

ORIGIN OF MOON BY DISINTEGRATIVE CAPTURE WITH CHEMICAL
DIFFERENTIATION FOLLOWED BY SEQUENTIAL ACCRETION. J. V. Smith, Dept. of the
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Most ideas on the Moon's origin fall into the categories of simple capture without disintegration, simple fission, volatilization-condensation, and simultaneous accretion of Earth and Moon as binary planets (e.g. 1,2). Chemically, ideas for the inferred bulk refractory composition of the Moon include accretion of the Moon as a high-temperature condensate (3), perhaps inside the orbit of Mercury (4); special processes when the Moon is in Earth orbit (5,6); single-stage volatilization of Earth-derived vapor (7); and volatilization at the Moon's surface (8); all bulk compositions would be modified by crystal-liquid differentiation (e.g. 9).

The present model expands on the ideas of Ruskol (10), who considered development of a circumterrestrial swam, and of Kaula and Harris (2) who considered dynamics of capture. It also uses some ideas of Öpik (11) for impact of earth-bound bodies during tidal recession of the Moon. Density variation of the Roche limit, and momentum effects of earth-bound debris, are used to give chemical differentiation, as well as the usual volatility and crystal-liquid effects.

I. Orthodox processes of condensation and accretion from the solar nebula are invoked to produce near-radial swarms of planetesimals plus minor debris about the Sun (e.g. 12). Chemical differentiation is assumed to correlate mostly with distance to the sun. Collisional heating results in a metal core and silicate mantle of larger bodies with loss of volatiles. The proto-Earth and pre-Moon are planetesimals with similar bulk starting compositions.

II. The proto-Earth interacts with bodies in similar orbits principally by direct collision or by near-collisions. Debris already in Earth orbit increases the capture probability (2,10). Near-collisions result in disintegration with material sprayed onto the Earth, into Earth orbit, or into escape orbits.

III. The Roche stability limit applies to a tiny, rotation-locked, non-turbulent liquid satellite in a circular orbit. Inside the Roche distance, the self-gravitation is insufficient to balance differential gravitation from the central body. The Roche distance is not fixed for the Earth at 2.88 radii. It is actually proportional to the inverse one-third power of the satellite density. Naively a differentiated satellite with a liquid iron core (7 g/cm³) and a liquid silicate mantle (~ 3 g/cm³) could lose the silicate under the Roche condition near 3 radii whereupon the iron core could be stable down to 2.24 radii. Accretion from a hot cloud of immiscible iron and silicate droplets could begin with the iron droplets at 2.24 radii, followed by mantling with silicate. The actual situation involves turbulence for liquids, cohesion for solids, the shape of the orbit, the rotation, etc. Nevertheless the variation of the Roche limit provides a possible mechanism for separating denser from lighter materials.

IV. Disintegration into Earth orbit would be affected by mechanical stability. Partial melting of the incoming satellite plus tidal heating

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during encounter would be important factors. Ductile iron should form more massive fragments than brittle silicates (cf. Orowan, 13). Feldspar is more prone to shock deformation and melting than olivine and pyroxene. Elastic collisions between two populations result in the more massive population losing velocity and being preferentially captured by Earth. A mass gradient with feldspar fragments favored at high radial distance might occur.

V. Of many possible scenarios, the following is fairly simple. In addition to capture and near-capture of minor planetesimals and debris (with decreasing flux, of course), the Earth near-captured a large planetesimal (pre-Moon) which disintegrated into hot debris. Much of the pre-Moon (especially the iron-rich material) was incorporated into the Earth but some stayed in orbit. High temperatures caused loss of volatiles (as in Ringwood's volatilization model), and collisions resulted in a radial gradient of decreasing mass. A hot iron-rich baby Moon accreted near the Roche limit for iron, receded and accreted a silicate-rich mantle. The iron-sulfur core of the spinning Moon developed a dynamo producing a magnetic field: further tidal recession plus rotation-locking between Moon and Earth ultimately led to factors which reduced the driving force of the dynamo, but not before extrusion of the last mare basalts (see 14 for problems of explaining magnetic field).

Crystal-liquid differentiation stripped the core and mantle of light, fusible material leaving a stable ferro-magnesian mantle and concentrating radioactive material at the temporary surface. This surface material was rejuvenated as accretion proceeded.

