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SOLAR SYSTEM

Calcium signals in planetary embryos

The calcium–isotope composition of planetary bodies in the inner Solar System correlates with the masses of such objects. This finding could have implications for our understanding of how the Solar System formed. [SEE LETTER P.507](#)

ALESSANDRO MORBIDELLI

For decades, researchers have debated how planetary bodies in the Solar System with diameters of more than a few hundred kilometres were formed. Current models¹ suggest that such bodies accumulated (accreted) small particles known as pebbles that were drifting towards the Sun in a cloud of gas and dust called the protoplanetary disk. However, these models have difficulty in explaining the diverse composition of objects in the Solar System: if all such bodies grew by accretion from the same flow of pebbles, then why do they have different compositions? On page 507, Schiller *et al.*² provide a possible answer to this question, on the basis of their observation that the composition of calcium isotopes in planetary bodies correlates with the masses of these bodies.

The authors measured the calcium–isotope content of samples from the parent bodies of types of meteorite known as angrites and ureilites, as well as from Earth, Mars and the asteroid Vesta. They present their data in terms of the value $\mu^{48}\text{Ca}$, which expresses the ratio of two calcium isotopes (^{48}Ca and ^{44}Ca) in a sample relative to that in a terrestrial reference standard, and is given as parts per million (p.p.m.). The authors identified a positive correlation between $\mu^{48}\text{Ca}$ and planetary-body mass for Earth, Mars and Vesta, which have known masses, and for the parent bodies of angrites and ureilites, the masses of which were inferred from thermal models^{3,4}.

Schiller *et al.* account for this correlation by assuming that the pebble-accretion scenario is correct, but by rejecting the conventional idea that bodies of different masses grew at different rates throughout the lifetime of the protoplanetary disk. Instead, the authors suggest that all bodies grew at the same rate, but stopped growing at different times: smaller bodies ceased accretion earlier than did larger ones.

This unorthodox view of growth is, in fact, supported by numerical simulations⁵, which show that growing bodies perturb each other's orbits around the Sun. Bodies that acquire eccentric or inclined orbits

stop accumulating pebbles, whereas those that remain on circular trajectories in the mid-plane region of the disk continue to grow. The correlation of $\mu^{48}\text{Ca}$ values with planetary-body masses therefore also becomes a correlation with the timescale of the growth of such bodies. The authors confirm this using growth timescales for angrites, ureilites, Vesta and Mars that were inferred by nuclear chronometry (a dating technique that uses the decay of radioactive isotopes) and thermal models.

Schiller and colleagues propose that material in the inner part of the disk initially had low $\mu^{48}\text{Ca}$ values (about –150 p.p.m.). Planetary bodies grew from this matter until they reached the size of the ureilite parent body (about 200 km in diameter). The inner disk then started to be fed with pebbles that drifted

Figure 1 | A model of planetary accretion. Schiller *et al.*² report a correlation between the calcium–isotope contents and the masses of planetary bodies in the inner Solar System, and propose a model to explain this observation. They present their data in terms of the value $\mu^{48}\text{Ca}$, which expresses the ratio of two calcium isotopes (^{48}Ca and ^{44}Ca) in a body relative to that in a terrestrial reference standard, and is given as parts per million (p.p.m.). In the authors' model, the disk of gas and dust that surrounded the newly formed Sun initially contained inner-disk material with low $\mu^{48}\text{Ca}$ values (–150 p.p.m.) and outer-disk particles with high $\mu^{48}\text{Ca}$ values (200 p.p.m.). The planetary bodies grew by accumulating (accreting) matter from the inner disk. Over time, the inner-disk material was replaced by particles that flowed in from the outer disk, which progressively increased the mean $\mu^{48}\text{Ca}$ value of the inner disk. Bodies continued to grow until they were displaced (curved arrows) from the mid-plane of the disk by perturbations from other bodies. The times indicate stages in the disk's lifetime; in particular, the stages at which various bodies were formed — the parent bodies of a type of meteorite known as ureilites, the asteroid Vesta, Mars and the planetary embryos that eventually produced Earth.

in from the outer part of the disk. Such pebbles had high $\mu^{48}\text{Ca}$ values (about 200 p.p.m.), which are typical of the most primitive meteorites (carbonaceous chondrites) that are thought to have formed beyond Jupiter⁶. The mean $\mu^{48}\text{Ca}$ value in the inner disk therefore increased progressively. As a consequence, bodies that continued to grow to the size of Vesta (530 km in diameter) reached $\mu^{48}\text{Ca}$ values of ~100 p.p.m., and those that grew to the size of Mars (6,800 km in diameter) reached $\mu^{48}\text{Ca}$ values of ~20 p.p.m. (Fig. 1).

