PART II

ORIGIN OF ASTEROIDS

INTERRELATIONS WITH COMETS, METEORITES, AND METEORS

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ASTEROIDAL THEORIES AND EXPERIMENTS

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Theories on the origin and evolution of asteroids are confronted with three types of experimental tests. The first refers to the dynamic state of the asteroids and consists of orbital and in some cases spin data for bodies as small as about 1 km. (There are reasons to assume that the size spectrum extends to very small objects but nothing is known about them.)

The second type consists of observations of the chemical and structural properties of objects fallen to Earth from space. Here the relationship to asteroids is much more tenuous. Nevertheless, the study of meteorites has provided important insight into the chemical evolution of small bodies in space. As long as one realizes that such data refer only to bodies of special structure, composition, velocity, and other orbital characteristics, they can be useful also for conjectures about asteroids.

The third source of information, also bearing indirectly on the structure and evolution of asteroids, is the lunar surface, which provides for the first time a display of the dynamic interaction between the surface of a celestial body and the space environment. To be applicable to the asteroidal environment, these results have to be scaled in a way that remains somewhat hypothetical.

BREAKUP AND ACCRETION IN THE ASTEROIDAL REGION

The mass in the asteroid region is small (fig. 1) and has not been collected into a small number of bodies as in the planetary regions. A similar situation seems to prevail in the satellite systems of Jupiter, Saturn (fig. 2), and Uranus, where analogous mass gaps are observed.

It is sometimes claimed that the present asteroid distribution has resulted from the explosion of one or a few larger bodies. Such an assumption meets with serious mechanical difficulties; some of these are examined below.

The distribution of particles in collectives such as the asteroidal and cometary jetstreams would appear to be a result of the two opposing processes of accretion and fragmentation. For reasons that are mainly historical, the emphasis has been placed mostly on the fragmentation process, which no doubt is important, but which alone cannot account for the observed distribution of bodies. One of the reasons for the biased interpretation is that

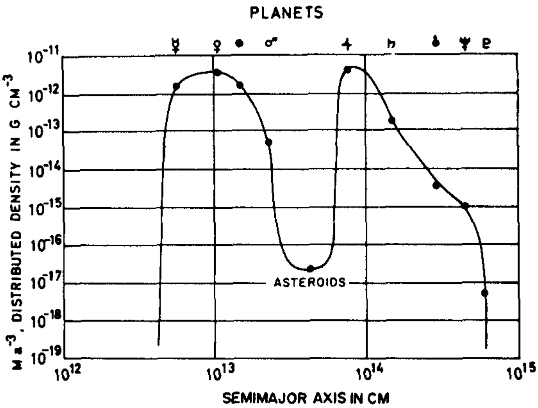

Figure 1.–Distributed density versus semimajor axis for the planets (from Alfvén and Arrhenius, 1970*a*).

for a long time we have seen the meteorites as direct evidence of breakup processes in space. In contrast, the processes responsible for accretion have been little known experimentally and theoretically until recently despite the realization that for larger bodies to break up, they must have first accreted.

Another reason for past emphasis of parent bodies of a size comparable to the Moon was the thought that high pressures and temperatures were needed to explain the phases observed in meteorites. These constraints may be largely relaxed as a result of recent experiments (Anders and Lipschutz, 1966; Arrhenius and Alfvén, 1971; Larimer, 1967; Larimer and Anders, 1967, 1970).

Until appropriate field and laboratory measurements on asteroidal properties can be made, appraisal of the rates of fragmentation and aggregation and their time evolution must be based on indirect evidence. Such evidence is provided primarily by distribution of asteroidal orbits, sizes, and spin states, and, in a more limited sense, by meteorites.

