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ASTEROID COLLISIONS, CRATERS, REGOLITHS, AND LIFETIMES

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Collisional and cratering processes in the asteroid belt fundamentally determine the physical character of the asteroids, including their present numbers, sizes, shapes, spins, internal properties, surface layer textures, and surface topographies. Recent research on these topics is reviewed here, in the context of both asteroidal science and potential mission-planning. Ground-based observational constraints on asteroid collisional processes are relatively weak and indirect. What we believe we understand about these processes results largely from preliminary attempts at theoretical modeling and extrapolation of experiments far beyond laboratory scales. Asteroids, including the larger ones, are a thoroughly fragmented population of bodies if our extrapolations of laboratory experiments to very large scales are at all correct. Interiors of most larger asteroids should be thoroughly fractured. Surface regoliths are probably substantial, except on the smallest and strongest bodies, but should be very poorly mixed in comparison with the lunar regolith. Lateral heterogeneities are probably masked by recent ejecta deposits, except on the smallest and largest bodies. Phobos and Deimos are probably *not* saturated with craters, but in any case do not provide exact analogs for asteroidal cratering. Asteroid crater statistics will provide chronological information pertinent to only very recent epochs of solar system history.

INTRODUCTION

The most important process affecting asteroids subsequent to the early epochs of solar system history has been their collisional interaction with each other and with the complete size-spectrum of interplanetary debris. Of course our knowledge of "geological" processes on asteroids must be based on inferences from remote observation and we may be surprised once we examine an asteroid "up close." But most asteroids are very small and cannot retain atmospheres or generate sufficient internal heat to drive geochemical or endogenic geomorphological processes throughout a major portion of solar system history. Thus we expect that the geological evolution of asteroids has been governed, as has that of the Moon for the last 2-3 AE, by their collisional interactions.

Understanding the collisional evolution of asteroids is now arguably the most important part of asteroidal science for several reasons. First, nearly every observable property of asteroids can be shown to be determined by, or substantially affected by, collisions. Asteroid sizes, shapes, and spins are believed to be due to collisional fragmentation and inferences from telescopic observations concerning asteroid surface compositions and textures depend substantially on the nature and evolution of asteroidal regoliths. A second reason for studying asteroid collisional evolution is that collisions serve partially to mask what asteroids might tell us about the early conditions during the accretionary period of planet formation. A dominant reason for scientific interest in asteroids is, after all, that many of them are--at least compared with the Moon and larger planets--relatively pristine and unaltered objects that preserve clues from the earliest epochs, *provided* we are able to disentangle effects of subsequent collisions. Finally, it is believed that the traits of many meteorites have been shaped by evolution in asteroidal regoliths and that the delivery of asteroidal meteorites into Earth-crossing orbits involves collisional fragmentation in the main belt. The study of asteroid collisional and regolith production processes, as constrained by the properties of meteorites, should help us to interpret meteoritical evidence in a planetological context.

At the high relative velocities in the belt, collisions erode or fracture asteroids as well as create regoliths. Asteroids are ultimately destroyed by catastrophic fragmentations which in turn "create" smaller asteroids. From the known diameters and orbits of asteroids, typical collision rates among objects may be readily calculated. More complicated is specifying the physical outcome of a collision, depending on the relative size of the colliding bodies and on their physical nature (*e.g.*, strength). Gross bounds are provided by conservation of energy and similar considerations. Theoretical and laboratory scale experimental studies of cratering and fragmentation physics have been applied to the problem, but we have no practical experience with collisions of the magnitude that shatter large asteroids. Also, we have only rough ideas about asteroid densities and strengths. Astronomical observations of asteroid sizes, shapes, spins, and inferred surface compositions provide some help in modeling collisional evolution as do meteoritical inferences concerning shock pressures and regolith processing. In summary, some important bounds may be placed on asteroid collisional evolution, but details remain a matter of informed speculation.

Several conclusions and important generalities that will emerge from this paper are summarized here:

1. Collision rates and kinetic energies are sufficient to fragment most asteroids well within the lifetime of the solar system; thus most asteroids, excepting perhaps only the very largest, are of a fragmental nature.

2. Many asteroids in excess of 100 km diameter are probably thoroughly fractured throughout their interiors.

3. Regoliths on asteroids are poorly mixed in comparison with the lunar regolith, except possibly for very large asteroids.

4. Regoliths are thin or absent on small asteroids, especially those of strong rocky composition.

5. Unlike the Moon, for which most crater ejecta are deposited in close proximity to the crater, asteroidal crater ejecta are commonly distributed entirely around the body, tending to mask any underlying lateral heterogeneity.

6. Straightforward approaches to interpreting crater populations on Mars, Mercury, and the Moon cannot be directly applied to craters on Phobos and Deimos, and none of these bodies serves as an exact example of what we might expect on asteroids. Crater populations on an asteroid will reveal the chronology and character of events that have occurred subsequent to the last major fragmentation event in which an asteroid has participated; since such events occur frequently, asteroid cratering records generally will not extend far back in time.

The above conclusions, and others to follow in this chapter, are derived from preliminary theoretical models and gross extrapolations of a few experiments far beyond laboratory scales. Thus, as is the case for any scientific topic for which the observations are mostly indirect, the analyses in this paper should be considered model-dependent and in need of further verification by additional theoretical, experimental and observational work and ultimately by direct examination of asteroids from spacecraft. It would be a mistake, however, to regard the conclusions in this paper as being mere "guesses." Asteroid collision probabilities may be calculated certainly to within a factor of two or three. Given conservation of energy, assessing the possible range of collisional outcomes then becomes a problem in understanding limits on the partitioning of the collisional kinetic energy. Reasonable judgements on this matter constrain the physical nature of asteroids to a considerable degree, but the possibility remains that something is being overlooked.

This paper treats three major topics: collisions and fragmentation, asteroid regolith models, and cratering on small bodies. Much of the paper is based on my own work in progress (in association with D. R. Davis and J. F. Wacker on collisional evolution and with R. Greenberg, K. Housen and L. Wilkening on regolith models). There is little recent literature dealing with asteroid collisional evolution, except for certain specific topics (*e.g.*, Harris, 1978, for discussion of asteroid spins; Wetherill, 1976, for discussion of asteroidal production of meteorite fragments and delivery to Earth). Work on regoliths has dealt almost exclusively with the Moon so far (see review by Langevin and Arnold, 1977). Interpretation of crater populations on small bodies (Phobos and Deimos) is in its infancy; the present paper and comments elsewhere in this volume by Veverka constitute the only extrapolation to asteroids.

