently intense to fragment them because of their being in the far outer regions of the solar system at that time. The breakup of water-rich bodies of this kind could be facilitated by conduction of heat into their interior after being placed in orbits with perihelia <1 a.u. This could cause release of highly volatile compounds which had been bound to water as clathrates. Gaseous pressure might augment the gravitational stress field arising from the close encounter and increase the effective Roche limit. Heating might also cause decreases in density following phase changes in ice which would result in cracking by expansion.

If these possibilities are included, the problem is too complex to permit an exact discussion of either the distance at which disruption can occur or the size distribution of the resulting fragments. The effect of the various conjectures mentioned above would be to make disruption easier, conceivably increasing its probability by up to factor of 10, corresponding to disruption at about 3 planetary radii. In any case, tidal breakup within the Roche limit is a dynamically probable mechanism for producing one or more episodes of heavy bombardment. Whether this heavy bombardment would consist entirely of basin-forming projectiles or would involve many small cratering events would depend on the details of the disruptive process, such as the probability of multiple close encounters and the previous state of fragmentation of the body.

6. CONSIDERATION OF SPECIFIC MODELS

The discussions given in the previous sections lead to the conclusions that a modest total mass of $\sim 10^{23}$ g will suffice to produce the late heavy bombardment, that storage places with sufficiently long lifetimes exist, and that there is at least one mechanism for producing simultaneous episodes of bombardment in the inner solar system. In this section preliminary treatments of some more specific models will be given in order to explore how these conclusions may be implemented in the solar system of 4 b.y. ago. These specific models are chosen to represent more general classes of models, and an attempt is made to choose parameters in such a way as to increase the success of the model. In spite of these attempts, some of the models will be found to possess serious defects. In other cases the models will appear to be more promising, but will still require further understanding before they can be regarded as satisfactory.

Model 1. Residual population of accretional debris in the inner solar system; no Roche limit disruptions

In this case the projectiles at 4 b.y. are simply those which have survived planetary impact and perturbation to Jupiter for 600 m.y. As given in Table 2, the half-life of such bodies is probably only about 30 m.y. However in order to make this model work as well as possible, a longer and less probable half-life of 70 m.y. has been used. Even with this longer half-life many original projectiles are required in order to have a sufficient number survive to 4 b.y. For example, if there originally were $\sim 10^4$ projectiles with mass greater than 10^{21} g, 26 would remain at 4 b.y. Using the data of Table 1, and the lunar and planetary areas there is a reasonable, but much less than certain chance that one of these would strike the moon and produce the Imbrium Basin. Using the mass-distribution law discussed in Section 2, about 3×10^{20} g of smaller bodies would strike the moon in the following 200 m.y., in agreement with the observed Orientale impact and the crater densities of the highland plains units.

The distribution of impact produced highland ages expected for this model is shown in Fig. 1. This calculation includes the effect of later impacts resetting earlier impact ages. In this calculation the mass flux was smoothed, eliminating the statistical fluctuations produced by the largest bodies. If included, these would appear as large "spikes" in the age distribution at <4.2 b.y. Beyond 4.2 b.y. the flux was sufficiently high to effectively eliminate older ages, regardless of whether they were produced by large or small bodies.

Comparison of the calculated ages in Fig. 3 with measured ages from the literature (Fig. 4) exhibits considerable similarity, as reported earlier by Hartung

