ORIGIN OF THE MOON BY A MODIFIED CAPTURE MECHANISM, OR HALF A LOAF IS BETTER THAN A WHOLE ONE, J. A. Wood and H. E. Mitler, Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory, Cambridge, Mass. 02138

Capture of the Earth's moon, intact, from an independent heliocentric orbit is dynamically difficult to accomplish and thus inherently improbable[1,2]. If a candidate for capture passed within 2.5 Earth radii of the Earth's center (the Roche limit), it would be disrupted by tidal stresses. Öpik[3] has recently drawn attention to differences in the subsequent orbits of the fragments produced by such an event. Assume a non-spinning object of substantial dimension entered the Earth's Roche limit at parabolic velocity: all fragments would be endowed with this same velocity at the moment of disruption. For those fragments detached from the near-Earth face of the object, however, this would amount to less than the parabolic velocity, since the distance from these fragments to the center of mass of the Earth is appreciably less than was the distance between the centers of mass of the original object and the Earth. These fragments would be projected into closed, elliptical orbits about the Earth. Conversely, debris from the farthest-out face of the object would be lost from the Earth in hyperbolic orbits. It is important to recognize that this partial capture of the substance of a passing object into geocentric orbit does not depend upon a special three-body configuration of Sun-Earth-object, or upon loss of orbital angular momentum to a tidally distorted Earth, or upon any other dissipative process; it follows naturally and inevitably from simple considerations of orbital mechanics.

One such encounter is modelled in Fig. 1. Parabolic velocity (i.e., $V_\infty = 0$) was assumed for the approaching object or protomoon, which barely entered the Earth's Roche limit. The gravitational influence of the Sun and the mutual gravitational interaction of fragments after disruption were neglected, as was the effect of any rotation of the protomoon. Some debris is lost, and some is captured; an intermediate category of fragments is nominally captured in extremely elongated orbits. Since the latter reach apogee at positions where the Sun's gravitational influence exceeds Earth's, and since the fragments have small (geocentric) orbital velocities and kinetic energies at apogee, their orbits are subject to radical change and they are likely to be lost to the Earth. The effect of passage of the protomoon deeper inside the Roche limit, and of greater-than-parabolic approach velocities, is to diminish the proportion of debris likely to be retained in Earth orbit (Fig. 2).

The early solar system probably contained more and smaller planets than it does today;[4] collisions and coalescence of these produced the present configuration of terrestrial planets. For every sub-planet that joined the Earth, ~5 would pass within the Roche limit but escape impact. It seems inevitable that a swarm of Earth-orbiting debris from these tidally disrupted near-misses would accumulate. The present moon could have accreted from such a swarm.

Of special interest is the localized source, from within a disrupted protomoon, of fragments that are likely to be captured into Earth orbit (Fig. 2). The central volume of the protomoon is largely or wholly lost; material retained in orbit originally occupied positions relatively near the surface of the protomoon. This has

