NEWS & VIEWS

PLANETARY SCIENCE

The Moon's mantle unveiled

An *in situ* investigation on the far side of the Moon has identified materials that might have originated from the lunar mantle. The results could lead to improved models of how the Moon formed and evolved. SEE LETTER P.378

PATRICK PINET

The Moon is a small planetary body that has separated into a crust, a mantle and a core, but has not been disturbed by plate tectonics. It is therefore of tremendous value for understanding the evolution of planetary interiors. However, the composition of the lunar mantle remains uncertain. In January, the Chinese spacecraft Chang'e-4 landed in a large impact crater on the far side of the Moon and deployed its rover, Yutu2. On page 378, Li *et al.*[1] use spectral observations by Yutu2 to infer the presence of olivine and low-calcium pyroxene — minerals that might have originated in the lunar mantle.

Similar to the other inner bodies of the Solar System, the Moon is thought to have gone through a magma-ocean phase, in which it was partially or completely molten[2,3]. As the magma ocean solidified, dense mafic (rich in magnesium and iron) minerals such as olivine and low-calcium pyroxene crystallized at the ocean's base. After three-quarters of the ocean had solidified, less dense minerals such as plagioclase (aluminium silicate) floated to the surface, which led to the formation of a highland crust composed mainly of calcium-rich plagioclase. And at the end of the ocean's solidification, minerals enriched in elements that were the last to enter the solid phase crystallized beneath the crust. This process therefore induced radial stratification — a series of compositionally distinct layers — in the lunar interior.

Despite regional variations in the Moon's crust[4], the observed composition and mineralogy of distinct surface regions called lunar terranes — as revealed by sensors on orbiting satellites and by samples returned to Earth — are consistent with this conceptually simple model of formation. However, the characteristics of the lunar mantle, especially in terms of its composition, structure and stratification, remain uncertain and poorly documented. Astonishingly, NASA's Apollo spacecraft and the Soviet Union's Luna probes, all of which landed on the near side of the Moon (Fig. 1a), did not return samples of the lunar mantle[5].

With the successful implementation of its Queqiao communications satellite, in May 2018, the Chinese Lunar Exploration Program has paved the way for *in situ* surface exploration and sample-return missions on the lunar far side. The oldest and largest structure on the Moon — the roughly 2,500-kilometre-diameter South Pole–Aitken Basin — is located on the planetary body's far side. This structure's size and regional crustal thickness (as estimated by NASA's GRAIL mission[6]) suggest that it might have been produced by an impact event that penetrated the Moon's crust and interior, excavating lunar-mantle material and distributing it on the Moon's surface. Consequently, *in situ* exploration of the South Pole–Aitken Basin has long been advocated by scientists internationally.

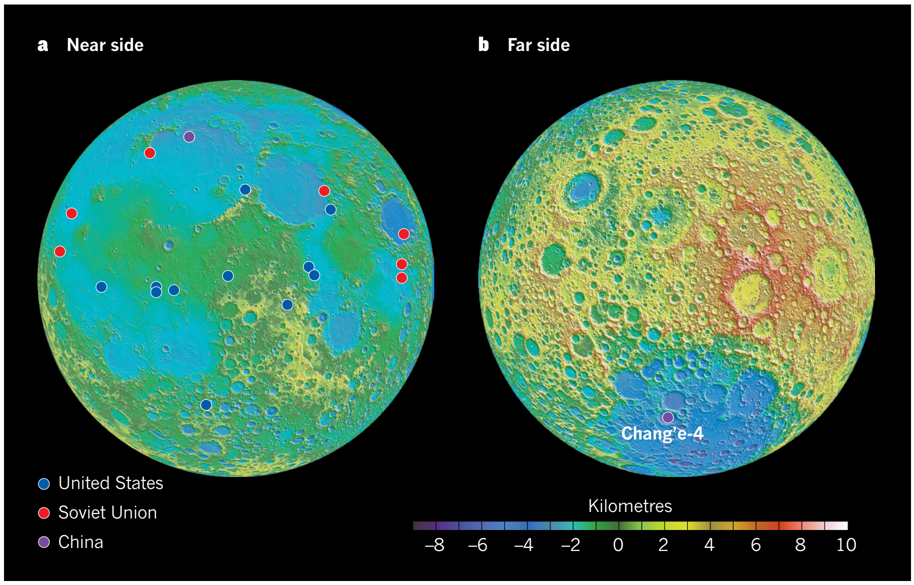

Figure 1 | Successful soft Moon landings and lunar topography. **a**, Previous missions to the Moon have landed on the near side. The coloured dots represent landing sites of spacecraft launched by various countries. The colour scale depicts the altitude of the lunar surface. **b**, In January, the Chinese spacecraft Chang'e-4 made history by landing in a large impact crater on the Moon's far side. Li *et al.*[1] use spectral observations by Yutu2, Chang'e-4's rover, to identify possible mantle-derived materials. The locations of past lunar landings are taken from go.nature.com/2vcecx7.

Li and colleagues describe results obtained by Chang'e-4, which touched down in the 186-km-diameter Von Kármán Crater on the floor of the South Pole–Aitken Basin (Fig. 1b). Their findings are based on the spectra of reflected light that were recorded by Yutu2 as it traversed the Von Kármán Crater. The authors report the detection of materials in the vicinity of the Chang'e-4 landing site that differ markedly from most samples obtained from the Moon's surface. In particular, the materials contain mafic components that seem to be dominated by a mixture of olivine and low-calcium pyroxene.

