A possible reason for the difference in optical characteristics of the lunar highlands and those of the maria (suggested by this investigation) is that the maria have somewhat more iron, since increasing the iron abundance decreases the albedo and makes the material bluer. The appearance of the moon suggests that the highland areas of the moon may be less differentiated than the maria, which are probably lava flows.

A higher iron content for the maria is consistent with this observation, since terrestrial experiments (*14*) have demonstrated that a basaltic melt differentiating under reducing conditions has a higher ratio of FeO to MgO than the parent material. Thus the highlands may be closer in composition to primordial lunar crustal material than the maria, which is the opposite of the situation on the earth. The lower iron content of the highlands is also consistent with the suggestion by Duke (*15*) that the maria have the composition of eucrite achondrites and the highlands of howardite achondrites, since the latter have somewhat lower iron abundances than the former.

Results from the Surveyor V α-scattering experiment have now become available (*4*) and indicate that the composition of the lunar surface near the southwestern edge of mare Tranquillitatis is similar to that of terrestrial basalts and also to basaltic achondrites. The resolution of the instrument was not sufficient to distinguish elements with atomic numbers between that of phosphorus and copper. My results suggest that iron is a major constituent of this group and that the mare material resembles terrestrial ferrobasalts. The optical properties of the moon imply that the composition determined by Surveyor V is representative of all the maria and, to a rough approximation, of the entire lunar surface.

Surveyor V also carried a magnet attached to one of its footpads. Some soil collected on the magnet, indicating the presence of a ferromagnetic mineral in the soil. From the amount of material clinging to the magnet the investigators estimated that there was less than 1 percent metallic Fe in the soil, a conclusion in agreement with my data (*4*).

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11. I thank the following persons and institutions for donating materials for this study: K. Fredriksson and R. Clark, Jr., U.S. National Museum; E. Lenker and W. LeMasurier, Cornell University; E. Olsen, Chicago Natural History Museum; R. Folinsbee, Univ. of Alberta; J. O'Keefe, NASA, Goddard Space-Flight Center; D. Chapman, NASA, Ames Research Laboratories; M. Duke, U.S. Geological Survey; A. Cohen, Univ. of Pittsburgh; T. Gehrels, Univ. of Arizona; D. Nash and J. Adams, Jet Propulsion Laboratories; W. Elston, Univ. of New Mexico; J. Green, Douglas Aircraft Co.
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4 October 1967; revised 1 November 1967

Stone Meteorites: Time of Fall and Origin

Abstract. *The fact that twice as many chondritic meteorites are observed falling in the afternoon as in the morning is not believed to be primarily of social origin, but to be a dynamic effect. Monte Carlo calculations show that the observed afternoon excess is not compatible with a lunar or Apollo asteroidal origin. Compatibility appears to require a source having an aphelion near Jupiter, such as could be provided conceivably by the Hilda or Trojan families of asteroids, or by short-period comets.*

It has long been known that considerably more chondritic meteorites are observed falling in the afternoon and evening hours than in the morning (Fig. 1A). Although the statistical significance of the data is much poorer, this fact does not seem to be true for the achondrites as a whole (Fig. 1B). It is certain that the principal reason for the rarity of early-morning falls is that there are then fewer observers; to a lesser extent this is also true of evening falls. This social bias probably is not very effective during daylight hours; most falls of meteorites have been observed by farmers working in the fields, and should have been observed essentially equally well during the morning or afternoon. Nevertheless, even if the hours between 1800 and midnight and between midnight and 0600 hours are excluded, the proportion of daylight falls occurring in the afternoon is still .66; that is, there are nearly two afternoon falls for every morning fall. If the true probabilities of morning and afternoon falls were equal, the probability of this proportion occurring by chance is less than 10^{-4}. If the true proportion is .62 or .70, the probability of statistical fluctuations causing an observed proportion differing by as much as .04 is about 5 percent. Therefore the statistical uncertainty in the proportion may be taken to be $\pm$ .04. The corresponding proportion in the achondritic data is .50 $\pm$ .14.