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Fig. 1. Fate of fragments produced when a protomoon is disrupted upon entering the Earth's Roche limit at parabolic velocity. Fragments from 10 orbitrary layers in the protomoon (upper left), each layer approximately equidistant from the center of mass of the Earth, are followed. 1–5 are lost in hyperbolic orbits (relative to a terrestrial reference frame). 8–10 are captured in closed orbits. 6 and 7 are nominally captured, but in orbits of such extreme elongation that subsequent escape from Earth orbit is likely. Gravitational accelerations due to Sun and Earth are equal along dashed curve (r = 259,000 km).
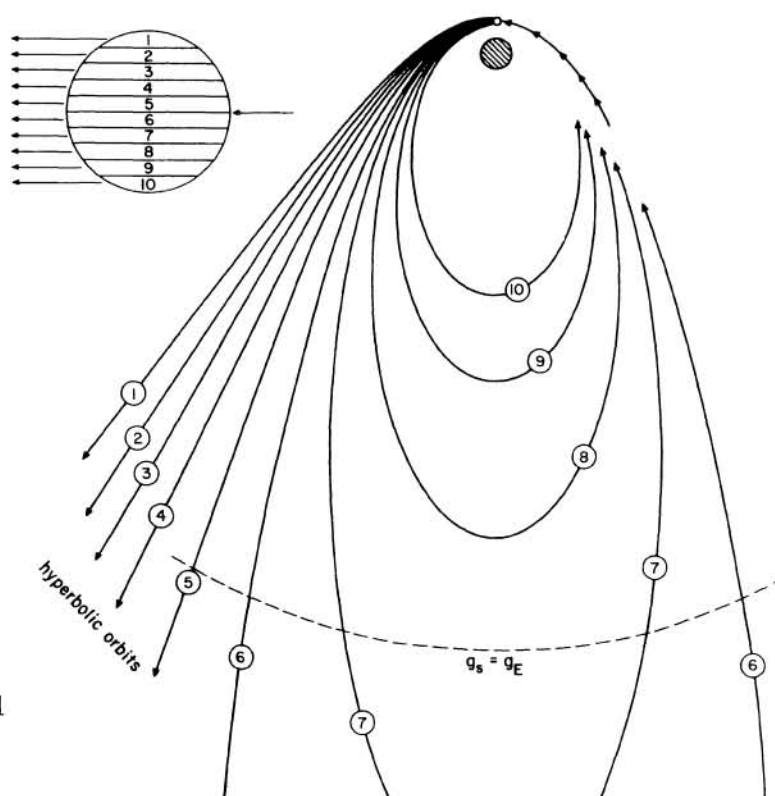
the potential of explaining the peculiar bulk chemical composition of the present moon, which has always been something of an embarrassment to those who would form it by capture or in orbit about the Earth. Accretion of the moon at the right time and place relative to the nebular condensation sequence[5, 6] is traditionally invoked to explain the moon's lack of metallic iron (and other siderophile elements), but, in fact, equilibrium condensation of metallic iron and Mg silicates takes place over essentially the same temperature interval in the solar nebula;[6] it is very awkward for the moon to have to shun metallic particles while it is accreting Mg silicates for its mantle.

If the protomoons that were disrupted within Earth's Roche limit had already melted and differentiated, however, it is clear from Fig. 2 that very little of their core material would be retained in Earth orbit. (Whether a protomoon core had solidified or not at the time of tidal disruption is immaterial.) Mantle and crustal material from the protomoons would be retained selectively in Earth orbit, and would provide a suitable raw material from which to accrete the moon as we know it.

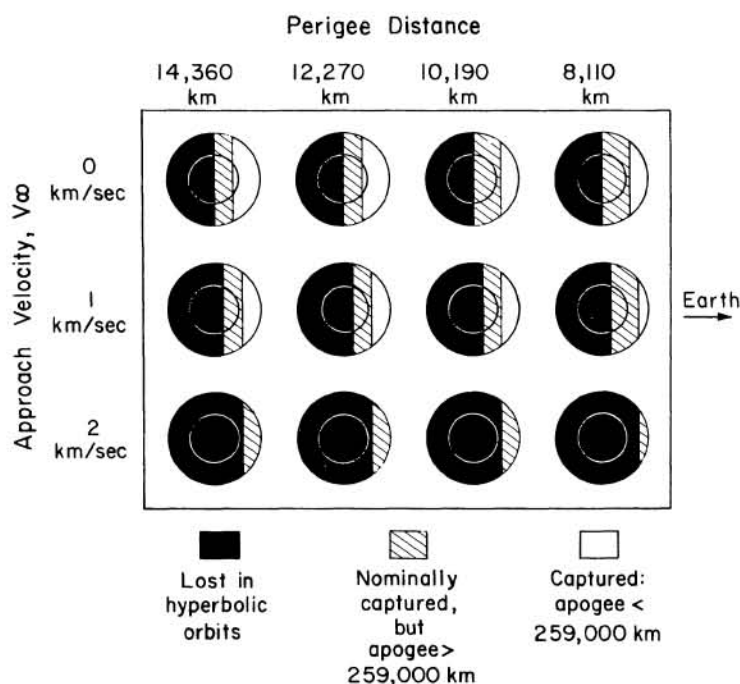# ORIGIN OF THE MOON

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Fig. 2. Zones of a hypothetical protomoon that would be lost, captured, and nominally (temporarily) captured, for several assumed values of approach velocity and perigee distance. 14,360 km is barely inside Earth's Roche limit; 8,110 km grazes the Earth's surface. The right side of each disk passes closest to Earth. Inner disks: boundary of hypothetical metallic core, in differentiated protomoon of Earth-like composition.

No important amount of debris is left in Earth orbit if $V_\infty > \sim 2$ km/sec. For protomoons to meet this velocity requirement, their heliocentric orbits prior to their approach to Earth must have had mean distances in the range 0.8–1.2 A.U. Thus, material made available to the moon by the mechanism discussed cannot have originated in a remote part of the solar system.

References

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