Earth and the Moon have $\mu^{48}\text{Ca}$ values of about 0 p.p.m. It is generally assumed that Earth formed after the disappearance of the protoplanetary disk, as a result of collisions of planetary embryos with masses similar to that of Mars; the body that collided with early Earth to give rise to the Moon was one of these embryos. However, this formation scenario is not possible if Schiller and colleagues' proposal is correct. Planetary embryos with the mass of Mars would have $\mu^{48}\text{Ca}$ values of ~20 p.p.m., and therefore an 'Earth' resulting from the merger of these bodies would have a similar composition.

Instead, for Earth to have a $\mu^{48}\text{Ca}$ value of about 0 p.p.m., the embryos would need to have grown by pebble accretion to masses roughly half that of Earth. In turn, the Moon-forming impactor would need to have had a mass comparable to that of the embryos to have the same $\mu^{48}\text{Ca}$ value, supporting the theory that the Moon resulted from the collision of two bodies with half-Earth masses⁷.

A potential problem is that hafnium–tungsten radioactive chronometry indicates that Earth reached 63% of its present mass only after a duration of between 11 million and 24 million years, depending on the type of core–mantle equilibration that occurred during the collision of the embryos⁸. It is therefore difficult to imagine that such embryos grew to bodies with half-Earth masses in the disk's putative lifetime of 5 million years⁹.

But perhaps the embryos did reach the size of one-third of Earth's mass (three times the mass of Mars). Such a proposal cannot be discounted as a compromise between the authors' correlation of calcium–isotope compositions with planetary masses and the chronological constraints on Earth's accretion. The fraction of Earth's mass that would have been accreted from the outer disk (estimated at about 40% in the authors' study) would be higher than calculated previously^{10,11}, but such computations did not consider some of the building blocks of Earth to have ureilite-like compositions.

Schiller and colleagues' view of accretion in the Solar System is in sharp contrast with that presented by two previous studies^{6,12}. These reports concluded that the flux of pebbles from the outer disk was shut down during the first million years of the disk's lifetime by the formation of Jupiter. This prevented bodies in the inner Solar System from accumulating

large amounts of water ice, explaining why such bodies are mostly dry¹², and maintained an isotopic dichotomy between two types of meteorite: ordinary and carbonaceous chondrites⁶.

The composition of ordinary chondrites is difficult to account for using Schiller and colleagues' model. Unlike large bodies, which should grow continuously by pebble accretion, the smaller parent bodies of chondrites should form suddenly, from clusters of pebbles that are generated by a mechanism known as a streaming instability¹. In the case of ordinary chondrites, this would have happened in the inner Solar System at a late stage in its formation, after the time by which Mars had accreted most of its mass. Ordinary chondrites should therefore represent a snapshot of the composition of the late disk, and have a positive value of $\mu^{48}\text{Ca}$ in the authors' model. But, in reality, such chondrites have $\mu^{48}\text{Ca}$ values of ~35 p.p.m.

Schiller *et al.* explain this discrepancy by speculating that pebble accretion and the streaming instability have differing preferences for pebble size. The pebbles that came from the outer disk were small and, although they were efficiently accreted by large bodies, they barely participated in the streaming instability. Consequently, ordinary chondrites formed mostly from larger pre-existing pebbles called chondrules, which typically have negative values of $\mu^{48}\text{Ca}$. The validity of this proposal

will need to be checked using high-resolution numerical simulations of the pebble-accretion and streaming-instability processes.

The authors' work adds a missing piece to the jigsaw puzzle of planet formation that will need to be connected with the other pieces provided by isotopic, chemical, chronological and dynamical constraints. Although the puzzle seems more complete than before, perhaps some other key pieces are still missing. ■

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NEURODEVELOPMENT

A mixed model of neuronal diversity

Two groups have sequenced RNA from thousands of single cells, making the deepest ventures yet into the origins of neuronal diversity in the neocortex of the developing mammalian brain. [SEE ARTICLE P.457](#)

**LUDOVIC TELLEY
& DENIS JABAUDON**

Biologists have long been preoccupied with classifying diverse objects into meaningful categories. Even at the beginning of genetics, Gregor Mendel classified peas as smooth or wrinkled, to infer the mechanisms underlying the inheritance of specific features. Neurons, like peas, come in different shapes and types, but how many neuronal cell types exist and how neuronal diversity emerges during development is unclear. Answering these questions is important, because the diversity of neurons determines the diversity of circuits that can be built and, by extension, the scope of an animal's

behavioural repertoire. Two groups (one writing in *Nature*¹ and one in *Science*²) now investigate the origins of neuronal diversity in the developing neocortex, a brain region that is the source of mammals' complex behavioural and cognitive abilities³.

Two opposing — although not mutually exclusive — scenarios account for the generation of distinct kinds of neuron across the nervous system, and in the cerebral cortex in particular^{3–6}. In the first scenario, diverse neuronal subtypes are born from correspondingly diverse progenitor cells (Fig. 1a). This is known as the premitotic model, because diversity arises in progenitors, before neurons are actually generated (neuronal birth occurs through mitotic cell division). In this