COLLISIONS, FRAGMENTATION, AND EVOLUTION OF THE SIZE DISTRIBUTION

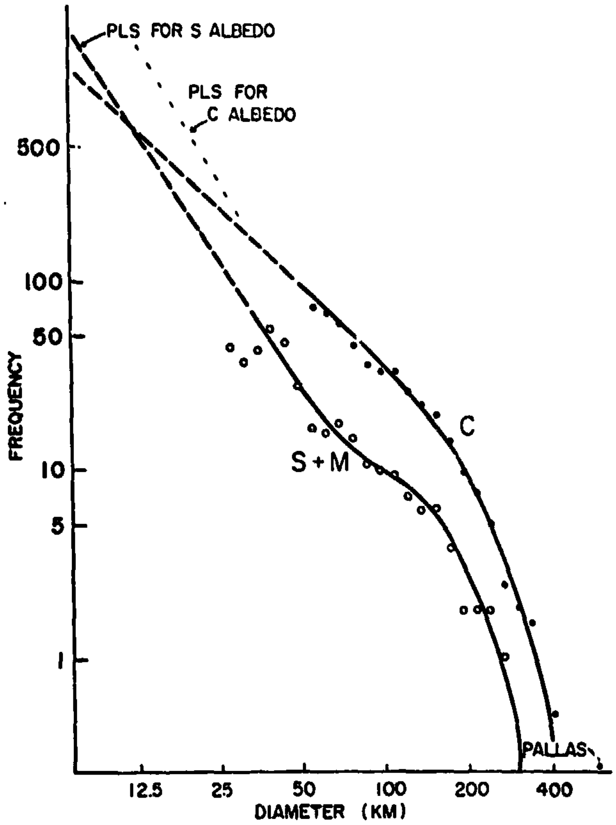
During the past decade, we have learned to measure asteroid albedos and hence diameters with considerable accuracy. Zellner and Bowell (1977) have calculated bias-corrected diameter-frequency distributions for the several spectral types down to 50 km for low-albedo asteroids and down to 25 km for higher-albedo asteroids. The Palomar-Leiden Survey (van Houten *et al.*, 1970) provides data pertinent to asteroids as small as a few kilometers in diameter, but since albedos are not known, the PLS constraints are not very strong (see Figure 1).

The rate of collisions between a target asteroid of diameter D_0 and a field of smaller projectile asteroids of diameters D_1 to D_2 is approximately equal to the collisional cross section of the target ($\pi D_0^2/4$) times the number of asteroids with diameters between D_1 and D_2 (taken from Figure 1) times the mean relative velocities of asteroids ($\sim$5 km/sec) divided by the effective volume of the asteroid belt (8.5×10^{25} km^3, according to Dohnanyi, 1969). Wetherill (1967) has shown that such particle-in-a-box calculations overestimate collision rates by factors of about 1.5 to 2.

We may usefully distinguish between two types of collisions: (a) those for which the ratio γ between target and projectile diameters is large, resulting in cratering and erosion of the target, and (b) those for which the projectile is sufficiently large (small γ) to result in catastrophic fragmentation of the target (defined as occurring if the largest object remaining after collision is $<$50% the original mass of the target). Because the exponent of power-law approximations to the incremental diameter-frequency relationship of asteroids has an absolute value $<$4, most mass (hence most kinetic energy) resides in larger asteroids; therefore the largest collisions are more important in destroying asteroids than the cumulative erosion by small cratering events. But cratering is by no means negligible and, in fact, is wholly responsible for creating asteroidal regoliths.

The fragments resulting from an asteroid collision (whether comprising the entire mass involved in a catastrophic collision or merely the ejecta in a cratering event) may be characterized by the diameter of the largest fragment, the power-law describing the size

Fig. 1. Diameter-frequency distribution for asteroids. Points are bias-corrected counts in increments of 0.05 in log diameter (Zellner and Bowell, 1977). Lines are possible fits and extrapolations, constrained at small diameters by Palomar-Leiden Survey data for two different possible albedos. Figure reproduced from Chapman *et al.* (1978). (Courtesy *Annual Review of Astronomy and Astrophysics*.)



distribution, and the distribution of velocities. The fraction of ejecta traveling at less than the gravitational escape velocity of the target falls back and contributes to the regolith. The remaining ejecta escape and become individual asteroids or smaller debris in their own right.

The previous three paragraphs have parameterized the problem. Let us now consider the collisional physics and what little has been learned from theoretical modeling and Earth-based experimentation. Cratering is somewhat better understood than is catastrophic fragmentation. Not only have more laboratory scale experiments been done on impacts into semi-infinite targets, but nuclear explosion craters provide some basis for extrapolation to larger-scale events. Moreover, computer codes have been written to model hypervelocity cratering, not fragmentation, events. Nevertheless, a catastrophic fragmentation event may be thought of crudely but usefully as the limiting case of a cratering event that consumes a significant fraction of the volume of the entire target. Laboratory-scale fragmentation experiments involving velocities in excess of 1 km/sec are reported by Moore and Gault (1965), Gault and Wedekind (1969), and Fujiwara *et al.* (1977).

The kinetic energy of the projectile is partitioned into several forms of energy upon impact. For rock-into-rock cratering impacts at 5 km/sec, O'Keefe and Ahrens (1977) compute that 20% of the energy goes into heating (including melting and vaporization) of the projectile, another 20% into heating the target, and about 50% into plastic work and comminution. The remaining 10% is partitioned into the kinetic energy of the ejecta. An experiment by Gault *et al.* (1963) shows the distribution of ejecta velocities as a function of mass-fraction. The fraction of ejecta failing to exceed the escape velocity falls back to the surface. It is uncertain to what extent such cratering models are applicable to fragmentation events. But the asteroid size-distribution is such that most catastrophic fragmentation events involve target-projectile ratios only slightly larger than is sufficient for fragmentation, so the events are not grossly dissimilar from large cratering events; hence one might expect roughly similar energy partitioning.