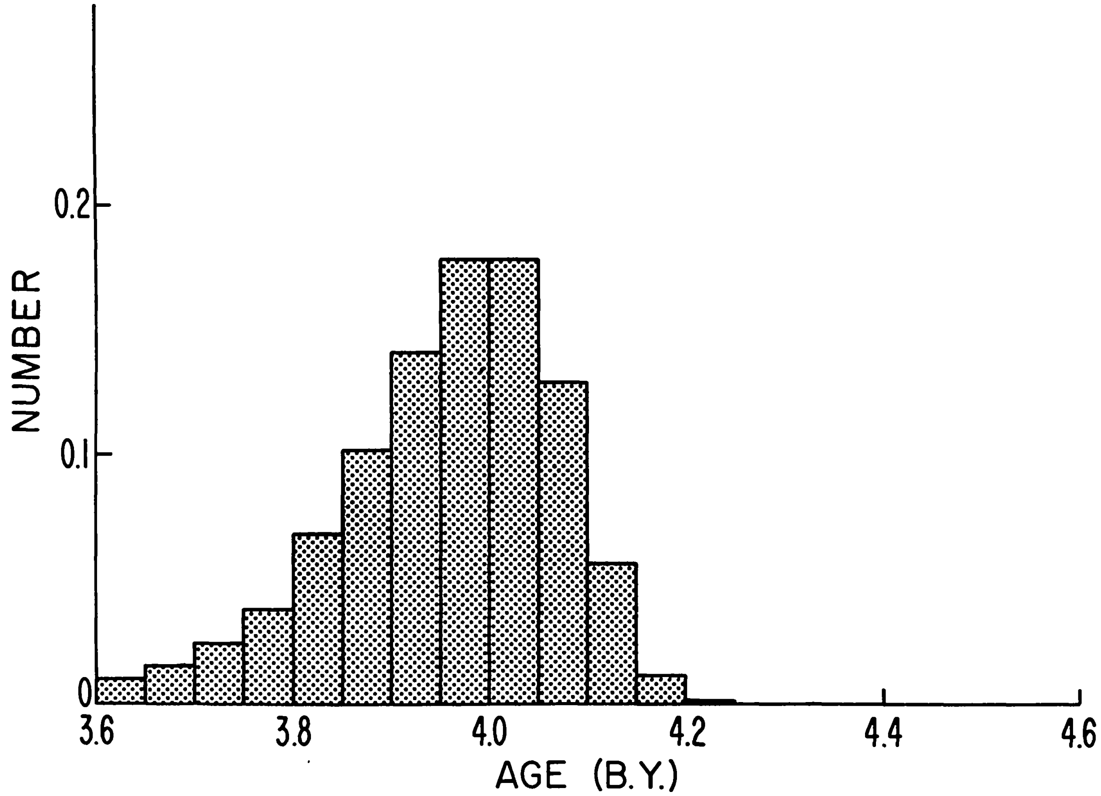

Fig. 3. Calculated distribution of impact-related ages for an initial earth-crossing flux decaying with a half-life of 70 m.y. (Model 1). The intensity of the flux was such that about 10% of the 3.6 mare basalt ages were reset by impact. An apparent peak at ~4 b.y. results from the combined effect of the intense flux eliminating ages >4.2 b.y. and then ceasing to reset ages at ~3.6 b.y. because of the decay in the flux.

