THE MAKING OF THE MOON

A.E. Ringwood, Research School of Earth Sciences, Australian National University, Canberra, A.C.T. 2601, Australia.

Geochemical observations cited in the accompanying abstract provide strong evidence that the material in the Moon was derived mainly from the Earth's mantle after core formation. A number of years ago, I proposed a model [1,2] whereby accretion of the Earth was accompanied by the formation of a primitive terrestrial atmosphere (PTE) comprised of gases evaporated from impacting planetesimals, mixed with hydrogen gravitationally captured from the solar nebula. The PTE became coupled to the Earth's rotation (by turbulent viscosity) and was spun out into a co-rotating disc (period 5 hrs). During the later stages of formation of the Earth, high temperatures were produced by a combination of rapid accretion and thermal insulation by the PTE. Material from the mantle was thereby evaporated into the PTE and spun out into the disc. As the PTE cooled and dissipated, the silicate components were precipitated to form a ring of Earth-orbiting planetesimals, from which the Moon subsequently accreted.

The principal problem with this scenario was the short time-scale ($< 10^6$ yrs) over which the Earth must form if the energy of impacting planetesimals is to generate the sustained high temperatures necessary to evaporate part of the upper mantle. The problem is neatly solved by the currently popular "giant impact" scenario [3,4]. Rather than achieve high mantle-evaporation temperatures via 'steady-state' accretion from a continuum of relatively small impacts over a short timescale (< 1 m.y.), giant impact models achieve these conditions in one or in a few transient ultra-high energy events, and permit a much longer accretion time-scale for the Earth (e.g. 10^7-10^8 y).

Potential problems [5] with the giant impact models arise from the large portion of the impacting body which may end up in the Moon [6]. Moreover, the large amount of gases lost from the Earth-Moon system according to this model [6] could cause unacceptable oxygen isotope fractionations between the two bodies [7]. Accordingly I prefer a scenario intermediate between my earlier rapid accretion models and the current giant impact models, as depicted in Fig. 1.

The co-rotating primitive terrestrial atmosphere plays a key role both in the accretion of the Earth and in the formation of the Moon. The PTE extended the capture cross section for incoming planetesimals, circularizing their orbits in the Earth's equatorial plane and also helped trap ejecta from large direct impacts. The solids accreting on the Earth were thereby processed through an "accretion disc" which contributed to the high rate of rotation of the growing Earth.

At a late stage of accretion, impacts of many large (100 < R < 1000 km), but not necessarily giant (R > 1000 km) planetesimals at velocities exceeding 12 km/sec caused extensive shock-melting and evaporation of material from the Earth's surface [8]. The shock-melted material was ejected as sprays of devolatilised droplets. Rapid expansion of the impact cloud caused acceleration of gases and liquid droplets to high velocities. Impact ejecta and condensates were trapped via viscous dissipation within the PTE to form a disc of Earth-orbiting planetesimals. The majority of planetesimals probably accreted inside the geosynchronous orbit (2.5 ER). They would have lost energy via friction in the co-rotating atmosphere and hence spiralled back to Earth. However, it is suggested that a significant proportion of planetesimals were formed beyond the geosynchronous orbit. This population would have been accelerated by gas drag from the co-rotating PTE, causing them to spiral outwards beyond Roche's Limit, when they accreted to form a ring of Earth-orbiting moonlets. The Moon, in turn, was formed by coagulation of this ring of moonlets.

References : [1] Ringwood, A.E. Geochim. Cosmochim Acta 30, 41, 1966. [2] Ringwood, A.E. Phys Earth Planet Inter. 6, 366, 1972. [3] Hartmann, W.K. and Davis, D. Icarus, 24, 504, 1975. [4] Cameron, A.G.L. and Ward, W.R. Lunar Science 7, 120, 1976. [5] Ringwood, A.E. in Origin of the Moon, Lunar Planetary Inst. Houston, 1986. [6] Cameron, A.G.L. Icarus 62, 319, 1985. [7] Clayton, R.N. and Mayeda, T. Proc. Sixth Lunar Sci. Conf. 2, 1761, 1975. [8] Boslough, M. and Ahrens, T. Lunar Planet Sci. 14, 63, 1983.

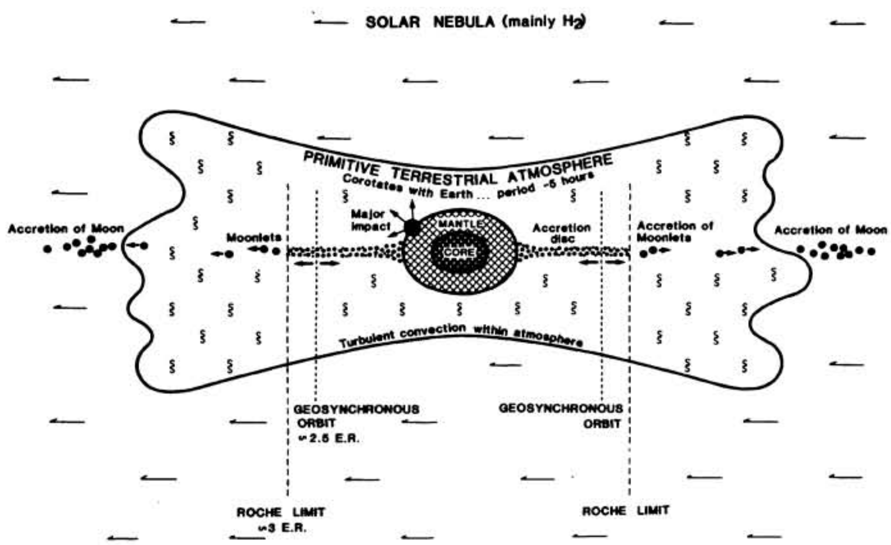

Fig. 1 Model showing formation of the Moon via the ejection of material from from the Earth's mantle by impacts from late-accreting, large planetesimals in the presence of a co-rotating primitive terrestrial atmosphere.