The most important variable, however, is the physical nature of the asteroidal material. Both dimensional analysis and actual experiments demonstrate that the energy (hence projectile mass) necessary to produce a specified amount of damage (*e.g.*, crater of a specified size or fragmentation of a target of specified size) scales roughly as the target strength. Interpretations of spectrophotometry are consistent with some asteroids being similar to carbonaceous chondrites, which have crushing strengths as low as 3×10^6 dynes cm^{-2}; others may be of strong metallic composition with crushing strengths exceeding 2×10^{10} dynes cm^{-2}. Of course asteroids may have bulk strengths much lower than that of their constituent materials if they are already fragmented, which might have resulted from previous collisional history (see below).

Considerable literature exists on energy/diameter scaling laws for craters, especially in rocky and sandy substrates. Much less is known about fragmentation events, but experiments summarized by Greenberg *et al.* (1977) suggest that the effective "impact strengths" of materials are about two orders of magnitude less than crushing strengths; *i.e.*, a basaltic body of crushing strength $\sim 10^9$ dynes cm^{-2} will be catastrophically fragmented if struck by a projectile with kinetic energy $\gtrsim 10^7$ ergs/cm^3. Of particular importance to asteroids is the fact that ejecta velocities from impacts into loosely aggregated material (*e.g.*, sand) are ~ 2 orders of magnitude less than velocities from impacts into rocks (Stöffler *et al.*, 1975); a general velocity dependence on strength is suggested and it may apply also to fragmentation events, but the phenomenon has not been well documented.

For 5 km/sec asteroidal impacts, catastrophic fragmentation may be expected to result when $\gamma \leq 18$ for hard, rocky bodies, $\gamma \leq 7$ for iron bodies (at temperatures above the ductile/brittle transition), and $\gamma \leq 50$ for very weak bodies. For "supercatastrophic" collisions, involving γ much less than the limiting values just listed, the excess energy produces more comminution resulting in a smaller diameter for the largest fragment and a larger population index for the fragmental size distribution (see discussion in Greenberg *et al.*, 1978).

In order for an asteroid to be "destroyed," it must not only be fragmented, but the fragments must have sufficient kinetic energy to overcome their mutual gravitational attraction. Roughly, this will happen if the portion of projectile kinetic energy that goes into fragmental kinetic energy (perhaps 5 to 10%) exceeds the gravitational binding energy of the target. In detail, it is required that most of the fragments, especially the most massive ones, are accelerated to velocities exceeding the body's escape velocity. For solid, rocky bodies $\lesssim 100$ km diameter, any impact sufficient to fragment the body will also be sufficient to disperse the fragments. But, for a larger, rocky body, it may be marginally fragmented but fail to be dispersed; such an event converts the body into a "pile of rocks" which no longer has substantial internal strength. Similar behavior would occur for weaker bodies $\gtrsim 10$ km diameter. Such asteroids will not be dispersed until involved in a "supercatastrophic" event that partitions sufficient energy into kinetic energy to overcome the gravitational binding. Of course, when that occurs the largest fragment from such an already broken-up body will be *much* smaller than the original body--to first order one might simply assume the body has disappeared as an observable asteroid and been converted into small interplanetary debris.

Chapman and Davis (1977) and Davis and Chapman (1977) have been investigating asteroid collisional evolution models, employing the parameters and concepts discussed above. In particular, they have considered the simultaneous collisional interaction of two populations of asteroids, one consisting of strong bodies, the other of weak bodies. They have studied the collisional evolution of the present asteroid belt (*e.g.*, the bias-corrected populations of Zellner and Bowell, 1977) as well as hypothetical augmented early asteroid populations. A number of important results are as follows:

(1) The asteroids presently impact each ot ›r with sufficient frequency that most large asteroids must be expected to have been cat.strophically fragmented within the last several billion years. Provided that 5% to 10% of the kinetic energy is available for fragment dispersal, most large asteroids have lifetimes against disruption shorter than the age of the solar system even with the present low population density. Thus those that we see now must be either (a) fragments of rare larger bodies that chanced never to have been converted into a "pile of boulders" by earlier catastrophic impacts prior to catastrophic disruption; or (b) remnants of rare larger bodies that chanced to escape disruption and have been whittled down by gradual erosion. Since the characteristic lifetime against catastrophic fragmentation varies roughly as the square-root of the asteroid diameter, all small asteroids must be regarded as being multi-generation and/or recent fragments of larger bodies. These expectations are in accord with several observations: asteroid spins are those expected for a collisionally evolved population (Harris, 1978) and asteroid shapes seem to be irregular except for asteroids sufficiently large and weak that gravity induces sphericity.

(2) Asteroid size-frequency distributions are not expected to be linear on a log-log plot. It had been argued previously that all asteroids (Dohnanyi, 1972) or at least collisionally-evolved C-type asteroids (Chapman, 1974) should exhibit such a linear distribution. But two effects lead to nonlinearities: (a) the effects of gravity holding together fragmented objects until supercatastrophic collisions disrupt them, and (b) the interaction of populations of different strengths. Figure 2 illustrates one run of the Chapman-Davis program, resulting in nonlinear size-distributions for two types of asteroids that mimic rather closely the observed distributions for C and S types.