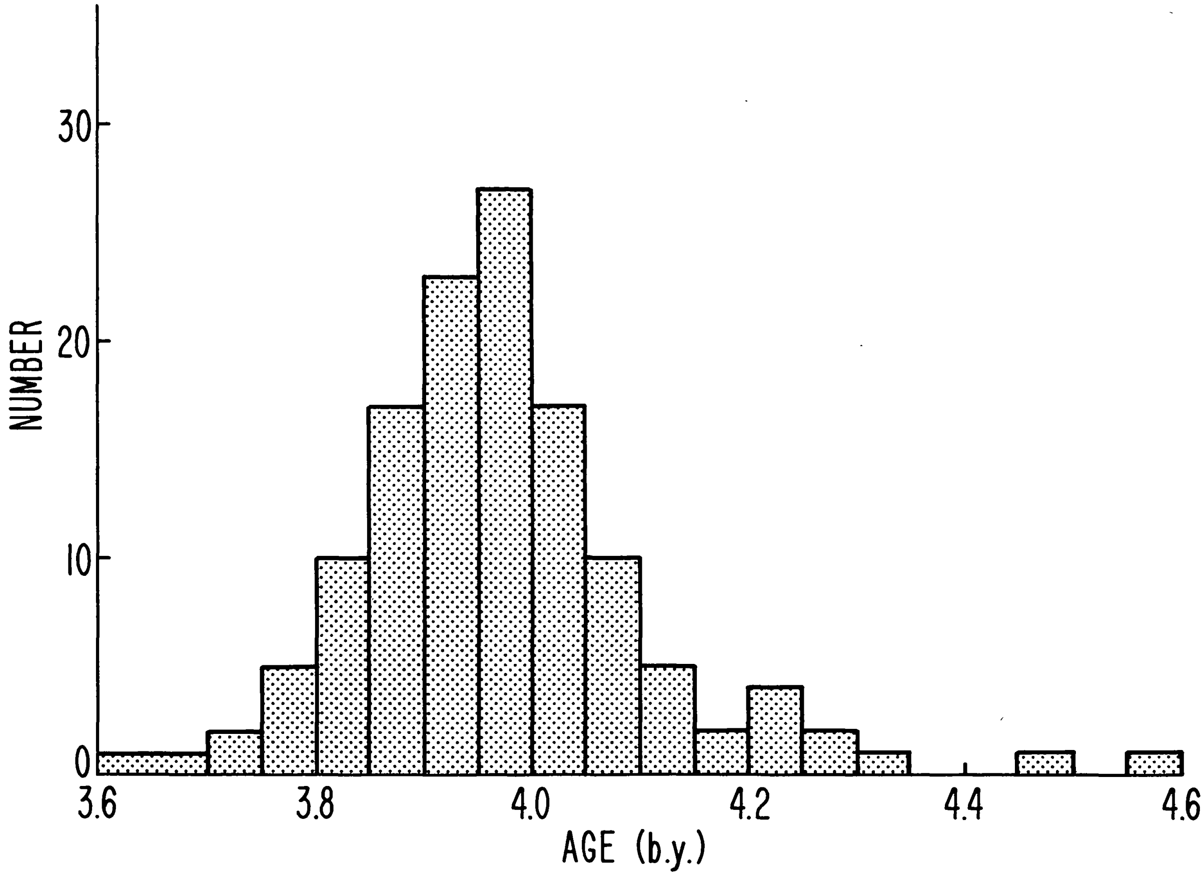

Fig. 4. Observed distribution of highland ages as determined from ^{87}Rb–^{87}Sr isochrons and ^{39}Ar–^{40}Ar plateaus, using data from the literature. Some of the dispersion of the ~4.0-b.y. peak probably results from interlaboratory differences. Some of the ages in the range 3.6–3.8 may be younger igneous rocks transported to the highlands by distant impacts. A few ages >4.2 b.y. appear to have survived the intense late heavy bombardment.

(1974). This similarity can be regarded as a success of this model, but it is also likely that in detail the agreement is only apparent. The spread in measured ages indicated by Fig. 4 is probably caused at least in part by interlaboratory differences, and by inclusion of some small fragments of mare basalts transported onto the highland terrains. In addition, the very heavy flux prior to 4.2 b.y. eliminates the possibility of older ages, for which there are some evidence (Papanastassiou and Wasserburg, 1975; Jessburger *et al.*, 1974; Kirsten and Horn, 1974).

The greatest difficulty with this model is the large mass of fairly high velocity objects required to remain in the inner solar system after the accretion of the moon and planets. If the number (~10^4) of 10^{21}-g objects is combined with the observed mass-distribution law, the total mass of this population turns out to be 2×10^{29} g. Even if it is conceded that the mass distribution should be cut off before this mass at which ~1 body should be present, it is hard to avoid requiring at least 10^{26} g, more than the mass of the moon, and about 100 times the mass of the present asteroid belt. The effects of the early heavy bombardment as well as subsequent mutual collisions between members of this residual large population would also be expected to generate a steady-state mass distribution, rather than the distribution observed.