The observed distribution of spin periods (fig. 3) demonstrates the marked similarity in spin rate within a factor of 2 between most of those bodies in the

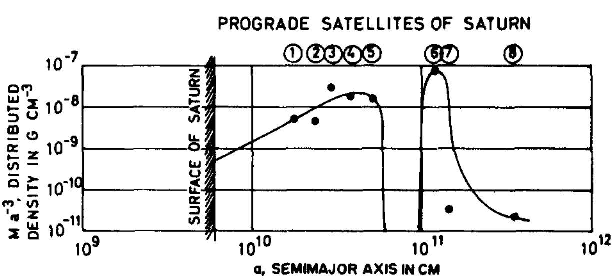

Figure 2.–Distributed density versus semimajor axis for the prograde satellites of Saturn.

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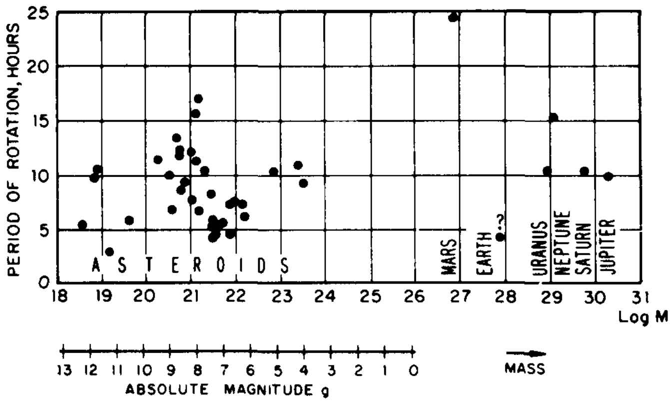

Figure 3.–Periods of axial rotation for the asteroids and some of the planets in relation to their masses (from Alfvén, 1964).

solar system that are unaffected by tidal braking. This isochronism of spin extends from small to large asteroids over the tidally undisturbed planets to the giant planets. If fragmentation played a major role after the accretion of the original bodies, one would expect to find, because of equipartition of rotational energy, a marked inverse dependence of spin period on size. This is obviously not the case despite the fact that observations extend over five orders of magnitude of mass. (Among the exceptions is the small asteroid Icarus with a spin period of only 2 hr; this high spin rate suggests that Icarus may be a fragment split off from a larger body.)

Another fact that is difficult to reconcile with extensive fragmentation in the upper range of presumed parent body sizes is that it becomes increasingly difficult to achieve a breakup by collision as the objects become larger. In the lunar size range, it would appear virtually impossible with the velocities allowed in the solar system.

ACCRETION PROCESSES

One reason why workers in the past concentrated on fragmentation and largely ignored accretion is that the nature of this latter process has remained enigmatic until recently. Electrostatic forces are effective at very small particle sizes (~10 cm) and small relative particle velocities (~10 cm/s), but rapidly become insignificant outside this range. Early in this century, it was also recognized that ices of various kinds could serve as bonding agents but only in a low-temperature regime such as outside the terrestrial planet region today.

For very large objects (~10^7 cm) gravitational attraction is obviously the most important accretional force; however, it still remains a problem to account for the inception and continuation of growth of planetesimal embryos of such small size that the gravitational cross section is negligible.

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Two recent developments may clarify this question. The first is the study of the focusing mechanism for gas and solid particles in asteroidal jetstreams (Alfvén, 1969, 1971; Baxter;[1] Danielsson;[2] Lindblad;[3] Trulsen[4]). This mechanism creates specific regions of high density and low relative velocities within the streams (Danielsson[2]) thus making net accretion possible.

The second is the recent exploration of the Moon. Consolidation of lunar particles appears to take place by three principal processes: (1) bonding by condensing silicate, sulfide, and metal vapor; (2) bonding by melts; and (3) shock lithification.