The outer part of the ring of debris accreted into moonlets, and captured further material from sun orbits. In general these moonlets would be dominated by ferromagnesian and feldspars. The content of volatiles and feldspars should increase for the more distant moonlets. The moonlets would be captured as a result of tidal recession of the baby Moon (Öpik) and by orbital perturbation of the moonlets during collisions with incoming bodies. A catastrophic perturbation of several moonlets might occur leading to near-simultaneous capture of several moonlets. The temperature of the moonlets could be low (several hundred °C), but capture by the growing Moon at low velocity (~ 3 km/sec) would increase the temperature. The low velocity would result in accretion of most of each moonlet with little loss to Earth. Planetesimals from sun orbit might also collide with the Moon, but the high velocity of impact would yield an explosion with little direct accretion (though exploded material might be captured later). The growing Moon would undergo continual crystal-liquid fractionation with re-working of fusible material.

Finally at about 4 g.y., the last large moonlets would be captured producing most of the circular basins. The dynamics of capture depend on the orbital parameters and nature of the perturbing force. One possibility is that at least the later impacts tended to occur at low velocity on the far side, bringing in large quantities of feldspar and Mg-rich pyroxene, which formed thicker ejecta blankets on the far than on the near side. If this can be justified dynamically, it may provide an explanation for the offset of the center-of-mass from the center-of-volume. Wood (15) showed that moonlets

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exterior to the Moon's orbit would tend to impact on the far side of the Moon, but further study is needed of the ballistics, impact processes and petrologic consequences. With a thinner crust on the near side, one can postulate that mare basalts would easily penetrate the crust into impact basins on the near side but would rarely penetrate the crust on the far side. With this model, a problem arises in providing missiles to impact on the near side for production of the circular mare basins. One possibility is serious perturbation of exterior moonlets in near-circular orbits by interaction with bodies from sun-centered orbits. Unfortunately a process like this is ad hoc, and difficult to quantify.

Asymmetry of the Moon might also result from or be augmented by the differential gravitational field from Earth. One possibility is a second-order tidal effect on a rotation-locked Moon which helps to concentrate dense Fe,Ti basalt at the near side (16): however, the first-order tidal effect should affect both front and back (15). An interesting item for study is convection of a liquid satellite under the differential gravitational field of the primary body: this might lead to asymmetric differentiation of crystals and liquid.

The number of models for generation of mascons is too big to list here. For low-velocity impacts, substantial accretion of the incoming body should occur: e.g. Gold (17) proposed that mascons resulted from contrast of accreted material with thick unconsolidated crustal debris. Isostatic uplift plus extrusion of Fe,Ti basalts undoubtedly complicate the problem and a complex model is needed.

Mineralogical study of breccias and soils has shown no clear-cut identification of debris from accreted moonlets. If the lunar crust is indeed composed largely of such impact debris, the moonlets would be dominated by similar minerals and rocks to those produced by melting of the early Moon. Anders et al. (18) have produced evidence on the content of various trace elements of accreted debris, suggesting that the impacting bodies have distinctive chemical compositions. At first sight, this argues against the bodies belonging to a common population as implied here for the earth-bound population (but not the sun-bound ones). However, the major chemistry of the accreting bodies might be dominated by silicates, and the distinctive differences might result from capture of sun-bound projectiles while the bodies were still in Earth orbit.

Many possibilities are apparent and the model is presented in the spirit of Chamberlin's multiple working hypotheses.

- 1) Urey & MacDonald 1971 Phys. Astr. Moon ed. Kopal:2) Kaula & Harris 1973 Nature 245 367:3) Anderson 1973 Moon 8 33:4) Cameron 1972 Nature 240 299:
- 5) Anders 1970 Science 169 1309:6) Singer & Bandermann 1970 Science 170 438:
- 7) Ringwood 1972 Phys. E. Plan. Int. 6 366:8) Biggar et al. 1971 PSLSC 1 617:
- 9) Taylor 1973 Nature 245 203:10) Ruskol Sov. Astr. AJ 1961 4 657 1963 7 221
- 1972 15 646:11) Öpik 1969 Ann. Rev. Astr. Astroph. 7 473:12) Alfvén & Arrhenius 1970 Astr. Space Sci. 8 338:13) Orowan 1969 Nature 222 867:14) Sonnett & Runcorn 1973 Moon 7 308:15) Wood 1973 Moon 8 73:16) Smith et al. 1970 J. Geol. 78 381:17) Gold 1973 Moon 7 293:18) Anders et al. 1973 Moon 8 3.