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LARGE PLANETESIMALS IN THE EARLY SOLAR SYSTEM

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Inventories in sizes of large planetesimals can be estimated for different periods in the late planet-forming process by different techniques. For example, tabulations of craters on Mercury, the moon, and Mars give direct evidence of asteroid-like size distribution including bodies in excess of 100 km diameter. Large bodies exceeding 1000 km diameter probably existed earlier. Consequences of interactions between planets and such bodies are considered.

INTRODUCTION

Papers in this colloquium by T. Gold. C. Chapman, F. Singer, and others converged toward the concept that numbers of large asteroid-like planetesimals moved among the planets during the early history of the solar system. This paper strengthens that conclusion by constructing actual inventories of such bodies by several different techniques. I would interpret these techniques to refer to different periods of the solar system's history. A mixture of direct observation and theory gives four independent ways to make such inventories:

1. Counts of interplanetary planetesimals today.

2. Counts of craters, converted to give sizes of impacting planetesimals. These are interpreted to refer to a period at the tail end of intense planetary cratering; this may have occurred about 4.0 billion years ago.

3. Obliquities, inclinations, and eccentricities interpreted in terms of impacts of large planetesimals. This is interpreted to refer to a period during the final stages of growth of the planets, presumably about 4.5 to 4.6 billion years ago.

4. Theoretical calculations of the sizes of the second-largest, third-largest,...body growing in each planet's zone of the solar system. This is interpreted to refer to a period of rapid growth of the planets, presumably 4.6 billion years ago.

Such inventories can give indications of at least the largest planetesimal sizes available during each period, and it will be concluded that these largest bodies were not only sizable, but very important in the evolution of the planets. In the space available it will be possible to do little more than summarize the work done so far.

A principle relevant to the first two techniques is that power-law size distributions represent to at least a first-order accuracy the size distributions of fragmented rock materials both on earth and in interplanetary space. This has been documented for

1. Naturally fragmented rocks (Hartmann 1969).
2. Crater-forming bodies hitting the moon, Mercury, and Mars (Hartmann 1973; Chapman and Jones, in press).
3. Asteroids including those in the belt and probably Mars-crossers and Trojans (Dohnanyi 1971; Van Houten *et al.* 1970; Hartmann 1971).

The significance of this result is that plots of log N vs. log D (N = number of bodies in log diameter increment; D = diameter) is a straight line whose slope is determined by the mechanics of the fragmenting process during collisions of the planetesimals. Marcus (1965) and others have described how a steady-state slope tends to be achieved after repeated collisions. Processes such as collisions with the (much larger) planets, and perturbations into distant orbits tend to remove the smaller objects from the swarm at random as far as diameters are concerned. Therefore, evolution of the population of smaller planetesimals tends to occur with the same power law being maintained but with decreasing numbers of bodies at all sizes. This means that we can anticipate more large planetesimals to have been present in the past; they have been removed as time progressed.

FIRST INVENTORY: PRESENT-DAY POPULATION

Most of this paper will concern the interplanetary planetesimals in the vicinity of the terrestrial planets. Data on the modern population indicate that the largest bodies of this type existing today are of the order of 30 km in diameter.

A second point of interest about the modern population is that the belt asteroids are widely regarded as a frozen tableau of an ancient planetesimal population. Its largest bodies are of the order of 1000 km diameter, giving an indication that 1000-km planetesimals are not unreasonable.

SECOND INVENTORY: CRATER COUNTS

Large craters have been catalogued on the moon, Mars, and Mercury. Relations by Baldwin (1963) and kinetic energy estimates allow these crater diameters to be converted to diameters of planetesimals required to form the individual craters. This gives an inventory of large planetesimals directly recorded in fossil evidence on planetary surfaces. For this purpose catalogs of large craters on the moon (Hartmann and Wood 1971), Mars (author's data), and Mercury (Wood and Head 1976) were used. Figure 1 shows the resulting size distribution of "detected planetesimals" directly tabulated in this method, compared to the size distribution of observed asteroids in the main asteroid belt (solid curve). The derived planetesimal size distribution is similar in form to that of the asteroids, especially the smaller asteroids that are widely believed to result from collisional fragmentation. (Larger asteroids' size distribution probably modified by accretionary growth). It is interesting that the craters directly photographed on the surfaces of the moon, Mars, and (the photographed part of) Mercury amount to about 7% of the number of bodies involved in the main-belt asteroid distribution. If the discussion is to be extended to terrestrial planets in general, then it is not unreasonable to assume that the surfaces of the earth and Venus, and the remaining half of Mercury, must have been once cratered to at least the same degree observed on the other planets. Therefore, in Figure 1 a new curve ("estimated planetesimals") has been generated by multiplying the previous curve ("detected planetesimals") by a factor of 8.4 (ratio of area of all terrestrial planetary bodies to areas of moon, Mars and Mercury so far photographed). The result indicates that about half an asteroid belt worth of particles would be required to crater all the planets to the degree now found on the moon.

