FORUM: Planetary science

Shadows cast on Moon's origin

Our knowledge of how Earth's natural satellite formed is increasingly being challenged by observations and computer simulations. Two scientists outline our current understanding from the point of view of the satellite's geochemistry and its early dynamical history.

A chip off the old block

TIM ELLIOTT

Not since NASA's scientists definitively announced that the lunar white stuff was non-dairy has the Moon faced such an identity crisis. Ironically, it seems that our satellite is compositionally too similar to Earth for a simple explanation of its origins. Most dynamical and even some chemical attributes of the Earth–Moon system have been successfully explained by a 'giant impact' scenario, in which a Mars-sized impactor collided with the proto-Earth. Yet the standard version of this model produces a Moon that is mainly made of the impactor and not the target (Fig. 1). As emphasized in a Royal Society meeting[1] in September that debated the origin of the Moon, the compositional differences between Earth and the Moon that would be expected as a consequence are increasingly at odds with diverse, high-precision isotopic observations.

The isotopic kinship of Earth and the Moon was initially apparent in their indistinguishable oxygen isotope ratios[2], which contrasted with analyses of meteorite samples from most other planetary objects in the Solar System. The dilemma of this matched isotopic composition has deepened with more-recent measurements — notably, analyses of tungsten[3] and silicon[4] isotopes, which are controlled by very different processes from oxygen.

The radiogenic-tungsten isotope ratios of different planetary mantles should vary because they record the stochastic growth of the parent bodies and the formation of their cores. For the impactor and the proto-Earth to have the same oxygen isotope ratio is unlikely[2], but for them also to have the same tungsten isotopic composition is highly implausible. The distinctive silicon isotopic composition of Earth's silicate mantle reflects the consequences of silicon sequestration by a core formed at high temperatures on a large planetary body. Despite its moniker, the Mars-sized impactor of the standard giant-impact model is not large enough to have experienced conditions that would generate an Earth-like silicon isotope ratio. Thus, differences in oxygen, tungsten and silicon isotope ratios between target and impactor seem inevitable, and so the standard model predicts isotopic differences between Earth and the Moon that are not observed.

These various isotopic embarrassments might potentially be explained away by rapid isotopic re-equilibration of Earth and the Moon in the vapour-rich aftermath of the Moon-forming collision[5]. But recent work has shown[6] that the isotopic similarity of the two bodies extends to refractory elements such as titanium, which should not remain in the vapour phase long enough to allow such re-equilibration.

New dynamical models that can produce the Moon from the proto-Earth do not have the inherent simplicity of the canonical giant-impact scenario, and some argue that there are crucial flaws in such models. The sequence of conditions that currently seems necessary in these revised versions of lunar formation have led to philosophical disquiet. From a naive geochemical perspective, however, the isotopic similarity of Earth and the Moon holds an obvious appeal; the proto-Earth represents an abundant local source of material from which to build the Moon. Whether or not this comfort of availability can be meshed with the rigours of celestial mechanics remains to be seen.

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Weak links mar lunar model

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The giant-impact hypothesis of lunar origin is celebrated for its simplicity: a late, grazing impact on the proto-Earth launches a portion of the rocky mantle into orbit and establishes the angular momentum of the Earth–Moon system (Fig. 1b). The Moon, depleted of iron and volatile elements relative to Earth, forms from this hot circumterrestrial disk of rocky mantle. Hydrodynamic simulations of giant impacts successfully produce disks of low iron content and sufficient mass to make this hypothesis plausible. The fatal issue is that simulations that lead to the present angular momentum derive most disk material from the impactor[7]. Thus, the giant-impact model predicts that Earth and the Moon should be derived from different source material, each with distinct isotopic fingerprints, and this contradicts the geochemical (isotopic) observations.

A possible way forward relaxes the constraints on the giant-impact model. Perhaps it was too much to ask that a single dynamical process should satisfy all the physical and geochemical observations. In fact, formation of the Earth–Moon system is thought to have been an extended, multi-stage process: a giant impact creates a disk (on a timescale of 1 day), the Moon accretes from the disk (hundreds of years), and interactions known as orbital resonances, which occur during lunar tidal evolution, establish the inclination and angular momentum of the system (up to tens of thousands of years).

However, two studies[8,9] last year proposed different giant-impact scenarios for generating a disk that is compositionally similar to Earth, and so meet the isotopic observations (Fig. 1c, d). These leave Earth spinning near the limit of its stability and require a separate mechanism by which the Earth–Moon system reaches the present-day angular momentum. The evection resonance, which occurs when the short axis of the Moon's elliptical orbit about Earth rotates synchronously with the orbit of Earth around the Sun, is encountered quickly during the tidal evolution of the Moon and could have transferred the excess angular momentum away from the Earth–Moon system[8]. These new solutions have broken the stalemate between the models and the geochemical data, and