In the first process, impact vaporization gives rise to high-temperature gas clouds that form, upon condensation, filamentary bridging structures and surface deposits, cementing together particles originally loosely attached (figs. 4 and 5) and increasing the geometric capture cross section of individual grains (Asunmaa et al., 1970). Such silicate, sulfide, and metal vapor condensates are widespread on the lunar surface. The actual process of generation of a local plasma cloud by impact was recorded by the Apollo 12 suprathermal ion detector and the solar-wind spectrometer (Freeman et al., 1971; Snyder et al., 1971). This mechanism could be of major significance in the accretion of individual grains and grain clusters into larger embryos because the equipartition of motion between grains in space by collision would probably lead to recycling of much of the mass through the vapor state.

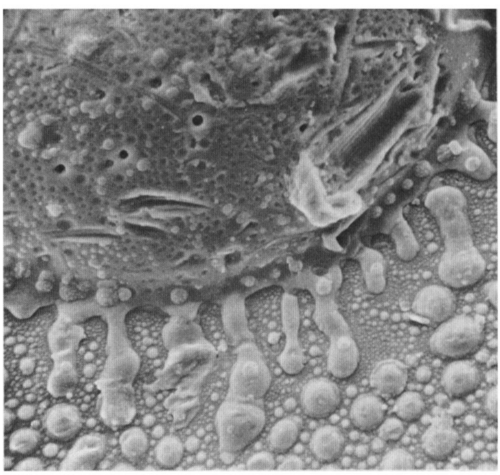

Figure 4.–Vapor condensate associated with deposition of glass splash on rock 12017. Original magnification: × 5000.

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[1]See p. 319.
[2]See p. 353.
[3]See p. 337.
[4]See p. 327.

Figure 5.–Filament structures, presumably vapor deposits, bonding lunar particles to substrate crystal surface. Scanning electron micrograph taken at a magnification of × 10 000 (from Asunmaa et al., 1970).

Figure 6.–Glass splash over friable breccia (rock 12017) from Oceanus Procellarum. Scanning electron micrograph taken at a magnification of × 50.

In the second process, certain types of impact generate silicate melts that splash over or permeate through loosely coherent material and cement it together. The resulting glass-bonded breccias and splash coatings are common in Oceanus Procellarum (fig. 6) and in Mare Tranquillitatis. (See also Morgan et al., 1971.)

In the third process, impact shock transforms loosely aggregated particles into cohesive clods that can attain large dimensions; e.g., the aggregates of boulder size found strewn over the Fra Mauro area (fig. 7).

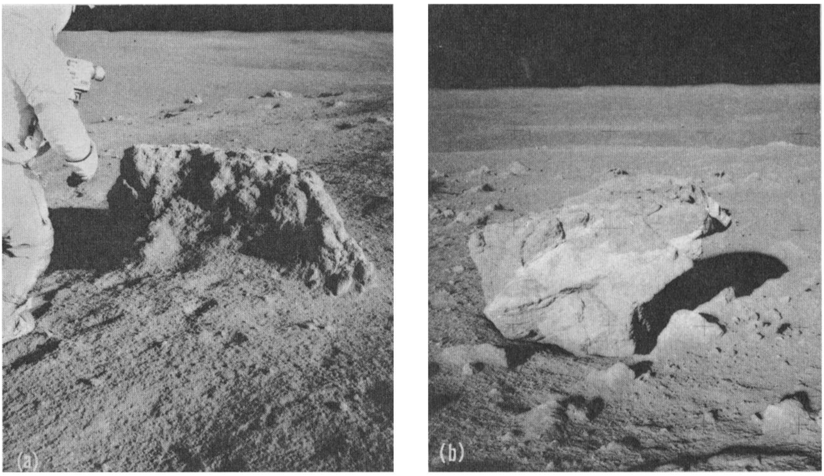

Figure 7.–Compacted aggregates of fine grained material at the Fra Mauro landing site. (*a*) NASA photograph AS14-68-9414. (*b*) NASA photograph AS14-68-9448.

The latter two mechanisms, of which the last is also recognized in meteorites, serve to compact material already aggregated. They could also be important in consolidating and compacting embryos already accreted but presumably would not assist in the accretion of single grains into clusters.