The first curve gives direct evidence that at least some planetesimals existed in the early inner solar system with diameters exceeding 100 km. The second curve, by reasonable extrapolation, indicates that objects exceeding 300 km in diameter were probably present, assuming that power-law-like size distributions are legitimate approximations.

It is probable that these are *not* the largest planetesimals involved with the terrestrial planets during their early history. The craters seen on terrestrial planets mark only the last objects to strike them. Judging from Apollo results, this cratering occurred during a period of intense but declining cratering about 4 aeons ago. This inventory, therefore, records only the last bodies to hit the planets, an unknown fraction of the total number of bodies to hit the planets during their entire histories. The number of bodies required to accumulate the entire masses of the planets exceeds this number by thousands of times, and it is likely that enough craterers struck the planets to saturate their surfaces with craters many times over. However, these events occurred, probably, prior to about 4 aeons ago and evidence of the early craters has been obliterated by later craters as well as melting and volcanism (for further discussion, see Hartmann 1975). Assuming power-law-like size distributions, the larger number of early bodies would define a curve higher on the graph; consequently, the largest objects to strike the planets must have been larger than the ones recorded in Figure 1.

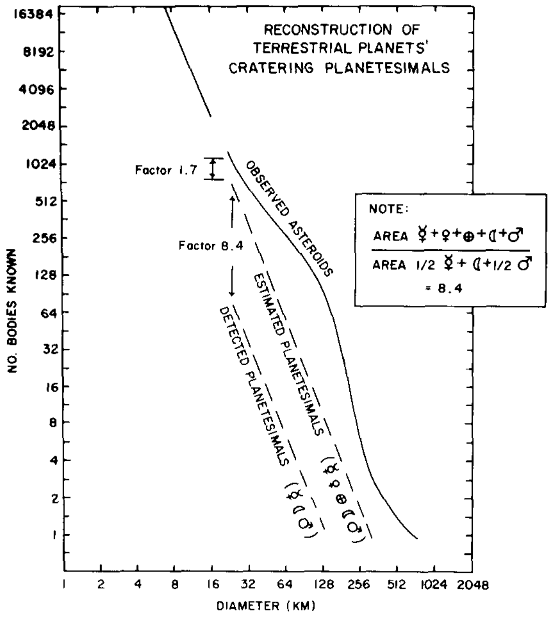

Figure 1. Reconstructed size distributions of bodies causing craters on terrestrial planets. Bottom line (dashed) based on direct counts of largest craters observed in photos of moon, Mercury, Mars. Middle line (dashed) shifts first curve upward by enough to crater all terrestrial bodies to same degree as heavily cratered parts of moon, Mercury, Mars. Upper curve (solid) indicates counts of observed asteroids in main belt. Size distributions probable during formation and earliest (now obliterated) planetary cratering are likely to have included planetesimals near or exceeding 1000 km diameter, causing significant effects in their interactions with planets.

THIRD INVENTORY

The third method of inventorying was pioneered by Safronov (1966). Safronov assumed that obliquities of planets were results of impacts with large bodies adding angular momentum. He extended the work more recently (Safronov 1972) where he computed that the largest bodies to strike the planets were typically 10^{-3} to 2×10^{-2} x planetary mass (as high as 8×10^{-2} in the case of Uranus).