It is commonly stated that this preponderance of afternoon falls for chondrites shows that the majority move in direct rather than retrograde orbits about Sun. While true, this is a considerable understatement of the implications of the data. Wood (*1*) showed that the observed time-of-fall

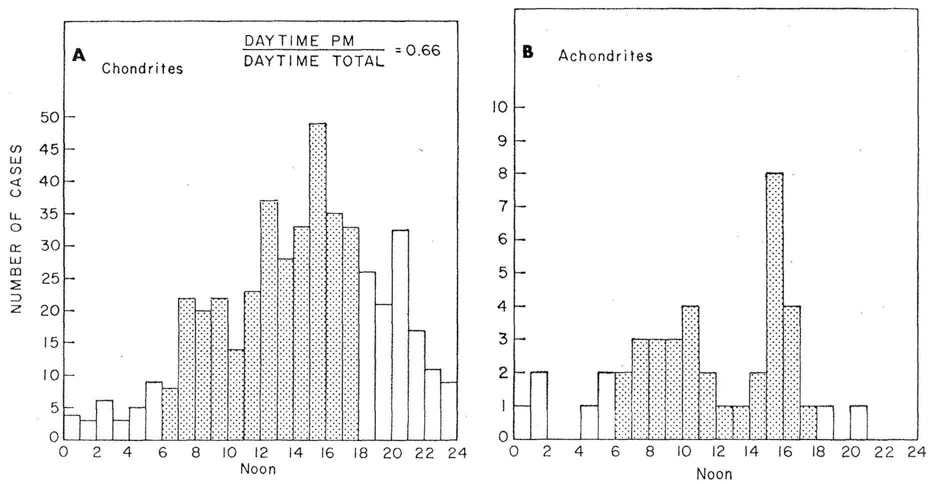

Fig. 1. Observed local times of fall of stone meteorites. The shaded portions between 0600 and 1800 hours, approximating the hours of daylight, should be relatively free of social bias. (A) Observed local times of fall of chondrites; afternoon falls predominate. (B) Observed local times of fall of achondrites; morning and afternoon falls are approximately equal in number, and the number of events is small.

data were inconsistent with a lunar origin. I shall show that they are also inconsistent with an origin in objects in considerably more eccentric orbits, such as the Earth-crossing Apollo asteroids or Encke's comet, and that the only sources that can be reconciled with the observations are those in direct orbits of low inclination, with aphelia near Jupiter and perihelia very near the orbit of Earth.

It has been pointed out that the short (0- to 100-million-year) cosmic-ray-exposure ages of stone meteorites indicate that they are very likely fragments of objects either already in Earth-crossing orbits or having a high probability of being perturbed into Earth-crossing orbits on a time scale of the order of 1 million years or less (*2–5*). Therefore principal attention will be given to sources with orbits of this kind. An alternative explanation of these short cosmic-ray-exposure ages is that stone meteorites are preferentially destroyed by interplanetary collisions on a time scale of a few million years. If this is true, the Mars-crossing asteroids also must be included as a possible source, but this alternative has been shown to be unlikely (*4*).

Afternoon and evening times of fall are characteristic of meteorites impacting Earth with their tangential component of heliocentric velocity greater than that of Earth; that is, their tangential component of geocentric velocity (U_y) is positive, and they are overtaking Earth (Fig. 2). Furthermore their radial (U_x) and perpendicular components (U_z) of geocentric velocity must be small compared to U_y. Positive heliocentric tangential velocities (direct orbits) by no means imply positive geocentric tangential velocities (U_y). Furthermore, even if U_y is positive, moderate inclinations (about 15 deg) and arguments of perihelion (for example, 30 deg) can cause U_x and U_z to predominate. In this case, meteorites will arrive approximately from the directions defined by lines from Earth's center through the great circle *ZSZ′* (Fig. 2).

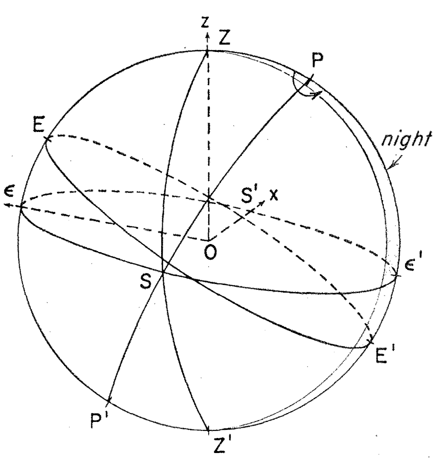

Fig. 2. Coordinate system used in calculations. The plane *E–E′* is that of Earth's equator, *S* is the subsolar point on Earth's surface, and *PSP′* is the great circle passing through Earth's poles and the subsolar point. The positive *x*-axis is directed radially in a direction opposite to that of Sun; the *y*-axis is perpendicular to the *x*-axis in the plane of the ecliptic as shown. The positive *y*-direction is approximately the direction of Earth's heliocentric motion. The *z*-axis is perpendicular to the plane of the ecliptic as shown. Meteorites with small values of the *x* and *z* components of geocentric velocity, and with positive *y*-component (U_y), will strike Earth predominantly on the right-hand side of the figure—the p.m. hemisphere.