METEORITE PARENT ENVIRONMENT COMPARED TO LUNAR ENVIRONMENT

Observations of the lunar surface provided a first insight into the processes that modify solids exposed to the space environment. Qualitative similarities can be seen between the products of lunar surface processes and certain components of meteorites. It is possible that similar relationships may exist with the asteroids. In this context, the differences between lunar and meteoritic components are as important as the similarities because these differences give some indication of the scaling of properties between the lunar environment and the yet largely unknown environments where comets and asteroids were born.

Consolidation Processes

On the Moon, the melt-splash process is very extensive in some regions of the lunar regolith but in meteorites it appears to be very rare.

Chondrules

In the most common type of meteorites, the chondrites, chondrules are a major component. They have been interpreted as solidified molten droplets or

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vapor condensates. On the Moon, chondrulelike objects occur but they are relatively rare. To explain the striking difference in abundance, Whipple[5] has suggested a sorting mechanism acting in the meteorite parent environment.

Those lunar glass bodies that are formed with free surfaces range in geometry from perfect spheres to teardrops, dumbbells, and rods. Analysis of physical and chemical characteristics of these bodies (Isard, 1971) suggests that they were formed by breakup in flight of thin jets of impact-melted glass from the lunar surface. In contrast, meteorite chondrules practically always occur as spheroidal shapes of varying complexity. Hence it would seem that there are considerable differences in the formation of flight-cooled impact glass on the Moon on one hand and chondrules in the precursor environment of meteorites on the other. It is difficult to explain these differences on the basis of gravitational or compositional effects.

Generation and Crystallization of Melts

The lunar igneous rocks were found by numerous investigators to show textural and chemical similarities to a specific type of meteorite, the basaltic achondrites. (See, for example, Arrhenius et al., 1970; Duke et al., 1970; Reid et al., 1970). However, these two types of objects have a distinctly different oxygen isotope composition (Taylor and Epstein, 1970) suggesting their origin in different environments.

Surface Irradiation

The frequently occurring grains in gas-rich meteorites that have been exposed to corpuscular irradiation in the range up to a few MeV, almost without exception show an all-sided exposure to this radiation (Lal and Rajan, 1969; Pellas et al., 1969; Wilkening et al., 1971). This has been interpreted by the discoverers of the phenomenon to be a result of exposure of the particles while they were freely suspended during the early stages of accretion. In contrast, such all-sided exposure is less common in the lunar regolith where a considerable fraction of particles, exposed to solar flare irradiation on the lunar surface, appear to have been irradiated mainly from one side before they were shielded by burial or a cohesive coating of fine dust.

One of the reasons for the occurrence of one-sided exposure of grains found on the lunar surface could be (Crozaz et al., 1970) that some of these grains received their irradiation while still part of exposed rock surfaces; the irradiated surfaces of these rocks subsequently would have disintegrated and the particles would have been transferred into the soil where shielding by material of the order of 10 to 30 μm thickness is sufficient to prevent further development of steep, high-density track gradients. The lack of the one-sided irradiation features in the achondrite crystals would then lead to the conclusion that in the parent environment of gas-rich achondrites, cohesive

[5]See p. 251.

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rocks did not serve as a source of surface-exposed grains and hence probably were not present. To the extent that asteroids were formed in a way similar to these meteorite parent bodies, and provided that the mechanism proposed by Crozaz et al. is quantitatively important, similar conclusions would apply to the asteroidal precursor environment.

Another characteristic feature of the meteorite grains with direct surface exposure to corpuscular radiation is the gentleness of the process that has brought the grains together without destroying their highly irradiated surface skin (Wilkening et al., 1971), whereas other grains and aggregates in the same meteorite bear clear evidence of shock (Fredriksson and Keil, 1963; Wilkening et al., 1971).

