THE ROLE OF LARGE IMPACTS IN THE FORMATION OF THE EARTH AND MOON. G. W. Wetherill, Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D.C. 20015

Most treatments of the thermal history of the moon, e.g. (1) have assumed that the gravitational energy of accretion was entirely released at the surface of the accreting body. This extreme assumption places severe constraints on the accretional time scale since these conditions facilitate radiation of the accretional energy into space. Only by accretion of the moon on a very rapid time scale ($\sim 10^3$ years) were temperatures found to be sufficiently high to account for the observed very early chemical differentiation of the moon. Accordingly, most workers have implicitly or explicitly adopted this rapid accretion model and the petrological model associated with such rapid homogeneous accretion - the "Magma ocean" hypothesis. If the success of this hypothesis in interpreting the chemical evolution of the moon had been overwhelming, this would have constituted strong evidence in support of this rapid accretion model. However, the success of this model has been limited, and it seems unlikely that at least in its simpler forms, this hypothesis will permit a full understanding of both the major element, trace element, and isotopic abundance distributions in lunar rocks.

Safranov (2,3) has challenged the validity of this short time scale, and has presented arguments for preferring a longer i.e. $\sim 10^8$ year time scale for formation of the terrestrial planets and the moon. A similar accretion time has also been obtained in other dynamical theories (4,5). It has also been pointed out that both the rapid time scale as well as this 100 m.y. time scale for lunar formation are compatible with lead, strontium, and xenon ages for the earth and the moon (6,7).

Extensive early heating is possible on the long time scale, provided that a significant fraction of the accreting bodies are $\gtrsim$ 200 km in radius, permitting release and trapping of their impact energy at depths sufficiently great to preclude transfer of the heat to the surface (2,3). This mode of heating can introduce thermal and chemical inhomogeneities which may alter the course of chemical evolution of the moon (3,7).

It is therefore of importance to estimate the fraction of large bodies in the accreting material. Theoretical treatments of accretion (8,9,10,11) have yielded differential mass power law relationships valid over much of the planetesimal mass range, with values of the exponent between 1.5 and 1.83. Naive use of these results suggests that between 50% and 20% of the mass will be in the single largest body, and most of the mass concentrated in the largest bodies. However, the power law relation is not valid at the high end of the mass range

THE ROLE OF LARGE IMPACTS

G. W. Wetherill

(12), and an alternative way of estimating the contribution of large bodies is required. One approach used by several authors is to invoke "runaway" accretion in which the enhanced gravitational radius of the single largest body permits it to emerge as a planetary embryo and dominate the final stages of accretion. Thus Safranov (2) concludes that the second largest body (excluding the moon) in the earth's accretional zone was about $6x10^{24}$g in mass, in agreement with his calculation of the largest single impact on the accreting earth as inferred from the inclination of the earth's axis with respect to the plane of the solar system (which may be considered independent observational evidence in support of the presence of large bodies). This result is based on a velocity distribution whereby the relative velocity of the planetesimals forming the "half-grown" earth is calculated to be ∿2.5 km/sec. As discussed earlier (7) it is quite likely that mechanisms such as the deviations of the earth's orbit from circularity and particularly merging of the accretional zone of earth and Venus, will result in higher velocities of ∿8 km/sec at this stage. Under these circumstances it is unlikely that a $6x10^{24}$g body would survive long enough to impact the earth.

An alternative way to produce the dominant earth embryo is suggested here, in which it is isolated as an attritional remnant, rather than emerging by runaway growth. Runaway growth will occur only if the mean relative velocity drops low enough to give a slightly larger planetesimal a marked accretional advantage. Safranov's theory (2) indicates that prior to the emergence of the dominant embryo the mean relative velocity may be considerably greater than the value he adopts, with the consequence that the second largest body may be larger, i.e. $\sim 10^{26}$g, and that as much as 20% of the residual mass in the earth's zone will reside in bodies of mass > 10^{25}g. During the final half of the earth's growth period, these large bodies will be slowly eliminated by fragmentation following approach to the earth (and Venus) embryos within their Roche limits (13-17), and by cratering collisions. They will supply a steady-state population of collision debris which will undergo further fragmentation by mutual collision before being swept up by the only body capable of growth under these high velocity conditions - the largest body, the earth embryo.

This variant of Safranov's theory results in larger impacting bodies during the final stages of accretion of the earth and moon, and will result in more heating of the interior of these bodies. It is even possible that an object impacted the moon with sufficient energy to cause complete disruption, followed by the rapid reaggregation associated with geocentric accretion and internal release of sufficient energy to cause

THE ROLE OF LARGE IMPACTS

G. W. Wetherill

complete melting. This is not so probable, but impact of not too much smaller, $\sim 5\times10^{23}$g (700 km diameter) bodies with the moon are quite probable. It is also likely that prior to being disrupted, the $\sim 10^{25}$g bodies in the earth's zone will be internally melted and differentiated by impacts with smaller bodies as required in the lunar accretion model of Kaula and Harris (18,19). This provides an additional way to produce the prior differentiation of the lunar planetesimals which is independent of the mechanism invoking the early heavy bombardment by Jupiter material (20) which could prove inadequate in the earth's zone, as believed by Weidenschilling (21).

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