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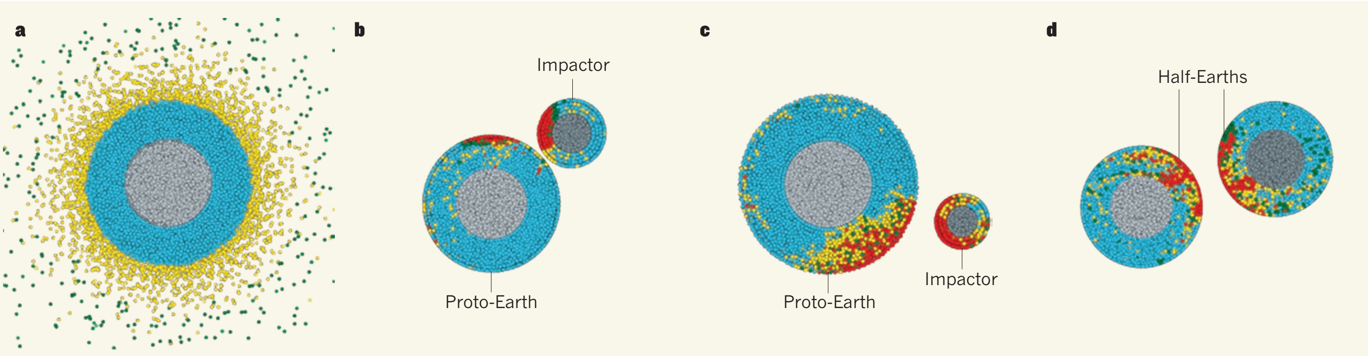

Figure 1 | Making Earth and the Moon into isotopic twins. After the giant impact, the Moon forms from a disk of material around Earth. In these views of an equatorial slice through the post-impact Earth (**a**) and impacting bodies (**b–d**), colours denote material that ends up in the core (grey), mantle (cyan), hot silicate atmosphere (yellow) and lunar disk (green). Red material escapes the Earth–Moon system. In the canonical giant-impact model[7], the lunar material is derived primarily from the impactor's mantle and the shallow mantle of the proto-Earth (**b**). Material from these sources is not expected to be identical to the bulk silicate Earth (see, for example, refs 2–4). In the new giant-impact models[8,9], lunar material is derived either from a range of depths in the proto-Earth's mantle (**c**) or equally from the entire mantles of two colliding half-Earths (**d**). These sources are more likely to produce a Moon with the same isotopic fingerprint as Earth.

have shifted attention towards the weak links between the major stages of lunar origin.

Now, the lunar origin cannot be addressed by a single (rather simple) hydrodynamic calculation. Modelling the formation of the Moon in greater detail poses challenges to both our understanding of the physics of what occurred and our technical capabilities. For example, seeding the lunar disk with Earth-mantle material might not be sufficient to explain the isotopic similarity. The initial conditions of the disk have not been robustly established by the hydrodynamic calculations, which neglect the disk's many chemical components and its multiphase flow. Coupled dynamical and chemical models for the lunar disk are in their infancy; mixing within the disk might eliminate some of the initial differences or generate new chemical differences during its evolution. Crucially, the time during which the Moon is caught in the evection resonance, the crux of the new class of impact scenario, is sensitive to its thermal state[1], which depends on the details of lunar accretion from the disk.

Within our current understanding of planetary and satellite formation processes, each stage of lunar evolution is plausible. But, with the nested levels of dependency in a multi-stage model, is the probability of the required sequence of events vanishingly small? Is there an alternative solution of greater simplicity and universality? Ultimately, the current detailed interrogation of lunar origin may demand answers that have an unexpected level of complexity. ■ SEE COMMENT P.27

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STEM CELLS

Dual response to Ras mutation

Proliferation-driving mutations in haematopoietic stem cells often result in the loss of stem-cell properties. But at least one common oncogenic mutation seems to enhance both proliferation and stem-cell self-renewal. SEE LETTER P.143

S. HAIHUA CHU & SCOTT A. ARMSTRONG

When a stem cell divides, it can either produce differentiated cells or self-renew to produce more stem cells. Because stem cells are thought to be the cells of origin for many types of cancer, understanding what controls this decision has become a central question in stem-cell and cancer research. During the formation of mature blood cells from haematopoietic stem cells (HSCs), these processes are often diametrically opposed: blood cells are produced through a hierarchical process of proliferation and differentiation, often at the expense of the stem-cell ability to self-renew. But how is this decision altered when a stem cell acquires a cancer-driving mutation? Previous studies have shown that mutations that increase the proliferation of HSCs tend to reduce the cells' potential for self-renewal. But on page 143 of this issue, Li *et al.*[1] report that HSCs harbouring an activating mutation of the protein Nras show not only enhanced proliferation but also enhanced self-renewal.

Nras is a member of the Ras family of proteins, which transmit cellular proliferation and survival signals in many different contexts and which are frequently mutated to become constitutively active in cancer cells. Li and colleagues found in mice that expression of an activating mutant version of the *Nras* gene in HSCs led to an increased number of the cells entering the cell cycle. In line with previous observations[2], the *Nras*-mutant HSCs outcompeted normal HSCs in their ability to reconstitute haematopoiesis when both cell types were transplanted into HSC-depleted mice. But surprisingly, the researchers also found that *Nras*-mutant HSCs could be serially transplanted in mice through more rounds of transplantation than normal cells, demonstrating enhanced self-renewal.

To determine how one signalling molecule, mutant Nras, could confer both enhanced proliferation and self-renewal potential on HSCs, Li *et al.* used *Nras*-expressing HSCs that expressed a fluorescent 'reporter' protein, so that they could monitor cell division by the dilution of fluorescence over time. Remarkably, they observed two distinct responses: mutant *Nras* reduced the division and increased the