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Planetary science: Birth of a Solar System

A. G. W. CAMERON

A. G. W. Cameron is at the Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA.
e-mail: acameron@lpl.arizona.edu

Radioisotope dating of meteorites suggests that planets formed in the Solar System over shorter timescales than had been thought. There are consequences for how the Moon formed, but is this the final word?

Fortunately for those who attempt to trace the origins of our Solar System, when the primitive solar nebula and planetary bodies began to form there were radioactive nuclei with a wide range of half-lives present. The detection of these nuclei and their decay products, particularly in meteoritic rocks, is a useful tool for working out when various features of the planetary system formed.

Two papers in this issue, by Yin *et al*.[1] (page 949) and Kleine *et al*.[2] (page 952), describe dating experiments on a selection of meteorites, based on the hafnium nucleus ^{182}Hf, which decays to tungsten, ^{182}W, with a half-life of about 9 million years. This decay is particularly useful for estimating the time at which the cores of planets formed, because undecayed hafnium was left behind in the planet's silicate mantle, but tungsten was absorbed into the planetary core. Both sets of authors have independently determined the initial ratio of ^{182}Hf to its stable isotope ^{180}Hf in the solar nebula, arriving at essentially identical values. But their ratio is less than half the previous value[3], with important implications for our understanding of how quickly the planets grew and how soon their cores were established.

Yin *et al*. and Kleine *et al*. calculate core-formation ages based on isotope data from a range of meteorites, including the eucrite meteorites that are believed to originate from the large asteroid Vesta. Their results indicate that the cores of Vesta, Mars and Earth all formed sooner after the formation of the solar nebula than previous estimates had allowed. According to the new data, Vesta's core formed only 3 million to 4 million years after the birth of the Solar System, in comparison with the previous value of about 16 million years; the cores of Earth and Mars formed at about 29 million and 13 million years, respectively. But the situation for the Earth and Mars is complicated because their growth involves absorbing bodies similar to Vesta and then reprocessing the cores within them. Yin *et al.* suggest that a more realistic picture is a continual core-formation process in Earth up to about the 29-million-year mark, or more.

The new estimates also put the formation of the Moon further back in time — both papers estimate its birth at between 25 million and 30 million years after the formation of the Solar System. The favoured explanation for the origin of the Moon is a giant impact between the growing Earth and a planetary body at least as massive as Mars[4, 5]. One model assumes that the Earth was half formed and had a double collision with a body twice the mass of Mars[4]; another model assumes that when the Earth was 90% formed, it was struck once, by a body similar in mass to Mars[5]. According to Wetherill[6], the growth time for Earth was about 100 million years, so these new timing measurements favour the double-collision model, but many more of these giant-impact simulations are needed. In any case, the iron core of the impacting body crashes through the planetary mantle and directly joins the core of the Earth.

Both papers suggest that the planets accumulated mass faster than had been thought. But how rapidly should we expect large asteroids and planets to form in the solar nebula? Astronomical studies of star-formation processes indicate that new stars are formed when a localized, dense region (a 'core') in an interstellar molecular cloud collapses. The timescale for the collapse of such a core in its own gravitational field is more than a million years. But if there is a super-nova nearby, the impact of its shock wave on the cloud core can shorten this timescale to a few tens of thousands of years[7, 8]. Furthermore, a supernova is the only astronomical object that can produce all of the radioactive isotopes known to have existed in the solar nebula but that are now extinct[4].

Once the solar nebula was established, the interstellar grains that it contained collided and stuck together (the kinetic energy of collision is likely to be radiated away before a rebound can occur[9]). In about 1,000 years, bodies of size 10–100 m had grown[9]. Wetherill's simulations[6] of subsequent planetary growth show that objects with the mass of Mars would have grown in about 100,000 years.

To form a core, the interior of the growing planet must be heated enough to melt the iron contained in its rocky mantle. This heat is generated partly through gravitational energy release and partly through radio-activity in the interior, particularly that of ^{26}Al (with a half-life of 740,000 years), which is expected to be the most important heat source for the smaller bodies such as Vesta. Accumulative collisions between these small bodies produce a planet. When they collide, the smaller body is splashed into the mantle of the larger body, and its molten-iron core (if formed) percolates down to the core of the larger body. So core formation is an extended process, and the formation time derived from samples of the rock is only an average. The two papers published here use three different models, so their differing core-formation times reflect the different parameters of those models.

However, another development in the study of now-extinct radioactive elements in the Solar System has an important bearing on these interpretations. A linchpin in these analyses is the assumption that millimetre-sized particles of calcium and aluminium silicates — calcium–aluminium inclusions (CAIs) — found inside some meteorites are the oldest objects in the Solar System, and that their formation marks the birth of the solar nebula.

But a recent discovery[10] suggests that the CAIs might, in fact, predate the solar nebula: the one-time presence of the very short-lived nucleus ^{7}Be (with a half-life of just 53 days) has been detected inside CAIs through abundance variations in its decay product, ^{7}Li. This finding suggests instead that CAIs might have formed in an expanding supernova envelope and were injected, along with the radioactive isotopes, into the molecular-cloud core whose accelerated collapse formed the nebula (my own unpublished data; a preprint is available on request).

One consequence of supernova-produced CAIs is that the initial, solar-nebula abundance of radioactive ^{26}Al would have been much lower (because of dilution by the stable isotope ^{27}Al during the injection process). So it would have been a considerably weaker heat source in young planets than expected. Reducing the initial Solar-System abundance of ^{26}Al also affects the timescales of core formation: although Yin *et al.*[1] and Kleine *et al.*[2] predict an earlier core formation and faster accretion than had been thought, the formation times would be reduced still further. The core-formation time for Vesta might in fact be only 20–40% of the estimates published here.

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