Since most meteorites will not be on trajectories aimed directly at Earth's center, but will be off-center by a good fraction of Earth's radius or more, meteorites arriving from these directions will divide nearly equally into a.m. and p.m. hemispheres. The effects of Earth's gravitational field on meteorites of low geocentric velocity, as well as the tilt of Earth's axis with respect to its orbital plane, will further diminish any morning-versus-afternoon fall-time asymmetry. If afternoon falls are to predominate despite these factors, it is necessary not only for U_y to be positive and high (for example, 6 km/sec), but also for the inclination to be low (in order that U_z be small). Furthermore, the node at 1 astronomic unit (A.U.) (a necessary condition for Earth impact) must be near the meteorite's perihelion for U_x to be small and U_y to be positive.

From this discussion one can see that only rather special distributions of meteorite orbital elements will lead to a marked excess of afternoon falls. If one states the problem in terms of the initial orbital elements of the meteorite rather than its final elements at the time of Earth impact, the observed afternoon excess is considerably more restrictive. This fact may be understood as follows: Consider a fragment spalled from an Earth-crossing body by a minor collision. At the low relative velocity characteristic of most ejecta of hypervelocity collisions (*6*), the initial orbit of the fragment will be essentially that of its parent body. If this orbit has its perihelion near Earth's orbit and is not too highly inclined, and if Earth impact occurs before the orbit of the fragment is significantly changed by planetary perturbations, afternoon impact is most probable.

However, after about 10^5 years planetary perturbations, primarily close approaches to Earth, will cause the orbital elements of the fragment to change. The total geocentric velocity will be approximately invariant (*7*), but its components U_x, U_y, and U_z will vary. After a time of the order of 10^7 to 10^8 years, the direction of the total geocentric velocity vector will be randomized, and aphelion at 1 A.U. will be just as probable as the initial condition of perihelion at 1 A.U. Thus, even if the initial orbital elements are those characterized by afternoon impacts, the orbit will tend to evolve with time in such a way as to destroy this initial asymmetry. In fact, with the passage of time, morning falls may tend to predominate because orbits of large semimajor axes and with perihelia near Earth are preferentially perturbed into Jupiter-crossing orbits and subsequently ejected from the solar system.

The evolution of the orbits of fragments of actual bodies in the solar system was studied by use of a modification of Arnold's (*2*) Monte Carlo procedure (*4*). For runs that terminated in Earth impact, the distribution of points of impact on Earth was then calculated. In this calculation it was assumed that the impact trajectory intersected a random point on a target circle, centered on Earth, perpendicular to the meteorite's geocentric velocity vector and having a radius equal to the gravitational radius of Earth:

$$r = R\ (1 + S^2/U^2)^{\frac{1}{2}}$$

where R is the physical radius of Earth, S is the escape velocity at Earth's surface, and U is the geocentric velocity (at infinity) of the meteorite. The equations relating the orbital velocity components and other relevant parameters to the point of impact have been given (*1*). The local time at the point of impact was then determined by a coordinate transformation using the present relation between the solstices and the position of Earth in its orbit; the latter quantity had been fixed by the last perturbation of the Monte Carlo calculation.

The calculated local time-of-fall distribution for fragments ejected from Moon at velocities up to 1 km/sec above the lunar escape velocity are shown in Fig. 3A (*8*). The proportion of the falls that occurs in the afternoon and evening between noon and midnight (f) is .51 ± .01. No marked structure is observable in the distribution of fall time. If very special initial ejection trajectories are assumed (for example, initial velocities relative to Moon of 3.5 km/sec, entirely in the forward or in the backward direction), calculated values of f lie within the range .49 to .54. If one assumes that our sampling of meteorites is biased by requirements for survival of passage through Earth's atmosphere in such a way that bodies impacting at high angles and high velocities are destroyed, the conclusions are essentially unaltered.

The distribution of local times of fall for fragments of a typical Earth-crossing (Apollo) asteroid, 1959 LM, are shown in Fig. 3B; for this body, f = .42 ± .02—that is, morning falls predominate. The distribution of fall times has a minimum during the afternoon hours for which the observed chondrite fall times (Fig. 1A) show a maximum. Similar calculations have been made for the other eight known Apollo asteroids: calculated values of f range from .27 ± .03 (Icarus) to .53 ± .02 (1950 DA). In no instance is a pronounced afternoon excess observed, and, insofar as any significant structure in the distribution is found, a minimum rather than a maximum around 1600 hours is obtained.