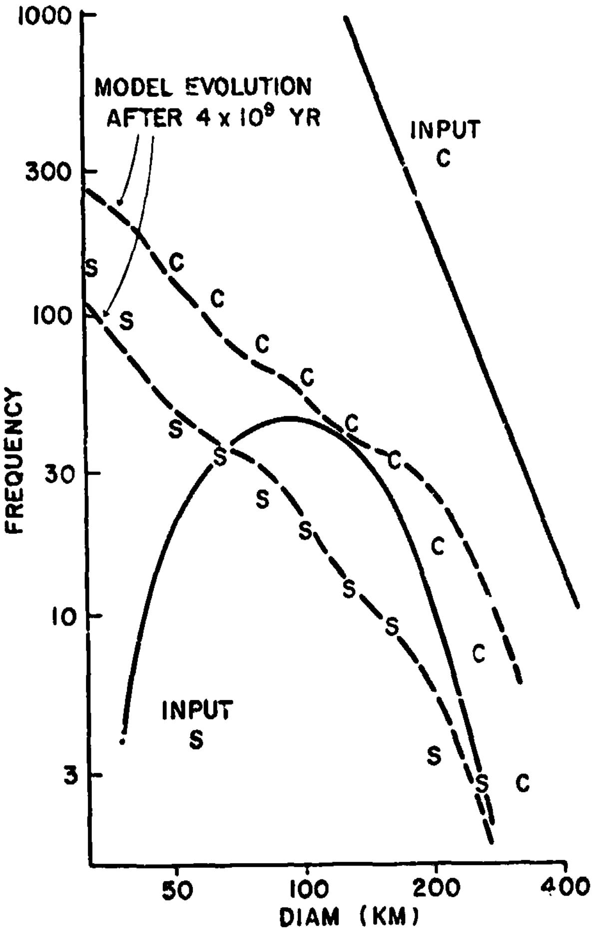


Fig. 2. Comparison of Chapman/Davis evolution model with observations. For this particular run, initial size-distributions were chosen (solid lines) to model the type of scenario described by Chapman (1976). C and S asteroids were taken to have crushing strengths of 5×10^7 and 2×10^{10} dynes cm^{-2}, and densities of 3 and 5 gm cm^{-3}, simulating carbonaceous and iron-rich asteroids respectively. Impact strengths were taken to be 6% of crushing strengths. The mass of the largest fragment involved in a supercatastrophic disruption was taken to be one-eighth the original mass; much smaller fractions, depending on energy density, might be more appropriate and would result in diminished production of middle-sized asteroids. The dashed curves show the evolved C and S populations after 4×10^9 years. Plotted for comparison are bias-corrected frequencies of C and S asteroids observed today (Zellner and Bowell, 1977). The frequencies are per interval of width 0.1 in log diameter.

(3) The present asteroid population *may* be a remnant of a much larger early population (Chapman and Davis, 1975). Figure 2 is typical of virtually all runs of the collision evolution model in that input populations orders of magnitude greater than the present belt (such as "input C" in Figure 2) always decay to distributions approximating the present belt (in both slope and intercept) after several billion years. The only [illegible] tial large populations that fail to evolve to the present belt are those in which [illegible] of the mass is originally stored in bodies substantially larger than Ceres approaching lunar size. Note that result (1), that asteroids are highly fragmented, does not depend on the early asteroid population being more populous than today; *present* impact rates are sufficiently high to lead to high fragmentation rates, even if the asteroid belt originally contained only a fraction more mass than it does today. In fact, the present distribution and nature of asteroids may provide clues as to whether the population truly was greater in the past. Chapman and Davis (1975) argued that the belt might have been ~300 times more populous based on the characteristics of an inferred remnant population of very strong iron-cores of precursor bodies. This inference is highly model-dependent and should not be regarded as a secure determination of the early asteroid population.

Several sources of uncertainty require emphasis. First, because of the relatively large values of γ sufficient for catastrophic fragmentation, the evolution of main belt asteroids of observable sizes depends on the frequency of very-much-smaller asteroids--those too small to have measured surface compositions and often so small as not to have been discovered or sampled at all. Thus future observations pertaining to the frequency and probable bulk compositions of asteroids in the 100 m - 10 km size range would be very important. Second, more experimental and theoretical work is necessary to understand how projectile kinetic energy is partitioned into comminution energy and especially into ejecta or fragmental kinetic energy. Large quantities of energy could be partitioned into heat without necessarily melting major amounts of rock. Should much less than 1 [illegible] of the energy be available for kinetic energy, asteroid lifetimes might be much longer than we think. Should smaller fractions of energy be available for comminution throughout the asteroidal volume than is true at laboratory scales, asteroids might be less fragmented than we think.

ASTEROID REGOLITHS

Lunar scientists have developed a comprehensive understanding of the lunar regolith (Langevin and Arnold, 1977). Asteroid regoliths have received little attention, however. Most discussion has concerned possible particulates in the optical surface layer that would influence polarimetric properties (*cf.*, Dollfus, 1971, and discussion of that paper by Anders and Chapman; also Dollfus *et al.*, 1977). More recent interest in asteroid regoliths has come from meteoriticists who require environments of substantial volume in which to produce the numerous gas-rich and brecciated meteorities (*cf.*, Macdougall *et al.*, 1974). If asteroid regoliths are, in fact, so thick as to constitute a substantial portion of asteroid volumes (*e.g.*, as argued by Anders, 1975, 1978), then models of the collisional evolution and lifetimes of whole asteroids must take regoliths into account, since crater volumes and ejecta velocities fr[illegible] impacts into regoliths are very different than for impacts into rock (see previous section).

Asteroids differ from the Moon in two important respects. First, in the asteroid belt the flux of impacting objects >10 km diameter is roughly three orders of magnitude greater than in near-Earth space. Second, asteroid gravities are much less than lunar gravity, with escape velocities typically ranging from meters per second to hundreds of meters per second. Lesser considerations are: (a) impact velocities are lower in the belt than for the Moon; (b) asteroid compositions are generally different from lunar composition; (c) most asteroids are more irregular in shape than the Moon; and (d) asteroids spin relatively rapidly.

Housen *et al.* (1978) have developed a model of asteroid regolith evolution. It considers the buildup and erosion of regoliths on asteroids from the time an asteroid is created with a bare surface to the time an asteroid is struck by a sufficiently large impact so that it is catastrophically fragmented. At that point, the whole asteroid, if it is not dispersed, is converted into a "pile of rocks" or a megaregolith. Housen *et al.* distinguish between a "typical region" on an asteroid and atypical localities where occasional sparsely scattered large impacts have occurred. The depth of regolith in the typical region is determined by competition between processes that create regolith and those that erode and eject it. Regolith is created by the deposition of ejecta from the large craters outside of the typical region. Regolith is also created by small craters in the typical region (and elsewhere) that penetrate existing regolith, comminute basement rock, and spread their ejecta around the typical region. Regolith is lost by the ejection of some portion of crater ejecta at greater than escape velocity.

