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PLANETARY SCIENCE

The Moon's tilt for gold

The Moon's current orbit is at odds with theories predicting that its early orbit was in Earth's equatorial plane. Simulations now suggest that its orbit was tilted by gravitational interactions with a few large bodies. SEE LETTER P.492

ROBIN CANUP

Four and a half billion years ago, a giant impact with Earth is thought to have created an Earth-orbiting disk of debris that coalesced to form the Moon. 'Inelastic' collisions between such debris would dissipate energy and remove relative up-and-down motions, so that the Moon that assembled from these collisions would orbit approximately in Earth's equatorial plane. Yet the Moon's current orbit implies that its initial orbit was substantially inclined relative to Earth's Equator[1], a troubling contradiction.

On page 492 of this issue, Pahlevan and Morbidelli[2] identify a compelling and simple solution to this problem — that the Moon's early orbit was gravitationally jostled into a tilted state by close passes of large objects left over from the formation of the inner planets. The existence of a population of these objects could also explain how elements such as iridium, platinum and gold were delivered to Earth's outer layers after the Moon formed[3].

The Earth–Moon pair is a dynamically coupled system. The Moon's gravity raises tides on Earth, most notably in the oceans, and gravitational interactions between these tides and the Moon is causing Earth's rotation to slow as the Moon's orbit expands. Tidal interactions also reduce the tilt of the Moon's orbit relative to a preferred plane. This would have coincided with Earth's equatorial plane when the early Moon was orbiting close to Earth and transitioned to the plane of Earth's orbit around the Sun as the Moon's orbit expanded. In the absence of other effects, the current 5° inclination of the Moon's orbit relative to Earth's orbital plane implies an initial 10° inclination relative to Earth's equatorial plane when the Moon formed[1], 10 times larger than expected according to theory[4].

A seemingly unrelated — until now — set of clues about the conditions soon after the Moon formed emerge from the abundance of precious metals in the Earth. Elements such as platinum and gold are highly siderophile, which means that they have strong chemical affinities for iron. Because Earth formed in a largely molten state, high-density iron would have readily sunk to the planet's centre to form a core, taking highly siderophile elements with it and efficiently removing these from Earth's upper layers. The fact that we find such elements in relatively high abundance in rocks at Earth's surface suggests that they were delivered to the planet after the end of core formation, through a 'late veneer' of material that added about the last 1% of Earth's mass[5].

If Earth's late veneer was delivered by a large number of small impactors, the Moon would have received about 1/20th as many impactors on the basis of its smaller cross section[3]. But lunar siderophile abundances imply that the Moon received much less than that amount. It thus seems probable that Earth's late veneer was delivered by only a few large impactors, each roughly comparable in size to the Moon, because the Moon would have received less than its proportionate share under these circumstances.

Pahlevan and Morbidelli use computational methods (Monte Carlo simulations) to consider the effects of such a population of large, late-accreting background objects on the Moon's early orbit. Their simulations begin with a Moon orbiting in Earth's equatorial plane close to our planet (Fig. 1). With time, the Moon's orbit expands because of tidal interaction with Earth, and is gravitationally perturbed by the background objects until this population is depleted over typically a few tens of millions of years.

Central to the new work is the recognition that each object that ultimately collides with Earth first undergoes many thousands of non-collisional close passes, a portion of which strongly perturb the Moon's orbit. An object approaching the Moon from a random

50 Years Ago

The use of rubber gloves during surgical operations became general about 1900 … The object of an investigation was to obtain an estimation of how frequently wound infection originates from bacteria on the hands of operating staff … Examination of the wounds following 433 'clean' operations, of the 3,125 rubber gloves used in those operations and of the bacterial flora of the hands which had worn 692 damaged gloves, revealed no connexion between the glove damage, the bacterial flora and the wound infections observed.
From *Nature* 27 November 1965

100 Years Ago

The *Times* of November 20 published a rather flamboyant little article, headed "A Surgical Schism." This article said: "Not for half a century at least has the medical world been so sharply divided as it is to-day in regard to the question of the treatment of wounds." Now, it is exactly half a century since Lister … first ventured to treat a compound fracture by plugging the wound with a strip of rag soaked in undiluted and impure German creasote. Pyaemia and septicaemia and erysipelas were ravaging the wards of the old Glasgow Infirmary, and he, relying on Pasteur's work on the "germs of putrefaction," and knowing that creasote was a good "disinfectant," plugged a wound with it. That was the beginning of everything, exactly half a century ago. To-day, there are many methods, but they do not all contradict or exclude each other … We must not imagine a sort of desperate squabble among our military surgeons … The suggestion in the *Times* article that an acute controversy is proceeding upon these matters is unfortunate and misleading.
From *Nature* 25 November 1915

