WHY IS THE MOON DIFFERENT FROM THE EARTH IN BULK COMPOSITION? William M. Kaula, Dept. of Earth & Space Sciences, Univ. of California, Los Angeles, CA 90024.

It is almost universally agreed that the formation of the planets and satellites was from a cloud of gas and dust in association with the formation of the sun, in a time short relative to the subsequent existence of the solar system: less than $10^8$ years for the terrestrial bodies. Given this transition from dust grains to planets, there must have existed intervening stages which were characterized by many bodies of intermediate size: planetesimals. The occurrence of collisions in such a population must have been frequent, and relative velocities must have been damped to permit growth of bodies large enough to capture additional material matter gravitationally. After protoplanets on the order of $M_{\oplus}/3$ developed, their perturbation of the remaining planetesimals would have caused relative velocities sufficient to cause shattering of quite sizeable planetesimals by collision (1). An additional significant effect was tidal disruption by close approach to planets (2). These effects tended to produce a progressive outstripping by the largest body in any zone of the next largest.

The frequent occurrence of satellites makes it desirable to account for their origin as by-products of this regime of a relatively few protoplanets and a much larger number of planetesimals. The evident mechanism is collisions between planetesimals close enough to a planet to lose enough energy to be captured by it, but retaining sufficient angular momentum to go into planetocentric orbit (3,4). Furthermore, the much greater abundance of small planetesimals makes it likely that satellites are formed in planetocentric orbit out of bodies much smaller than themselves. This manner of formation implies that satellites formed from matter in the same zone as the planets with which they are associated, but probably suffered volatile loss because of later formation and a more intensive collision history. (Later formation also makes the recently revived hypothesis of Al26 heating (5) implausible for satellites).

It is desirable to account for the moon as a consequence of the same processes as other satellites. However, the moon has two properties which have traditionally inspired hypotheses requiring it to be an exception: its large mass relative to its primary, 0.0123, and its appreciably lower density than the earth reduced to 10 kb pressure: 3.34 vs. 4.03 gm/cm$^3$. The large size of the moon now appears to be satisfactorily explained by the earth differing from the major planets in having a much higher tidal dissipation; from Mars and Mercury, in not having a much larger body nearby; and from Venus, in having a rapid spin (4,6). The Apollo project confirmed that the low density is due to a deficiency of iron rather than an excess of volatiles compared to the earth. However, it raised the further problem that the
MOON'S COMPOSITION
KAULA, W. M.

The moon is estimated to have an excess of refractory silicates: at least a factor of 2.5 above chondritic from the mean crustal thickness estimated from gravimetry, altimetry, and seismometry (74 km, using the newest Bouguer anomaly map (7)), plus petrologically based considerations for the mantle (8). A factor of three is obtained using the heat flows from two Apollo sites plus the lunar K/U ratio of 2000 and the chondritic Al/U ratio of $10^6$ (9).

Lunar rocks are depleted in siderophiles in a manner inconsistent with any sequence of condensation from a nebula, so it is generally agreed that an intermediate stage of igneous differentiation is required (10,11,12). The problem is the locus of this differentiation: the earth (10,12,13), or in a Mars-sized body which is tidally disrupted on close passage to the earth (14), or in orbit about the earth (11,15) or in an earlier planetesimal stage (16). All of these loci entail dynamical difficulties. Fission from the earth requires not only an extraordinary energy input—impact by a body much larger than the moon (17), or rotational instability (plus an implausible tidal rheology and further impacts (18)), or a formation time on the order of $10^3$ years (19)—but also a selective blow-off mechanism to dispose of the great amount of excess material. The tidal ripoff hypothesis (14) is somewhat less implausible (2), but still requiring an anomalously large body and certainly not worked out in its implications. Relevant to differentiation in a swarm of matter around the earth (11,15), known dynamical effects—increase of the earth's mass, tidal friction, and collisions—all act to increase iron and decrease alumina in the proto-moon, given that iron tends to be associated with larger pieces from mechanically strong cores and the alumina with smaller pieces from crusts. An earlier stage of igneous differentiation within a planetesimal (16) entails not only specification of a sorting mechanisms of large versus small pieces upon infall into the earth-moon system, but also an energy source for the planetesimal differentiation. This latter difficulty is one the moon has in common with several other objects: differentiated meteorites, such as the irons and eucrites (12,20,21), plus various asteroids (21,22).

Auxiliary evidence is the discrepancy of the siderophile depletion from that expected from low-pressure equilibrium between silicates and a metallic phase (10). This evidence can be used to argue either in favor of a large body (because of pressure effects on the equilibria) versus a small (10) or in favor of a sporadic energy source, such as collisions (16), versus a steady source, such as electromagnetic induction (23). Also favoring collisional energy sources are non-equilibrium depletions of siderophiles in eucrites (20) and calculations of impact energy partitioning that indicate a much greater portion...
MOON'S COMPOSITION

KAULA, W.M.

into heat (because of phase transitions) than heretofore believed (24).

The pure capture hypothesis of lunar origin has not been mentioned here, because it has never been suggested by anyone paying serious attention to the moon's composition. Adoption of a pure fission origin (10, 13) apparently requires ignoring not only dynamical plausibility, but also the eucrite phenomenon and geophysical evidence of lunar alumina enrichment. The intrusion of a Mars-sized body into the earth-moon system cannot be ruled out (25) and may be the eventual solution to the lunar problem by process of elimination. However, meanwhile it is desirable to seek explanation of lunar composition by a hypothesis consistent with both the more frequent processes in a general model of the progression from dust grains to planets and the observed compositional properties of other small bodies. Other evidences bearing thereon which we do not have space to discuss here are the indications of an early lunar magnetic field (5) and the need for an early heat pulse to differentiate the lunar crust (26).