An essential assumption of the Housen *et al.* model, in its present state of development, is that crater ejecta are widely distributed around an asteroid. Figure 3 shows how ejecta distributions are localized on large bodies, such as the Moon, and on smaller bodies of sandy composition. But on still smaller sandy bodies (<10 km diameter), or on rocky bodies smaller than a few hundred kilometers diameter, the predominant ejecta velocities approach escape velocity and the fraction of ejecta that fails to escape surrounds the asteroid with a blanket of roughly uniform thickness.

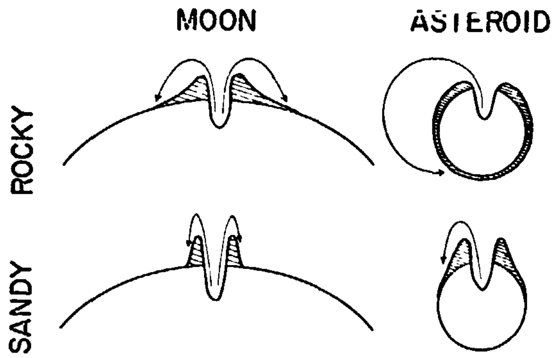


Fig. 3. Schematic illustration of the distribution of crater ejecta on Moon-sized and asteroid-sized bodies with rocky and sandy substrates. Typical trajectories are shown. Ejecta velocities are greater from craters created in rocky surfaces. Ejecta blankets are relatively localized on a Moon-sized body but may completely surround an asteroid, especially a small, rocky one. Vertical relief is exaggerated 10:1.

The incremental size-distribution of interplanetary debris is believed to be roughly described by a power law with an exponent between -3 and -4. Such a distribution is characterized by having the predominant surface *area* in the small size fractions but the predominant *mass* in the large size fractions. Provided that energy-scaling applies (*i.e.*, crater volumes vary as projectile volumes for constant impact velocity), an asteroid surface area is predominantly covered by small craters, yet most of the ejecta are produced by the largest craters. It is for this reason that it is useful to study the "typical region" described above, which is defined as that spatially evolving fraction of an asteroid surface that contains craters smaller than D_s, the diameter of the largest crater that "saturates" the surface of the asteroid. (D_s is obtained by integrating the areas of all large craters formed from t = 0 to the current time-step, from the largest crater down to craters of diameter D_s, constraining the total area to be one-third of the area of the asteroid. Thus, two-thirds of the asteroid surface is deemed to be "typical.") As time evolves, larger and larger craters contribute to saturating the surface, so D_s increases and the "typical region" changes shape to include them and to exclude recently formed craters larger than D_s.

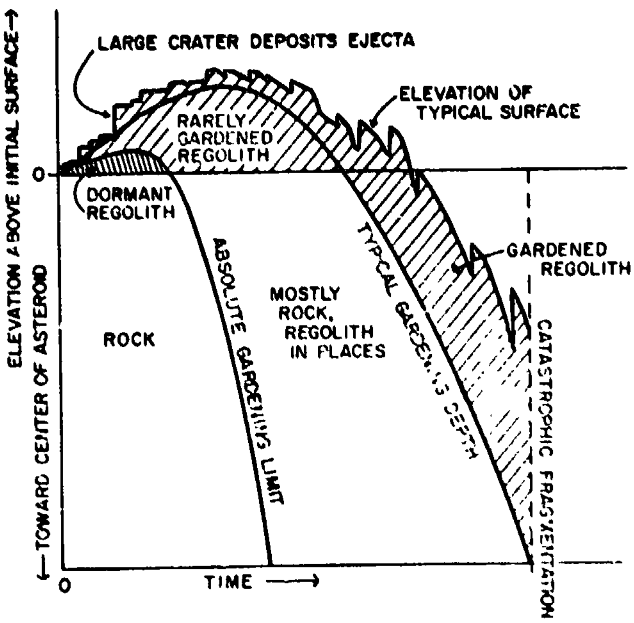


Fig. 4. Schematic illustration of regolith evolution on a typical region of a small asteroid. Regolith is built up mainly by ejecta from occasional large, sparsely scattered craters outside the typical region and is "gardened" by numerous small impacts within the region. The jagged shape of the surface elevation curve is due to discontinuous deposition. In reality, the typical and absolute gardening depth lines, here shown as smooth, would mimic the jagged shape of the elevation line. There may be a dormant zone in which ejecta once deposited is buried too deeply to be gardened for a while. The "typical gardening depth" is the depth at which one turnover occurs per characteristic time scale. Catastrophic fragmentation usually occurs before the asteroid is completely eroded away.

Figure 4 illustrates the evolution of regolith on the typical region. Initially only the smallest craters saturate the surface, hence little ejection of material occurs. Larger craters in atypical regions deposit ejecta all over the asteroid and, in particular, onto typical regions, causing the elevation to rise. The regolith is built up discontinuously, with the biggest jumps being due to the largest craters. During the early period of maximum deposition and minimal erosion, a dormant zone may be created in which ejecta deposits are shielded from the subsequent excavations by craters smaller than D_c. Note that the vertical distance between the curves for the surface and the "absolute gardening limit" corresponds to the depth of a crater of diameter D_g. While regolith or rock can be excavated down to the absolute gardening limit, the material remains undisturbed in most places. The *typical* depth at which material is gardened at least once during typical time scales for deposition or erosion of regolith is the depth of the (smaller) craters that saturate the surface during such short time scales.

With passing time, larger and larger craters are included in the typical region and ejection becomes more efficient. Simultaneously, because there is a maximum size crater that can impact an asteroid without catastrophically fragmenting it, the range of crater sizes that contributes to deposition from afar onto the typical region shrinks. Increasing erosion and decreasing deposition lead to a maximum in surface elevation, followed by net erosion from the typical region. Eventually a sufficiently large impact occurs that the asteroid is fragmented and the regolith evolution model is no longer applicable.