Model 2. Same as Model 1, but with Roche limit breakup of ~10^{23}-g bodies

This model has many features in common with that discussed above, but differs in that the mare basins are excavated by fragments of larger bodies disrupted by close encounters with the earth and Venus. In order to have about one chance in three of one such 10^{23}-g body surviving to 4 b.y. so as to produce the Imbrium and Caloris (Mercury) impacts it is necessary that there be ~100 such bodies remaining in high-velocity orbits in the inner solar system after the accretion of the moon and planets. The residual flux of small bodies and the predicted distribution of impact-produced lunar ages are very similar to those of Model 1. The total mass requirements are somewhat less than for Model 1. The need for ~100 10^{23}-g bodies at 4.6 b.y. when combined with the $\gamma = 0.5$ mass-distribution law leads to a total requirement of 2×10^{27} g. Again, there could be a high mass cutoff at about a lunar mass which would reduce the total mass requirement to ~10^{26} g. As before, no high ages would be expected, and the absence of a collisional steady-state age distribution is still unexpected. However this argument is weakened by the superposition of the unknown mass distribution following close encounter.

Model 3. Mars-crossing population with Roche limit breakup

The high total mass requirements of the earth-crossing population found for the two previous models was primarily the result of the short lifetime of bodies in this type of orbit. This difficulty can be avoided by supplying the projectiles from a storage place with a longer lifetime. Mars-crossing orbits have this property (Table 2). This can be illustrated by a model in which a Mars-crossing half-life of 200 m.y. is used. After the bodies are perturbed by Mars into earth-crossing, their residual lifetime in the inner solar system is assumed to be 40 m.y. As before, minimum mass requirements are associated with models invoking Roche limit disruption, and this dynamically plausible process is therefore assumed. In order to have about one chance in three of a ~10^{23}-g body still in Mars-crossing orbit at 4 b.y. only 3 such bodies need be initially present. The previously used mass-distribution law requires a total high velocity mass of only ~10^{24} g in the inner solar system. The resulting smaller lunar flux >4.2 b.y. ago now permits some survival of ~4.6-b.y. lunar ages, and the mass and half-life of the residual post-Imbrium flux will be in accordance with observations. The low total mass requirements eliminate the expectation of a collisional steady-state mass spectrum, provided this had not already been imposed by the early heavy bombardment associated with the formation of Jupiter. Even this may not be a problem as the superposition of the very uncertain mass distribution of the close encounter fragments on the collisional spectrum could distort the latter considerably.

Therefore in many ways this model is very attractive, and to some extent contributions from such Mars-crossing sources are probably unavoidable. A consequence of this model constituting the *dominant* explanation for the late heavy bombardment of the moon and Mercury is that the Mars-cratering time scale would not be the same as that of the moon and other terrestrial planets. As may be seen from Table 1, initial Mars-crossing orbits have about a 10-fold greater probability per unit area of striking Mars than striking elsewhere in the inner solar system. Therefore decay to a flux equal to that of the lunar and Mercurian plains units would require an additional 3 half-lives, or about 600 m.y. Present understanding of the Martian time scale is certainly not sufficient to rule out this possibility. Therefore this difference in the time scales should be regarded simply as a consequence of the model, rather than as a difficulty.

There is a problem with this model which appears more serious, and which was avoided only by the somewhat arbitrary assumption of a 200-m.y. half-life for Mars-crossing bodies. Although initial Mars-crossing orbits with this half-life can be easily found, Monte Carlo calculations of the evolution of many Mars-crossing orbits also yields much longer lifetimes, up to ~2000 m.y. If the residual post-accretion population of Mars-crossing bodies were some sort of a random one rather than the special one assumed, a major contribution from these long-lived bodies would be expected. The absence of post-Orientale mare basins and the rapid decay of the post-Imbrium flux of small bodies argues against this possibility. An initial distribution of this kind may also be in conflict with the present mass of only $\sim 10^{19}$ g in distinctly Mars-crossing orbits. A conceivable way to avoid this difficulty may involve elimination of these otherwise long-lived orbits by interaction between Mars perturbations and the secular resonances discovered by Williams (1969, 1971) as mentioned earlier (Wetherill, 1974b). However this will remain only a speculative possibility until a more serious evaluation of this mechanism is carried out.