Encke's comet is the only observed Earth-crossing comet having aphelion less than 4.5 A.U. and thus removed from Jupiter's sphere of influence; the comet is known (*9*) to be a significant source of shower meteors. For fragments of this body, f = .34 ± .02, and the number of falls between 1500 and 1600 hours is only about half the average hourly number.

The calculated fall times of fragments of all these bodies are inconsistent with the observed fall times of chondrites. When one considers the poor statistics for the achondrite falls, together with the absence of any pronounced p.m.-versus-a.m. effect, a lunar or Apollo-asteroidal origin for these meteorites cannot be excluded by these data. Furthermore, again because of poor statistics, any minor class of chondrites—for example, the type-I or type-II carbonaceous chondrites—could be lunar ejecta. However the time of fall of the bulk of the chondrites, primarily consisting of the "ordinary" bronzite and hypersthene chondrites, cannot be reconciled with any of these sources. Insofar as the rarer types of chondrites have textural or chemical characteristics that make it seem unlikely that they originate in bodies entirely different from the source of the ordinary chondrites, these restrictions apply to these meteorites as well.

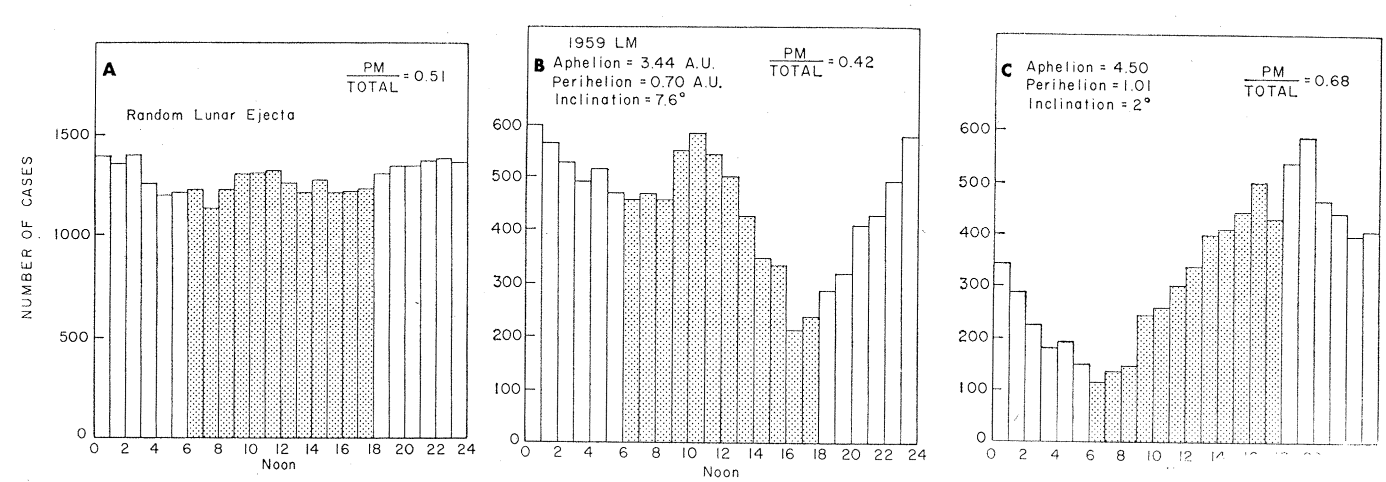

Fig. 3. Theoretical distribution of fall times, calculated by the Monte Carlo procedure; hours between 0600 and 1800 are shaded. (A) Calculated fall times for meteorites ejected from Moon at velocities up to 1 km/sec above lunar escape velocity in random directions; very little structure is seen, especially for the daylight hours. (B) Calculated fall times for fragments of a typical Earth-crossing (Apollo) asteroid; a pronounced minimum occurs in the late afternoon. (C) Calculated fall times for fragments of a hypothetical body having aphelion near Jupiter and perihelion near Earth. The calculated results resemble the chondritic data of Fig. 1A in that afternoon falls predominate, with a maximum in the late afternoon.

One can find initial orbits that lead to time-of-fall distributions similar to those found for the chondrites; these have perihelia barely within the orbit of Earth, low inclinations, and aphelia in the range 4.2 to 4.5 A.U. For such orbits, evolution into orbits having aphelia near Earth is suppressed by the proximity of their initial aphelia to Jupiter; relatively small Earth perturbations will cause the aphelion to cross Jupiter's orbit, after which Earth impact is extremely improbable. Thus most of the Earth interactions take place near perihelion, resulting in the predominance of afternoon falls.