Cases have been run for rocky asteroids ranging from 1-300 km diameter and for weakly cohesive asteroids between 1-30 km diameter. A weakness in the present Housen *et al.* model is that large, rocky asteroids that develop appreciable regoliths are treated as wholly rocky bodies, in calculating ejecta volumes and velocities, rather than as two-layer bodies with a weakly cohesive layer overlying a rocky substrate. Nevertheless, we can qualitatively understand such bodies by recognizing that they respond to smaller cratering events like weakly cohesive bodies. The Housen *et al.* model is especially inapplicable to large, weakly cohesive bodies for which ejecta velocities are insufficient to surround the asteroid with ejecta. Local gardening and erosion must occur on such bodies as on other asteroids, but deposition from large, distant craters is not uniform across the typical region. Instead, there are regions adjacent to atypical regions with much greater deposition and regions far from atypical regions with much less deposition than would be calculated by the model.

Housen *et al.* have varied model parameters. The following conclusions seem to be reasonably secure. Small (*e.g.*, 10 km diameter) rocky asteroids generate virtually no regolith and simply erode away until the asteroid is catastrophically disrupted. Rocky asteroids of >100 km diameter generate regoliths of hundreds of meters in depth, but the regoliths are very poorly mixed compared witn the familiar lunar case. Small (10 km), weakly cohesive asteroids generate a few meters of poorly mixed regolith. Large, weak asteroids have not been treated because of the inapplicability of the uniform-deposition assumption, but may be expected to have large but variable depths of regolith. Regolitns on such asteroids are better mixed than on other asteroids, but probably are less well-mixed than the lunar regolith.

The upper couple of meters of lunar mare regolith is the classic regolith. Since Apollo, meteoriticists have recognized some similarities between meteorites and lunar soils and breccias. But there are important differences, mainly in tne sense that the regoliths on meteorite parent-bodies are less "mature" than the lunar regolith. This is understandable because meteorites sample greater depths than do lunar samples and because asteroid regolith processes differ from those occurring at the lunar surface.

Although it is beyond the scope of this paper to describe ways that meteorites are produced and delivered from the asteroid belt, suffice it to say that because the asteroid size-distribution contains most volume in large bodies it is required that meteorites must come chiefly from large-scale collisions. The exact scale of collisions depends on the efficiency with which meteorites are delivered to Earth from various collisions, but meteorites must typically sample parent-bodies to depths of kilometers. Thus, tne lunar megaregolith (and examples of it among highland breccias) provides a better analog for meteorites than does the surficial regolith studied from lunar core tubes and other means. The size distribution of lunar cratering projectiles that yield craters with depths greater than a few hundred meters is known to be relatively shallow on a log-log plot, yielding more blanketing and less repetitive gardening than is true at smaller scales; the same should be true of asteroidal regoliths sampled at depth.

Two factors applicable to smaller and rockier asteroids that distinguish them from the Moon are ejection of substantial fractions to space and deposition from afar. Both factors tend to reduce the chances that a grain can be repeatedly bombarded. After participation in only one or a few cratering events, the probability becomes great that a near-surface grain is ejected to space. Also, each sizeable impact anywhere on the asteroid results in deposition of a layer that protects a grain from being involved in a crater-forming event. Another distinction between asteroids and the Moon is that the damage done by an impact at 5 km/sec in the belt is much less than that done at ~15 km/sec on the Moon; thus agglutinate formation should be much reduced on asteroids, compared with the Moon, even if all other factors were equal. Interplanetary comparisons of regolith maturity have been made by Matson *et al.* (1977).

The Housen *et al.* regolith production model for smaller, rockier asteroids implies that any impact in an atypical region would blanket the rest of the body with ejecta from that locality. In effect, such asteroids "paint themselves gray" (or whatever color) during each major impact event, masking whatever compositional heterogeneity may lie beneath. In reality, of course, a crater volume of ejecta is not spread uniformly over an asteroid, but must cluster somewhat due to variable ejection velocities and angular heterogeneities (*e.g.*, lunar rays). Furthermore, the coarser the ejecta are, without a preponderance of fines, the larger a crater must be for its ejecta to mask the entire surface of an asteroid. In the absence of any firm constraints on ejecta trajectories and size distributions, it might merely be noted that virtually all measured asteroids are compositionally homogeneous on a global scale, which may reflect the efficiency of regolith distribution processes or, alternatively, an underlying compositional uniformity for most asteroids (Degewij and Zellner, 1978). Vesta is one asteroid for which regional color and albedo differences are well documented, but it is a large body well outside the range of applicability of the Housen *et al.* model. Crater ejecta are far too localized to mask Vesta's underlying compositional heterogeneity. Lateral heterogeneities would be expected to be absent from all asteroids except the following: very large rocky asteroids, moderate to very large weak asteroids, small rocky asteroids (that lack regolith altogether), and relatively "new" asteroids of any size.

CRATERING ON SMALL BODIES

Most of our experience in studying lunar and planetary cratering processes has involved the Moon and larger planets. With Mariner and Viking imagery of Phobos and Deimos now available, there have been initial attempts to understand the cratering records on much smaller bodies. Some interpretations have been formulated in terms applicable to larger bodies, but which may not be relevant for small bodies. More recently, there has been some thinking about Phobos and Deimos as asteroid analogs and we must bear in mind certain differences between these small satellites, located deep in Mars' gravity well, and heliocentrically orbiting asteroids of various sizes.

Cratering on small satellites and asteroids differs from planetary cratering in several respects. Some differences are discussed in the previous section, including the fact that crater ejecta often completely surround small bodies and much may escape such bodies altogether. Another difference is that although smaller bodies are hit less frequently by very large impacts, when they are hit, they may catastrophically fragment, whereas planets are never hit by impacts sufficient to destroy them. We may compare the evolution of craters on a small body with the evolution of craters on a small portion of the Moon having the same area. To the extent that the local lunar area is affected by very large events occurring elsewhere on the Moon (a basin-forming impact, for instance), the small body would be totally unaffected (*i.e.*, the projectile would miss the body entirely). The small lunar area may, alternatively, be struck directly by a moderately large cratering event (*e.g.*, crater diameter half the diameter of the region) while such an event on a small body would catastrophically fragment it, ending the evolution of that body. Moreover, those projectiles that *do* strike the small body without fragmenting it will produce different effects from those of a similar projectile striking the small lunar region because of different gravity and possible differences in competence of the surface layers. Generally, as argued in the previous section, there is more uniform deposition of ejecta on a small body than on a large one.