Model 4. Outer solar system source with Roche limit breakup in the inner solar system

Most of the mass of the solar system, exclusive of the sun, is in the region of the major planets. Previous authors (Öpik, 1965, Safranov, 1972) have shown that in the final stages of accretion of the major planets, masses of planetesimals approaching the masses of the major planets themselves will be perturbed into highly eccentric orbits, penetrating into the inner solar system as well as into hyperbolic escape orbits. This acceleration is the mechanism proposed by Oort (1950) for obtaining the long period orbits of the comets from the region of Jupiter. Subsequent authors, e.g. Kuiper (1951) have proposed that the region of Uranus and Neptune represent a more plausible source of the original cometary bodies, otherwise the mechanism is similar to that of Oort. The acceleration of residual material from the formation of Jupiter into the inner solar system (Wetherill, 1972; Kaula and Bigeleisen, 1975) has been discussed as the cause of an early heavy bombardment accompanying the $\sim 10^7$-yr accretional phase of the solar system.

The large mass of Jupiter and Saturn results in the lifetime of the early heavy bombardment being limited to 10^6–10^7 yr. However the analogous process associated with the formation of Uranus and Neptune is a possible source of a late heavy bombardment persisting until 3.9 b.y. ago, associated with the longer characteristic lifetime (Table 2) of bodies from this region of the solar system. Evidence that large "planetesimals" existed in that region of the solar system is not based entirely on theoretical arguments. The existence of Pluto, of mass $\sim 10^{27}$ g in Neptune-crossing orbit (stabilized by resonances) suggests that unstable orbits in Pluto's vicinity were also populated early in solar system history. The inclination of the axis of Uranus to the plane of the solar system also suggests that there were separate very large bodies present in that region at the time that planet was formed.

The process considered here involves perturbation of the bodies into Saturn and then into Jupiter-crossing from which time on the further evolution of their orbits would be similar to those of short-period comets (Everhart, 1973a,b). This required chain of events decreases greatly the inner solar system mass flux expected from the region of Uranus and Neptune, as it is necessary that bodies evolving into inner solar system orbits, similar to that of comet Encke, traverse the "Jupiter barrier," which much more often results in ejection from the solar system. Cometary observations and crude theoretical calculations suggest an efficiency of $\sim 10^{-3}$ for capture of a Jupiter-crossing object with aphelion near Neptune into an Encke-like orbit with aphelion near 4.2 a.u. Non-gravitational forces (Marsden and Sekanina, 1971) would be expected to play an important role in this process, that of sometimes permitting the aphelion of the body to evolve safely inside the orbit of Jupiter.

Monte Carlo calculations have been used to calculate the time dependence of the evolution into Jupiter-crossing of an initial population consisting of an equal number of Uranus-crossers and Neptune-crossers. Following Jupiter-crossing, further evolution of the orbits will take place on a much shorter time scale of 10^5–10^7 yr. Therefore the time dependence of any late heavy bombardment of the inner solar system will be the same as that given by the injection rate into Jupiter-crossing. The results of these calculations are given in Fig. 5 in the form of a cumulative impact rate (in arbitrary units) as a function of time. These calculations give about a 5-fold decrease in this cumulative impact rate prior to 4.0 b.y. This factor could be raised considerably by use of different numbers of Uranus-crossers relative to Neptune-crossers. If there were originally $\sim 2 \times 10^3$ objects in the outer solar system with mass greater than 10^{23} g, there would be a good chance of one such body being transferred to an Encke-like orbit as late as 4.0 b.y. ago. The associated lunar flux of smaller bodies (using $\gamma = 0.5$; see section 2) will be 2×10^{20} g, in agreement with observation. A large portion of the impact-related ages would be produced by the single randomly timed 10^{23}-g body after disruption by close encounter to the earth or Venus. A significant number of 4.6-b.y. ages would survive, and there is no necessary reason for the mass distribution to represent a collisional steady-state.

