# Tungsten isotope models and the giant impact theory of lunar origin

A. N. Halliday
D.-C. Lee

Department of Geological Sciences, The University of Michigan, 2534 C.C. Little Building, Ann Arbor, MI 48109-1063, USA

The Giant Impact Theory of lunar origin was formulated and extensively debated in the 1980s and has, thus far, provided the most successful explanation for many of the features of the Moon. As originally conceived, the model proposes that the Moon formed because a body about the size of Mars struck the proto-Earth with a glancing blow in the final stages of Earth's accretion (Cameron and Benz, 1991). This late origin of the Moon is entirely consistent with isotopic data. More than twenty years ago G. J. Wasserburg and co-workers summarized the state of knowledge at the time: "The actual time of aggregation of the Moon is not precisely known, but the Moon existed as a planetary body at 4.45 Ga, based on mutually consistent Rb-Sr and U-Pb data. This is remarkably close to the $^{207}Pb$-$^{206}Pb$ age of the Earth and suggests that the Moon and the Earth were formed or differentiated at the same time." (Wasserburg *et al.*, 1977). Tungsten isotope data for lunar samples are also consistent with such a late origin of the Moon. An age of $50 \pm 10$ Myrs after the start of the solar system was proposed by Lee *et al.* (1997) which put the age of the Moon and the two-stage model age of the Earth's core within a very similar time frame, entirely in agreement with most estimates based on U-Pb data.

The rate of accretion of the Earth has been modeled by Wetherill (1986). The cumulative fractional mass as a function of time is similar to accretion at an exponentially decreasing rate with a mean life of ~ 12 Myrs (Halliday *et al.*, 1996). On this basis the Earth should have almost reached its present mass by 50 Myrs after the start of the solar system, when the Moon is thought to have formed. Therefore, all these results appear to form a consistent story.

However, a major problem with this accretion rate is that if the Earth segregated a core as it grew, the W isotopic composition of the silicate Earth would be expected to be radiogenic, whereas in fact it is chondritic (Halliday *et al.*, 1996, Lee *et al.*, 1997). This result holds even if the major portion of the W in the silicate Earth was added at a late stage (Halliday *et al.*, 1996). The simplest explanation for the W isotope data is that terrestrial core formation was late (>50 Myrs) and possibly related to impact phenomena. However, there is substantial evidence that other planetary cores formed at an earlier stage than this. A resolution of this dilemma may lie in a slower accretion of the Earth.

Recent dynamic simulations of the giant impact yield viable solutions that are very different from earlier models and raise new questions about the accretion rate of the Earth. In particular, the possibility is being explored that the proto-Earth may have only half accreted at the time of the impact and that the impactor may have been much larger than the 'Mars-sized' object commonly considered (Cameron, 1997). If these models are correct, and the Moon did not form until about 50 Myrs after the start of the solar system, then the accretion rate of the Earth was significantly slower up until the formation of the Moon than has hitherto been assumed. Furthermore, when the Moon formed, a substantial fraction of the Earth's mass was added from the impactor in a late stage of very rapid accretion.

The effect of lowering the accretion rate of the Earth, or the impactor itself if it formed in a similar accretionary environment, is that the W in the silicate portions will not be as radiogenic and will eventually become chondritic even if the core starts to form at an early stage (Halliday *et al.*, 1996). The W isotopic data for the Moon indicate that the Moon probably accreted from material with a high Hf/W but an initial W isotopic composition that was chondritic (Lee *et al.*, 1997). To achieve this with continuous core formation requires considerably lower accretion rates than any previously considered. The mean life for accretion (and the core) would be about 60 Myrs if the silicate portion of the body had high Hf/W but chondritic W at the time of the impact. If the Earth had an accretionary rate this slow it would only be half formed at the time of the Giant Impact, consistent with the dynamic simulations. If a major fraction of the Earth's present mass were accreted in the Giant Impact the $^{207}Pb/^{206}Pb$ isotopic ratio and 'age' of the silicate Earth would be similar to that deduced in many previous studies (see references in Wasserburg *et al.*, 1977, or Halliday *et al.*, 1996, for example).

Tungsten isotope data for martian meteorites, eucrites and chondrites indicate that the parent bodies of these meteorites stopped accreting at a much earlier stage than the Earth, but there is no isotopic evidence that the rates of growth were faster at a comparable mass. The prevalent concept of rapid accretion of these bodies is better viewed as simply reflecting the early cessation of the accretionary process, presumably in response to the growth of Jupiter.

## References


Cameron, A.G.W. (1997) *Proc. Lun. Sci. Conf. 28th*, 203–4.

Cameron, A.G.W. and Benz, W. (1991) *Icarus,* **92**, 204–16.

Halliday, A.N., Rehkämper, M., Lee, D-C. and Yi, W. (1996) *Earth Planet. Sci. Lett.,* **142**, 75–90.

Lee, D.-C. and Halliday, A.N., Snyder, G.A. and Taylor, L.A. (1997) *Science*, **278**, 1098–103.

Wasserburg, G.J., Papanastassiou, D.A., Tera, F. and Huneke, J.C. (1977) *Phil. Trans. R. Soc. Lond. A.,* **285**, 7–22.

Wetherill, G.W. (1986) In: *Origin of the Moon*, W.K. Hartman, R.J. Phillips and G.J. Taylor, eds., 519–50, Lunar and Planetary Institute, Houston, Texas.