There are two major differences between martian satellites and asteroids of similar size. First, the impact rates are far less in the vicinity of Mars than in the asteroid belt. Second, ejecta that escape Phobos and Deimos rarely if ever can escape the gravity of Mars itself. As argued by Soter (1971), the ejecta orbit Mars; eventually most of this may be reaccumulated by the satellites. Because of this effect, the martian satellites may be like the Moon in that most ejecta returns to the body, but unlike the Moon in that ejecta are rather uniformly distributed over the whole satellite.

Craters have been used to address a number of important planetological questions, including the relative and absolute ages of units and the effects of endogenic processes on planetary surfaces. A critical question in all interpretations of cratering populations is whether or not the crater populations are in equilibrium between crater-formation and crater-destruction. The most important crater-destruction process on a body that is geologically "dead" is the cratering process itself (overlap, erosion, and deposition of ejecta). It has been commonly thought (*cf.*, Thomas and Veverka, 1977) that the crater populations on Phobos and Deimos are "saturated" (*i.e.*, in equilibrium with the cratering process) because crater densities approach a lunar "saturation curve" due to Hartmann. But the differences bet martian satellites and the Moon described above yield different expected saturation densities. In particular, one would expect higher saturation densities on martian satellites, for at least two reasons: (1) Marcus (1970) has shown that the equilibrium crater density varies inversely as the logarithm of the dynamic range of the crater dimensions. Since the largest crater on Phobos is much smaller than lunar basins, the saturation density of small craters on Phobos should be higher than for craters of the same size on the Moon. (2) To the extent that crater ejecta are widely distributed, hence thin, on small bodies, moderately large craters on small bodies cannot be obliterated by blanketing, whereas those proximate to cratering events can be obliterated on large bodies.

Further analysis of cratering on small bodies is required, but it seems likely that the apparently sub-saturated crater populations on Phobos and Deimos imply that the surfaces of these bodies are relatively "fresh." This could have resulted from the creation of these satellites by fragmentation of larger precursor bodies at a time sufficiently recent that saturation has not yet been reached. Such a situation is not unreasonable, since the probability of catastrophic fragmentation becomes large as saturation is approached, provided (as seems to be true for craters larger than about 1 km) the slope of the incremental power-law describing the cratering distribution has an absolute value $\lesssim 3$. Surely, in the asteroid belt, and possibly near Mars, the impact rates are so high that the lifetimes of small bodies are much shorter than the age of the solar system. Therefore, crater counts on asteroids will provide information pertinent to recent epochs only and cannot shed light on absolute or relative chronologies of events happening earlier in solar system history.

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DISCUSSION

VEVERKA: Could you summarize for me the physics of breaking up an object?

CHAPMAN: There is a certain kinetic energy in the projectile, which is well defined and gets liberated by the impact into several kinds of energy. It breaks the bonds that are holding the material together. Some of it is converted into kinetic energy of fragments.

VEVERKA: But isn't the problem knowing whether it makes a lot of little pieces or a few big pieces?

CHAPMAN: That is right. What is the size distribution of crater ejecta or fragments of some large broken up asteroid? We don't have any experiments on this scale. Certainly experiments have been done over a range of sizes on a laboratory scale, and I believe the basic physics is understood. When you impact something a shock wave will propagate across the body. You are going to deposit more energy per unit volume near the point of impact than you do farther away. So on a qualitative level, at least, one can be quite sure the target is smashed up into a lot of small particles right at the point where the impact occurred. The far side of the body will split apart into a few big pieces simply because a few fracture planes went through. I would add, however, that the velocity associated with the resulting fragments is also critical. The low gravity of an asteroid is a very fundamental characteristic; unlike the Moon where all the ejecta falls back, for an asteroid some really significant fraction of the ejecta escapes.

ZELLNER: What is the time scale in the present asteroid belt to crater a freshly broken surface?

CHAPMAN: The lunar mare surfaces are saturated with craters less than about 100 m in diameter. So if you are talking about that size crater and if the time scale is three orders of magnitude shorter than for the Moon, then the surface is cratered in about 4 million years.

VEVERKA: There is a difference between an equilibrium density and a saturation density. The latter is determined by seeing how many circles of a given diameter you can fit into a given area. But there will be fewer craters of a given size in the equilibrium situation because in the real world craters are destroyed by a variety of processes which are not modeled adequately by simply drawing circles on a plane. Even on a small asteroid craters are affected by ejecta from other cratering events, but the effect may not be as important as it is in the case of the Moon. Thus we might expect crater densities higher than those in the lunar uplands, but still below the theoretical saturation limit. The important question is how much higher might the equilibrium crater densities on a small body be?

SHOEMAKER: Quantitatively, the lunar crater equilibrium distribution is the result of the smaller craters destroying the big ones by local transport of surface material. Qualitatively, you would expect the same thing to happen on Phobos and Deimos because most of the ejecta that escape from these moons is swept up again. If you are correct about asteroids, that most of the ejecta are lost, the equilibrium density will be higher.

CHAPMAN: What is happening on the Moon happens the way you say it does because of the size distribution of small ejecta. Marcus (1970) discussed the size distribution of larger craters on the Moon for which the production function has a shallower slope. I think his concept is relevant for interpreting the number of moderately large craters on Phobos or on any asteroid. I agree when you get down to the smallest craters, where the size distribution is very steep, then it happens as you describe.

GROSSMAN: You say that the impact rates in the asteroid belt are so high and for many asteroids a very large fraction of impact ejecta may be lost from the body completely. Has very much attention been paid to the possibility that the regoliths on some of those bodies, maybe many of them, may not be from the body itself but from others?

CHAPMAN: Yes, I think that has been thought about. You can apply this kind of analysis to see what happens when a grain of sand or a tiny little pebble impacts a large asteroid. If you are in a regime where you are losing most of the mass by big impacts, you will probably lose most of the ejecta from small impacts, too. The velocity of the ejecta depends mainly on the velocity of the impact and is nearly independent of the mass of the projectile. The small impacts therefore produce erosion, too, and there is a net erosional regime on all asteroid surfaces. On the Moon, where you may or may not have net erosion, meteoritic material accounts for 2% of the regolith. It is going to be less than that on any asteroid.