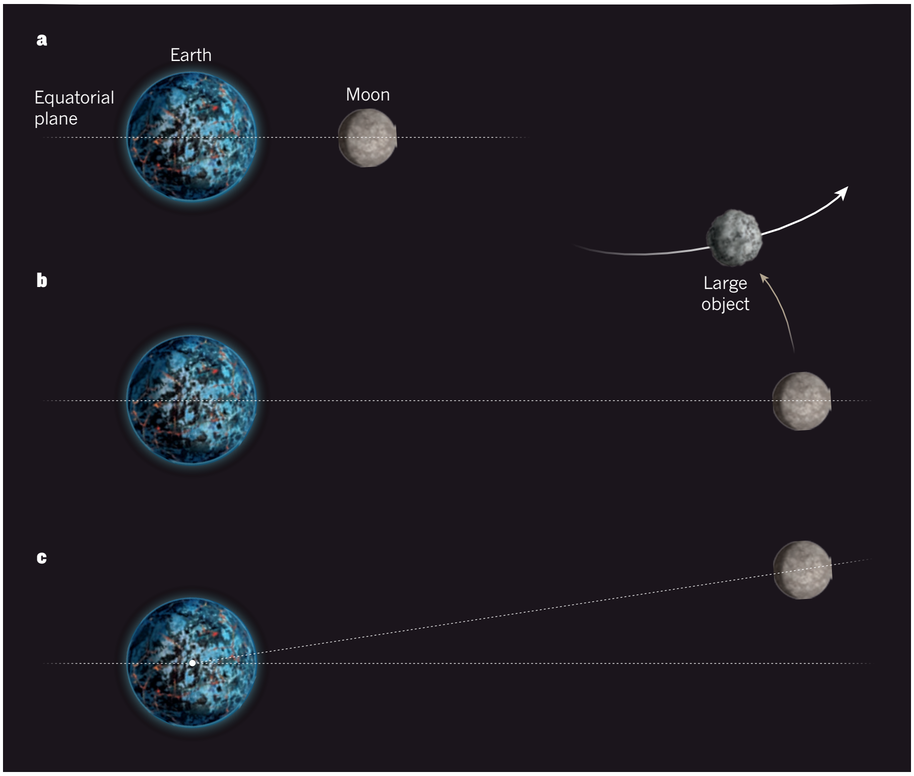

Figure 1 | Collisionless interactions could have altered the early Moon's orbit. **a**, When the Moon first formed, its orbit was approximately in the plane of Earth's Equator. Over time, its orbit then expanded. **b**, Pahlevan and Morbidelli[2] propose that collisionless interactions with large objects passing through the early Solar System would have strongly perturbed the Moon's orbit. **c**, The cumulative effect of such interactions would have tilted the Moon's orbital plane sufficiently to explain the current inclination of the Moon to Earth's orbital plane around the Sun. The Moon's orbital radius in **b** and **c** is not shown to scale.

direction may increase or decrease the Moon's orbital tilt. But just as a series of steps, each equally likely to be forward or backward, causes the standard deviation in the net distance travelled to increase with time, so too does a series of randomly oriented kicks to the lunar orbit lead to a general increase with time in the probability of exciting a minimum tilt.

Pahlevan and Morbidelli's results show a high likelihood that such random scattering events can cumulatively produce the necessary early tilt in the Moon's orbit, as long as the number of objects that deliver the final approximately 1% of Earth's mass is small (fewer than 5) and the rate of early tidal expansion of the Moon's orbit is sufficiently rapid. The rate of early tidal expansion needed is broadly consistent with the average tidal properties inferred for Earth on the basis of the expansion of the Moon's orbit to its current orbital distance. However, the specific values that would have applied to the earliest Earth remain uncertain.

The magnitude of the excited tilt scales roughly linearly with the late mass delivered to Earth. It is not known what fraction of the siderophiles that were concentrated in the cores of such large impactors would have been retained in Earth's upper layers. Improved models of late-veneer impacts should therefore be used to better constrain the late-accreted mass; this would in turn allow a closer approximation of the inclination expected from scattering. Moreover, the new scattering model is most effective if the Moon's inclination has been damped only by tides. If other forms of inclination damping have occurred, then — depending on the timing of this damping — the required initial inclination might increase, and with it the required mass of background objects, perhaps to unrealistically high values.

Previously reported models for the origin of the Moon's inclination rely on more-complex processes involving either a periodic gravitational interaction (gravitational resonance) with the Sun[6] or a resonant interaction between the Moon and its precursor disk[7]. Both require rather narrow sets of conditions for success. The new mechanism is simpler than these models, and the population of late lunar-sized objects that it requires is compellingly consistent with that needed to account for the delivery of Earth's precious metals, a completely independent constraint. Had such a population of objects not existed, the Moon might be orbiting in Earth's orbital plane, with total solar eclipses occurring as a spectacular monthly event. But our jewellery would be much less impressive — made from tin and copper, rather than from platinum and gold. ■

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BLINDNESS

Assassins of eyesight

A molecular cascade involving the transcription factor SIX6 and its target gene *p16INK4a* causes the death of neurons that link the eye to the brain. This discovery deepens our understanding of a common form of blindness, glaucoma.

ANDREW D. HUBERMAN & RANA N. EL-DANAF

Vision might feel easy, but an immense number of neurons are required to perform routine visual functions, such as reading, navigating the street or recognizing faces. Tightly lining the back of the eye is a layer of approximately 1 million neurons called retinal ganglion cells (RGCs), which take information encoded by the retina and pass it to the brain[1]. Glaucoma — a disease marked by progressive, irreversible degeneration of RGCs — is a common form of blindness, affecting more than 60 million people worldwide[2]. Although many studies have sought to understand the cellular and molecular basis of glaucoma[3], the mechanisms that drive RGC death in this debilitating disease have remained mysterious. But writing in *Molecular Cell*, Skowronska-Krawczyk *et al.*[4] report that certain glaucoma-associated mutations in humans are linked to a defined molecular pathway that accelerates RGC ageing and death.

A constellation of risk factors has been