An example of the distribution of fall times from such an initial orbit is shown in Fig. 3C. For this initial orbit, $f = .68$, and the shape of the distribution is similar to that of the chondrites for daylight falls. It is unlikely that the discrepancy between the observed and calculated falls for the hours between 1800 and midnight is of dynamic origin, because of the symmetry of the dynamic equations with respect to positive and negative values of U_x. The fact that most of the recovered meteorites have fallen in rural areas prior to electrification more likely suggests that during the evening a higher fraction of meteorites is not recovered, because of the scarcity of observers as well as the greater difficulty of locating fragments in the dark. It may even be surprising that in spite of these difficulties more meteorites have been recovered during these evening hours than between 0600 hours and noon.

Similar distributions, with lower values of f (ranging up to .57) have been obtained by use of the initial orbits of Mars-crossing asteroids. However, the predicted cosmic-ray-exposure ages of these bodies (about 10^9 years) are inconsistent with those of stone meteorites. Attempts to reduce these calculated exposure ages by collisional destruction are not satisfactory for several reasons, one of which is that the contribution of meteorites produced as fragments of Mars-crossing asteroids, perturbed into Earth-crossing orbits, then becomes very significant. As I have mentioned, these Apollo asteroid-like orbits do not yield the observed afternoon excess.

Thus it appears that an Earth-crossing source for the chondrites requires the existence of unobserved bodies of low inclination, with perihelia very near 1 A.U. and aphelia in the vicinity of Jupiter. The fact that such bodies have not been observed is not a strong argument against their existence; bodies as large as 30 km in radius in such an orbit may have escaped discovery (*5*). One can also reconcile the data with the calculations if there exist sources not necessarily in Earth-crossing orbits, the fragments of which nevertheless may be placed in an Earth-crossing orbit on a time scale of 10^6 years. The lifetime of either the hypothetical parent body or fragments in an Earth-crossing orbit will be of the order of 10^7 years, the lifetime being primarily controlled by the time required for the objects to be ejected from the solar system by Jupiter.

Some observed bodies in the solar system that might serve as the necessary continuing source for either the hypothetical large Earth-crossing bodies, or the Earth-crossing fragments, are the periodic comets of Jupiter's family, the Trojan asteroids, the Hilda asteroids, or possibly 279 Thule.

If they possess stony cores (*10*) the periodic comets will spend a significant portion of their dynamic lifetime of 10^5 to 10^7 years in Earth-crossing orbits. However, there is no observational or theoretical basis for belief that these Earth-crossing orbits will usually have perihelia near 1 A.U., as is required. Encke's comet is typical of comets "decoupled" from Jupiter; it has been shown that its orbit leads to a morning rather than afternoon excess.

The Trojan asteroids move in relatively stable Jupiter-crossing orbits within the 60-deg-libration regions of Jupiter's orbit. It is conceivable that because of perturbations by Saturn the orbits of the bodies themselves may become unstable; in this case they will be frequently perturbed into Earth-crossing orbits before they are ejected by or collide with Jupiter. Alternatively, their collision ejecta may undergo a similar history. Again, it is unlikely that the necessary perihelion at 1 A.U. would be sufficiently well stabilized.

The Hilda asteroids have aphelia within Jupiter's sphere of influence and therefore might be expected to be short-lived. However, their orbits are stabilized because the ratio of their periods to that of Jupiter is very nearly 2 : 3. As with the Trojans, the orbits of either these bodies or their ejecta could become unstable and frequently Earth-crossing on the appropriate time scale. Stabilization of the perihelion at 1 A.U. seems more likely in this case, because the orbits are not initially Jupiter-crossing; the consequent smaller perturbations by Jupiter may be expected to cause the orbits to become Earth-crossing in a more gentle way. However, approximate calculations of Jupiter perturbations on these orbits indicate that in the great majority of instances the bodies become Jupiter-crossing before they are Earth-crossing.

In any case, quantitative treatment of the evolution of these orbits with aphelia in proximity to Jupiter, and involving commensurability, is beyond the scope of present Monte Carlo techniques, as well as of conventional celestial mechanical methods applicable to time scales of 10^4 years or longer. Further evaluation of the role of these bodies in the origin of chondrites will depend to a large extent on the development of new theoretical techniques.

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11. I thank H. C. Urey, J. Wasson, and J. G. Williams for discussions; and A. D. Sharbaugh for assistance in compilation of data for the figures. Free use of the U.C.L.A. computing facility is gratefully acknowledged. Publication costs were provided by NASA grant NsG 313-63.

15 September 1967