ANDERS: The amount of extraneous meteoritic material in gas-rich achondrites ranges between 0.3 and about 5%. So, judging from these meteorites, the amount of extraneous material that falls on asteroidal regoliths is indeed a small fraction.

ARNOLD: An effect which is small on the Moon, but which is responsible, I think, for the smoothness of the Moon's surface, is the fact the low velocity ejecta tend to move down slopes rather than up slopes. A fresh surface is rough, but after a while the little hollows fill in. On the smaller asteroids, the difference in gravitational potential between one point and another is comparable with the total gravitational potential. So even though things are thrown around much more widely, there may very well be a strong tendency for things to move down-slope, to move into the lows and to expose the mountains, ridges and high spots. If that is correct, it may well turn out there are high bare patches and filled low patches on small irregular asteroids.

CHAPMAN: I would have thought it would be the other way around. If the gravity were low, wouldn't the ejecta go to any point independent of whether it were a mountaintop or not?

ARNOLD: I am saying the difference between the gravity at the highest point and at the lowest point is a large part of the total gravity. In a situation like that, I don't care how low the total is, the material that doesn't escape is going to accumulate in the lows, whether it starts in the highs or the lows. I think that is a big effect.

WOOD: But the frictional forces that tend to resist down-slope motion are constant, and must more effectively inhibit down-slope movements where g is small than where it is large.

ARNOLD: Well unfortunately it isn't clear but it has an exciting potential. If it were true, it would expose clean surfaces on the highs. It is an experimental fact, whether my model is right or not, that the lunar rocks are clean and stand out. Although fillets are observed they are never very prominent. I don't know whether this effect would be more pronounced on the asteroids, but for now I am prepared to defend it.

FANALE: It is interesting, philosophically, because this is the first time that idea has been mentioned. It may be an example of a whole class of things have haven't been discussed here because they haven't been thought of yet.

CHAPMAN: That is entirely correct, and I want to say again that my comments about asteroid collisions, regoliths, and craters represent, as far as I know, a fair summary of the very limited state of knowledge about these matters. It is theoretical. There are no laboratory observations at appropriate scales.

WOOD: What is the basis for thinking that crater ejecta distributes itself evenly over the surface of an asteroid instead of being concentrated near the crater rim? My physical intuition doesn't lead me to that conclusion.

CHAPMAN: Consider the material which is launched into space and then lands. (I am not talking about crater rim material which has simply been shoved.) It goes much farther if you have low gravity. Clearly if you are losing some substantial fraction of the ejecta entirely to space, the area over which the rest of the ejecta is distributed is going to be pretty large.

SHOEMAKER: Let me describe one feature of an experiment done repeatedly at Ames Research Center--firing shots into a sawn vertical rock face. A tremendous flood of material is ejected from each at high velocity. But if you look at the high-speed pictures in addition to all the rapidly moving objects, there are very often big spalls that are just barely ejected and fall to the floor of the shot chamber. In the typical crater formed in hard rock, some big chunks of rock are just barely lofted out of the crater. Thus, I expect that even on very small asteroids some material will pile up near each impact crater.

WETHERILL: Generally, I am sympathetic with the idea that the small asteroids are a steady-state population, being produced from their larger neighbors, and destroyed by collisions. I think there are also some observational data that might make one worry about how far this concept should be extended. In particular, the Hungaria region is an isolated region of the asteroid belt fenced off from everywhere else by several resonances. The largest object in there is 434 Hungaria which is a small object, about 10 km. It is not really a family; there is a group of things that are probably fragments from Hungaria gathered around it and some more dispersed objects which are very unlikely to be direct collision ejecta from that object. They are typical PLS objects, 1 km size. So in this region of the asteroid belt, as far as we know, there is no way to replace what gets destroyed. You may say they don't collide much because their semimajor axis is 1.9 AU. That doesn't really hold up too well because a lot of asteroids get into that region and their collisions with the Hungarias occur at high velocity.

You make up for the small number of collisions with very catastrophic collisions. Somehow or other the Hungarias are preserved. You might say it all broke up yesterday and some of the fragments had much more velocity than we thought. Put them all together and most of the mass is still in 434 Hungaria.

CHAPMAN: Another example which is very peculiar is the size distribution of asteroids between the 2:1 and 3:2 commensurabilities with Jupiter. They are outside the main belt but should have fairly significant collision interactions. Yet, there are no small asteroids in this region; they are all large. The PLS turned up almost no new asteroids just interior to the Hildas.

SHOEMAKER: An important issue here is the size distribution of fragments. There is an easy "kitchen experiment" one can do to see what kind of fragment distributions you get when you are right at the threshold between making a crater on an object and knocking the thing apart. All you need is a hunting rifle and a collection of rocks. With a little experimentation you will find the critical rock size. Once you pass the threshold of catastrophic fragmentation, lots of fine fragments are produced. But there is a critical interval, as this threshold is approached, where a peculiar variation in the distribution of large fragments relative to little pieces is found. When I look at the magnitude distributions of asteroids in some of the Hirayama families it reminds me of this critical range.

CHAPMAN: The paper by Fujiwara *et al.* (1977) has some improvements in the theory of size distributions from such marginally catastrophic events and I think that regime is better understood now.

VEVERKA: When I said that the physics might be different in the case of a typical asteroid, what I had in mind is that even before an asteroid suffers the ultimate catastrophic impact which demolishes it, it has already suffered a whole series of slightly less severe collisions which have caused a lot of internal fracturing and weakening. Thus when the big impact does take place, how the asteroid comes apart must be determined in part by how it was pre-fractured.

SHOEMAKER: Gault and Wedekind (1969) did a relevant experiment in which they repeatedly fired projectiles at spheres. Damage was accumulated in the spheres. Their experiment is an idealized version of the problem, but I think that their results give a quantitatively correct picture.

CHAPMAN: It is quite clear that there ought to be many impacts on the larger asteroids, larger than 50 km or so in diameter, that are sufficient to break the object up but insufficient to loft large pieces into space. Before you catastrophically rupture something entirely and disperse it into a Hirayama family, you will have created basically a pile of boulders.