At the time of the discovery of the skin implantation of low-energy cosmic-ray particles in grains now located in gas-rich achondrites (Eberhardt et al., 1965; Wänke, 1965), the isotropic distribution of impinging atoms, revealed by track techniques, was not known. Nor was the inhibited turnover behavior of aggregated particles in space yet known; this became evident only as a result of the lunar exploration (cf. the following section). Nonetheless, the perceptive suggestion was already at this stage made by Suess et al. (1964) that the irradiation took place while the individual particles were floating free in space, before their accretion into meteorite parent bodies. Lacking more direct evidence for this, and under the influence of the planetocentric reasoning of the time, the implantation process was relegated to surfaces of large bodies in most subsequent discussions.

The recent discovery of Lal and Rajan (1969) and of Pellas et al. (1969) returned the attention to the interesting alternative that the isotropic irradiation dates back to the largely unknown freeflight particle stage, preceding or concurrent with accretion. This interpretation avoids the difficulties associated with shielding at turnover of an accreted aggregate and is mechanically understandable in terms of theory and observation of particle streams in space (Alfvén, 1969, 1971; Alfvén and Arrhenius, 1970*a,b*; Danielsson;[6] Lindblad;[7] Trulsen[8]). It must be remembered, however, that predictions from meteorites and lunar sediments constitute extrapolations, and the lesson drawn from the Moon suggests caution in the reliance on prediction in complex natural systems. Meteorites cannot be expected to furnish well-defined information on surface-related problems because the critical interface between the parent body and space, even if it were represented and preserved in the fragments that are captured by Earth, is destroyed at the passage through the atmosphere. Hence, actual samples collected in a controlled fashion on asteroids and comets and returned to Earth would be of unique value for the reconstruction of their surface evolution and of the preaccretive history of the materials.

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[6]See p. 353.
[7]See p. 337.
[8]See p. 327.

SURFACE PROPERTIES AND SOURCE MATERIALS OF ASTEROIDS

The question of the physical behavior of fine grained particle aggregates in space is crucial for reconstructing the accumulation of primordial grains into planetesimal embryos and, until direct studies are possible, for postulating the conditions on the surface of the asteroids. In the time preceding lunar exploration, widely divergent estimates were made, ranging from vacuum welding of solid particles into a crunchy aggregate, to dispersion of particles by repulsive electrostatic forces into highly mobile, fluffy dust. Actual observations on the Moon have provided the first factual information and show that finely divided dielectric materials exposed to the space environment form a relatively dense, cohesive aggregate but without perceptible cold contact welding.

This marked cohesion is probably the reason why, as discussed above, lunar soil particles do not appear to turn around freely in the exposed surface monolayer of grains and that, as a result, surface grains with isotropically irradiated skins are in the minority on the Moon. Because this effect would appear to be independent of gravitation, a similar situation is likely to prevail on the surfaces of asteroids, regardless of their size.

IMPORTANCE OF FIELD RELATIONSHIPS

The materials that make up the asteroids and comets may be found, wholly or in part, to be similar to those that we already know from meteorites. It has been suggested (Anders[9]) that such an identification would be an embarrassment to the exploration effort. On the contrary, this would make it possible for us to apply the large body of experience in meteoritics to the problems of primordial solar system history in a more realistic fashion than is possible at the present time.

The critical information to be obtained from asteroid missions concerns not only the materials from which the objects are constructed. The explorations of Earth and the Moon have demonstrated that it is equally or more important to establish also the field relationships of these materials and the physical properties of the whole body. Only controlled probing and sampling of the asteroids will make it possible to seriously approach the problems of the original mechanism and timing of accretion, the relative role of breakup, the sequence of formation of material units, the possible effects of differentiation before and after accretion, the internal and surface structure of the bodies, and their record of the history of the asteroidal and Martian region, the Earth-Moon system, and the Sun.

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[9]See p. 479.

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