The authors suggest that these components represent deep-seated materials, potentially from the lunar mantle, that were excavated when the South Pole–Aitken Basin formed and then, possibly, redistributed as ejecta from the impact event associated with the creation of the nearby 72-km-diameter Finsen Crater. On the basis of these observations, the Moon's upper mantle might be composed predominantly of both olivine and low-calcium pyroxene.

The methods and tools that Li *et al.* used for the spectroscopic analyses were handled with great care, and the authors' detection of the minerals is highly reliable. But the precise determination of the relative mineral abundances in the mineral assemblages — which might include small amounts of plagioclase and high-calcium pyroxene — is a contentious issue, because of the complex nature of the minerals' overlapping spectral features. Further modelling efforts will certainly be required, with a focus on the size distribution of mineral grains, to attain a well-constrained assessment of the olivine composition[7].

In future work, Li *et al.* should characterize at the landing site not only soil samples but also samples of rock. This task could be carried out through a comprehensive *in situ* exploration of the area that surrounds the Chang'e-4 landing site, with the acquisition of reflectance spectra from selected bedrock targets. Such exploration is also crucial to better document the geological context of the detected materials, so that potential issues that might call into question the authors' interpretation of their results can be addressed. These issues include the possibility that the impact that created the South Pole–Aitken Basin led to the formation of a massive sheet of melted rock that is tens of kilometres thick and has compositionally distinct layers[8,9]. Another complexity could arise from the regional emplacement, after the formation of the South Pole–Aitken Basin, of cryptomaria[10] (lava flows buried by subsequent crater ejecta).

Nevertheless, Li and colleagues' results are thrilling and could have considerable implications for characterizing the composition of the Moon's upper mantle[11–13], and for establishing constraints on characteristics of the lunar magma ocean that would have varied with time. Such characteristics include the ocean's depth, its rate of cooling and its rate of evolution — the latter of which is controlled by magma viscosity, convection processes and the subsequent development of instability. In a broader sense, the authors' findings might also affect our understanding of the formation and evolution of planetary interiors. It is of the utmost importance to make progress towards unpacking the geology of the lunar far side, expanding our fundamental knowledge of the Moon's formation and the origin of the crustal asymmetry that exists between its near and far sides[14], and preparing future sample-return missions. ■

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QUANTUM PHYSICS

Scaling up quantum simulations

It is difficult to carry out and verify digital quantum simulations that use many quantum bits. A hybrid device based on a digital classical computer and an analog quantum processor suggests a way forward. SEE ARTICLE P.355

JÜRGEN BERGES

Devices known as universal quantum computers can be programmed to run different algorithms, thereby dispensing with the need to build new quantum computers for different functions. Fully fledged digital quantum simulations on such a device would allow substantial progress to be made in a wide range of disciplines, from quantum chemistry and materials science to fundamental high-energy physics. However, for this approach, it remains difficult to incorporate the many quantum bits (qubits) that are required for complex simulations. By contrast, large-scale analog quantum simulators already exist in today's laboratories. But, unlike their digital counterparts, these simulators are not programmable in general, and are often considered to be dedicated, single-purpose machines. Now, on page 355, Kokail *et al.*[1] report a programmable analog quantum simulator that is versatile and has the potential to be scalable.

The authors' simulations run on a combination of a classical digital computer and an analog quantum processor. The latter does the hard work of preparing trial states — quantum states that are used to evaluate physical quantities. The classical computer analyses the results of these evaluations, with the aim of optimizing certain adjustable (variational) parameters on which the trial states depend. This computer then suggests improved parameters to its quantum co-worker in a feedback loop. In the study, the quantum device contains a line of atomic ions that each represent a qubit. Such trapped ions can be used for analog simulations of other quantum systems, which can be very different from the ions themselves.

> ***"There are many pressing problems for which simulators involving analog quantum devices could be a game-changer."***

Kokail and colleagues use this set-up to carry out quantum simulations of the ground state of electrons coupled to light — a system that is described by the theory of quantum electrodynamics in one spatial dimension. Some of the authors were involved in the first digital simulation of this theory, on a four-qubit universal quantum computer[2]. By contrast, the current set-up includes up to 20 qubits. And although it is non-universal, the same analog quantum simulator could be used to study a wide range of models that can be defined on a lattice in condensed-matter and high-energy physics. These applications are restricted only by general requirements, such as the symmetries of the physical system to be simulated.

Similar hybrid classical–quantum algorithms have been demonstrated, using up to six qubits, in quantum chemistry, condensed-matter physics and high-energy physics[3–5]. With regard to the key property of potential scalability, the computational capabilities of the classical computer involved can be very restrictive. However, Kokail *et al.* show a promising way forward, which is mainly based on identifying and using approximate physical symmetries to reduce the number of variational parameters that need to be determined by the classical computer.

Kokail and colleagues also address the crucial question of how to verify that the outcome of a large-scale quantum simulation is correct. In addition to computing the mean energy of the ground state in their set-up, the authors calculate how much the energy varies from this mean value. They find that the variance is small enough for the results to be considered reliable. The ground-state energy of quantum electrodynamics might not seem the best example with which to demonstrate the power of the authors' approach — in principle, the results in this case could be obtained on any ordinary computer using standard classical-simulation techniques. But it is precisely this fact that makes the example a valuable test case.

There are many other pressing problems for which simulators involving analog quantum devices could be a game-changer. An