

THE ORIGIN OF THE MOON, A. G. W. Cameron and W. R. Ward, Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory, Cambridge, MA. 02138.

A key constraint on the origin of the Earth-Moon system is the abnormally large value of the specific angular momentum of the system, compared to that of the other planets in the solar system. At an early stage, when the Moon was close to the Earth, most of the angular momentum resided in the spin of the Earth. This spin was presumably imparted by a collision with a major secondary body in the late stages of accumulation of the Earth, with the secondary body adding its mass to the remainder of the protoearth. The collisional velocity must have been close to 11 km/sec, and if the impact parameter was one earth radius, then the mass of the impacting body was comparable to that of Mars. It is probable that the largest accumulative collision should have involved a mass of this order, but the size and location of the impact parameter would have been a matter of chance. It is likely that both bodies would have been differentiated and possibly molten at the time of impact.

Consider the consequences of this tangential impact. The outward-facing hemisphere of the smaller body would be sheared off and shock-retarded in its motion; its many resulting fragments would reimpact upon and amalgamate with the Earth. The inward-facing hemisphere would undergo collision at 11 km/sec. At this velocity most silicates vaporize upon shock-unloading<sup>(1)</sup>, but the metallic core of the smaller body probably would not. Thus the mantle material of both bodies in the region of the collision would shock-unload predominantly in the forward direction relative to the collision velocity and much of the material would vaporize. The subsequent motion of this material is not just a set of ballistic trajectories; the early motion of the material is entirely governed by gas pressure gradients in the vapor which is expanding into vacuum. If the material were to remain in vapor form the bulk velocity of expansion would approximate sound speed (~5 km/sec) and the surface layers would be accelerated to several times this value. Actually, the more refractory silicates would condense into particles in the centimeter size range<sup>(2)</sup> early in the expansion and the more volatile materials would condense into a finer dust at a later stage when the expansion velocity is closer to its asymptotic value. Most of this fine dust probably escapes from the system or is otherwise segregated from the refractory materials by magnetic effects.

A simple geometric consideration shows that most of the

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shock-unloading of the silicate materials takes place while the outward-facing hemisphere of the smaller body is separating from the collision area; the expansion of the vaporized rocky material thrusts against this hemisphere, so that the main velocity vector of the expansion is rotated and the periaipse of the motion lies above the radius of the protoearth. Gas pressure gradient acceleration produces a substantial dispersion in velocity vectors about this direction. A substantial portion of the material shock-unloaded in the forward direction should go into orbit; only a small portion of that ejected toward the sides would go into orbit.

The initial trajectories are highly eccentric. Because of the enormous numbers of small particles, mutual collisions will rapidly circularize the orbits and form a thin disk of the refractory particles. A very eccentric orbit that is circularized with conservation of angular momentum raises its periaipse distance by a factor of two. Hence the initial disk would have a large amount of material in the range two to four Earth radii, with smaller amounts inside and outside those limits.

Collisions continue to be important among the small particles in the disk, so that the disk behaves as though it were a viscous gas. Hence there will be an outward transport of angular momentum, an inward transport of mass near the protoearth, and an outward transport of mass near the outer edge of the disk. Beyond the Roche limit near three Earth radii, a collective gravitational instability can take effect and produce gravitational clumping of the particles<sup>(3)</sup>. The range of the instability progressively increases beyond the Roche limit, and the clumps that form will have a substantial tidal interaction with the Earth.

We estimate that the Moon can form very quickly from this disk. Its composition reflects two stages of processing; chemical differentiation in the colliding bodies followed by volatilization of mantle and crust material and selective retention of the refractory condensate. The Moon should thus be deficient in metallic iron and volatile elements and mildly enriched in crustal materials such as Ca and Al.

Not all of the material in the disk would be accumulated into the Moon. That left in orbit close to the Earth would be dissipated either by magnetospheric interactions, by orbital resonances with the Moon, or by the Poynting-Robertson effect.

We wish to emphasize that this picture follows as a logical

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consequence of the process needed to provide the angular momentum of the Earth-Moon system. The process can form a large satellite only for a body comparable in mass to the Earth where the escape velocity is sufficient to vaporize silicates. If a similar large collision happened in the late stages of accumulation of Venus, the orbit of any major satellite formed would have decayed into the planet long ago<sup>(4)</sup>.

## References

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