The total mass required in the outer solar system is very large but not

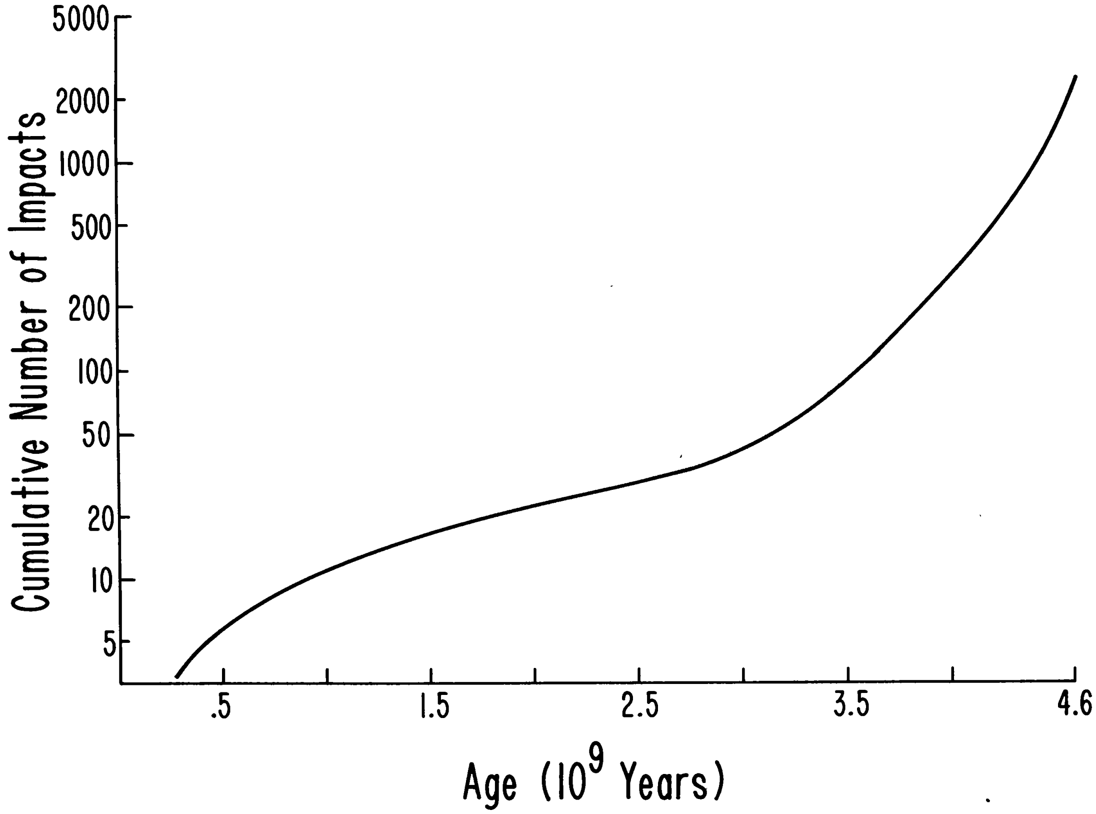

Fig. 5. Calculated time dependence of impacts in inner solar system by bodies initially in Uranus- and Neptune-crossing orbits. An equal number of Uranus- and Neptune-crossers were used, and a range of initial eccentricities were employed. It is assumed that a swarm of these bodies were in these initial orbits 4.6 b.y. ago. The cumulative number of impacts less than a given age are given in arbitrary units (on a logarithmic scale) on the ordinate.

