WHICH IMPACT ORIGIN OF THE MOON?

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INTRODUCTION. An impact origin of the moon is currently in favor (1,2) and seems to have the fewest problems in explaining the facts. However, many basic issues remain unresolved, perhaps unresolvable at present. Here, I adopt the view that the moon did form as the outcome of a giant impact and ask the next most important question: Was the moon made "overnight" or did formation take 10^2-10^3 years? The "overnight" origin arises in some of the computer simulations of Benz et al. (3,4), where gravitational torques propel a blob of the projectile's mantle into a bound, non-colliding orbit about the Earth. The slower impact origin (5) arises when impact debris is emplaced into a "magma disk" which evolves viscously, spawning many protomoons at or near the Roche limit. These protomoons subsequently coalesce to form the moon as we know it. The choice between these two "extremes" of impact origin is not merely an esoteric dynamics issue because the two models have very different implications, as outlined below. I conclude tentatively that both models have problems, but the slower disk origin seems preferable in terms of chemistry and initial thermal state of the Moon.

DYNAMICAL ISSUES. Computer simulations produce both possible outcomes. The prompt formation seems somewhat preferable because it is very mass selective (impactors below ~ one Mars mass will not cause it to happen), and emplaces sufficient mass in a non-equatorial orbit. I have carried out approximate numerical calculations on the disk evolution case which suggest that it is possible to get ~ one Moon mass to coalesce, but only with a disk more massive than ~3 to 4 Moon masses. The non-equatorial nature of the early lunar orbit is compatible with the equatorial disk, however, because of later impacts and uncertainties in the tidal evolution. In summary, purely dynamical issues do not provide a strong argument for or against either model, but mildly favor prompt origin.

THE IRON-POOR MOON. An attractive feature of recent prompt origin models is that the moon is derived almost entirely from the projectile mantle. Disk-forming models tend to mix in the metallic iron. However, my numerical calculations of the disk show that (a) the iron and silicates may not homogenize in the age of the disk by "eddy" diffusion; (b) there is a small but steady inward drift of iron blobs relative to the silicate (i.e., an imperfect compositional filter) despite the presence of turbulence; (c) the moon is derived from the periphery of the disk. The uncertainties in these calculations are large but the suggest that the disk evolution may produce an iron-poor moon even when the initial disk contains substantial iron, especially if the iron starts out concentrated toward the inner part of the disk. I conclude that the iron-poor nature of the moon does not discriminate between the two models.

VOLATILE DEPLETION. Both Earth and moon are depleted relative to carbonaceous chondrites, with the moon even more depleted than earth by an approximately constant factor (6). This argues **against** selective devolatilization as the sole cause of the lunar pattern. The most plausible model is to take as protolunar source material a reservoir that is very volatile-poor and then mix in (by later impacts) some volatile-rich material. It is important to realize that the prompt lunar origin by impact will **not** efficiently devolatilize the moon, because the self-gravitating blob will contain deep within it the volatile inventory of the pre-impact projectile, which may have an earthlike inventory for at least some volatiles. The disk evolution model (5) **can** eliminate a small mass of volatiles with high efficiency by hydrodynamic outflow and dry out the magma with spectacular efficiency (the moon has less than 1 ppb H_2O). Contrary to wishful

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thinking on the part of some, it is probably not possible to dry out the Moon, if it formed "wet", to this remarkable level, even allowing for H_2O-metallic Fe reactions. I conclude that the volatile depletion of the Moon favors the disk origin over prompt origin, although the qualification is difficult and suspect.

THE INITIAL LUNAR TEMPERATURE. The absence of compressional tectonics on the Moon has been used to argue against an initially molten Moon (7). This argument can be relaxed somewhat by allowing for the expansion accompanying migration of Al_2O_3 out of the garnet stability field during subsequent gabbroic differentiation (8). Nevertheless, it seems desirable to have an initial moon that has a significantly subsolidus interior. This can be provided by disk evolution because of the formation of many small protomoons, each of which cools substantially before rather gentle coalescence into the present moon (5,8). I conclude that the inferred initial thermal state of the moon is not compatible with prompt origin but is compatible with disk origin,

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