I have extended Safronov's work by considering sizes of impacts required to produce not only obliquities but also eccentricities and inclinations of planets. Most non-tidally affected planets have these properties accounted for by impact with bodies ranging from 10^{-2} to 2×10^{-1} their own mass. However, these results are somewhat model-dependent, depending on size distributions assumed and growth rates of planetary bodies. Nonetheless, the implications in this type of work is that the largest planetesimals among the terrestrial planets may have ranged between 1000 and 4000 km diameter. That is, they were lunar-size bodies.

My colleague Donald R. Davis and I, have approached this hypothesis from a different point of view, namely computing statistics of obliquity distributions derived by impact, using Monte Carlo analysis of impact events. In general, with various power-law distributions we have found that mass distributions, with maximum mass ratios of 0.01 produce obliquities that are too small, while mass distributions with maximum mass ratio 0.03 tend to produce too many high obliquities.

Since the planets probably formed in a few million years, based on geochemical evidence, it is concluded that this inventory of planetesimals indicates lunar-sized planetesimals among terrestrial planets during a period before 4.5 aeons ago.

FOURTH INVENTORY: THEORETICAL RECONSTRUCTION OF LARGE PLANETESIMALS

Hartmann and Davis (1975) have used Safronov-type accretion theory to calculate sizes of second-largest, third-largest, ... etc. planetesimals that grew during the time that the largest bodies became planets. These results, of course, are fairly model-dependent, but the results in general indicate the possibility if not the probability that bodies several thousand km in radius would grow in the same time that the dominant body in each solar system zone reached terrestrial planet size. This is supported by the size distribution of the asteroids; while the largest has grown to a diameter about 1000 km, the next two are about 560 to 500 km in diameter.

These results also indicate that planetesimals as much as a few thousand kilometers across, and a host of still smaller bodies, were present during the formation of the terrestrial planets.

IMPLICATIONS

The most important result of this study is that it explains certain important characteristics of the solar system. As a result of modern accretional theory, it is widely accepted that the planets grew during interactions of a vast swarm of small particles. The original intent of such accretionary theory was to account for the general regularities of the planets: for example, the similar circular orbits of low inclination the usually direct rotations, the generally low obliquities, and properties of the swarm of asteroids and meteorites.

Nonetheless, the solar system does *not* have the uniformity that would be expected if planet growth had involved statistics of only vast numbers of tiny particles. Instead, one planet out of nine has been virtually stopped in its rotation, one planet out of nine has a satellite of diameter comparable to itself, one planet out of nine has a ring system, and one planet out of nine has a typically rapid rotation but with its rotation axis tipped nearly along the invariable plane. These kinds of differences are difficult to explain if only negligibly small planetesimals existed; but they can be explained by small-number statistics of encounter geometries with a very few large planetesimals. The basic concept is that in the case of each planet one planetesimal must have been the largest one ever to strike the planet. If this largest one was of the order of a few percent the mass of the planet, then various anomalous effects would be predicted, depending on the actual encounter geometries; more importantly, a solar system of the type actually observed would be a natural consequence. One or two planets out of nine may have had their rotations or obliquities grossly changed in this way; other inclinations and eccentricities would have been moved to small non-zero values; a few satellites might have originated by capture; some planetesimals might have been captured in Trojan swarms; some satellites might have been destroyed by collisions with planetesimals leaving groups of fragments in similar orbits as found among the Jupiter satellites, or small fragments as found near Mars; ring systems might have evolved from such debris; planets might have acquired significant inhomogeneities in their earliest crustal structures as seems to be the case on the earth, moon, and Mars. We have also suggested (Hartmann and Davis 1975) that a large impact with the earth could have raised a cloud of hot, refractory-rich, volatile-poor material which might have contributed to the formation or properties of the moon. The question of the sizes of the largest planetesimals in the early solar system is therefore a problem of distinct importance to the evolution of the planets.

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DISCUSSION

SINGER: Would you not agree that the large objects which lead to obliquities are also the ones you calculate as 2nd and 3rd largest?

HARTMANN: Yes. I separated them here because the lines of evidence are independent (observational in the case of the obliquities, theoretical in the case of calculated growth rates). But in physical reality they should be viewed as the same bodies, or perhaps members of the same evolving population at slightly different times during planets' accretional growth. Collisions with these might have occurred well before the planet was formed. A collision with Uranus, for example, might have tilted it before the circum-Uranus nebula collapsed to form satellites; the cloud would collapse in the equatorial plane and the satellites would form in that plane.