necessarily prohibitive. If the mass-distribution law is extended to the mass of the single largest body, a total mass of $\sim 10^{29}$ g is required, comparable to the mass of Uranus and Neptune. As in the previous cases it is probably not necessary to go this far, and $\sim 10^{28}$ g will probably suffice, equal to about 1 earth mass. This is similar to or less than the mass required to produce the cometary cloud, particularly when the inefficiency of placing comets into the necessary long-period orbits rather than into hyperbolic orbits is considered. If the late heavy bombardment is considered as the effect on the inner solar system of the formation of the cometary cloud, the observed lunar and Mercury effects are about those to be expected.

It is believed that this model of the late heavy bombardment should be taken seriously, rather than dismissed as *ad hoc* (Hartmann, 1975). It is not *ad hoc*, being associated in an essential way with other processes in the solar system, namely major planet and comet formation, rather than simply being invented to explain the late heavy bombardment. However there is much to be done before this model can be considered a probable one. Most of the problems which need to be solved have been alluded to, such as the efficiency of transfer into an

Encke-like orbit, the details and time scale of the accumulation of the major planets, and the actual process by which the cometary cloud was populated. It should also be pointed out that the possible effects of resonances in the outer solar system could not be incorporated into the calculations leading to Fig. 5; this aspect of outer solar system dynamics has barely been considered (Williams, 1969).

7. CONCLUDING REMARKS

The central question of whether it is dynamically permissible to extend to other planets the late heavy bombardment observed and dated on the moon can be answered. The answer is yes: bodies in a wide class of orbits will have very similar probabilities for impacting the moon and terrestrial planets, there exist at least two "storage places" which are sufficiently long-lived, the mass requirements are not excessive, and there is a dynamically plausible mechanism for producing simultaneous episodes of heavy bombardment on all the terrestrial planets.

Attention can then be shifted from the question of whether this hypothesis of simultaneous late heavy bombardment is permissible to the much more difficult question of whether or not it actually occurred. Evidence for a negative answer could come about if more detailed studies of the problems discussed in this paper brings out serious difficulties which have escaped attention herein. It is also possible that future photogeological studies will require differences in the impacting flux which cannot be explained in terms of a common source.

Positive evidence for the hypothesis may some day come from radiometric dating of impact-related rocks from other terrestrial planets. At present the only bodies in the solar system other than the earth and the moon which can be dated in this way are the parent bodies of the meteorites. As reviewed elsewhere (Wetherill, 1974b) there is considerable uncertainty concerning the location of these parent bodies in the solar system. It seems likely that at least most differentiated meteorites–achondrites, irons and stony-irons are of asteroidal origin, even though skepticism on this matter would prove difficult to refute. The projectiles of the late heavy bombardment should have spent much of their time in the asteroid belt, and thereby increased the impact rates on the parent bodies of these differentiated meteorites, and this should be reflected in the result of meteorite age measurements.

Even if it occurred, this increased impact rate in the asteroid belt may not have been very pronounced, because of the high background collision rate in this region of the solar system. For example, there are at present about 30 asteroids equal to or larger than the Imbrium planetesimal ($R \cong 50$ km). If the late heavy bombardment involved an additional 100 projectiles of this size, the number of such bodies would be increased by only a factor of four. The duration of the bombardment would be ~30–100 m.y., and the integral flux on the asteroids would primarily represent impacts unrelated to the late heavy bombardment. It may also prove difficult to distinguish between impact metamorphism and melting and similar rocks resulting from internal heating of the meteorite parent bodies. At present there is some evidence for differentiated meteorite ages in the vicinity of 3.8 b.y. (e.g. Burnett and Wasserburg, 1967; Papanastassiou *et al.*, 1974). However it is premature to say whether these data argue for or against a simultaneous late heavy bombardment in the inner solar system.

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