NEWS & VIEWS

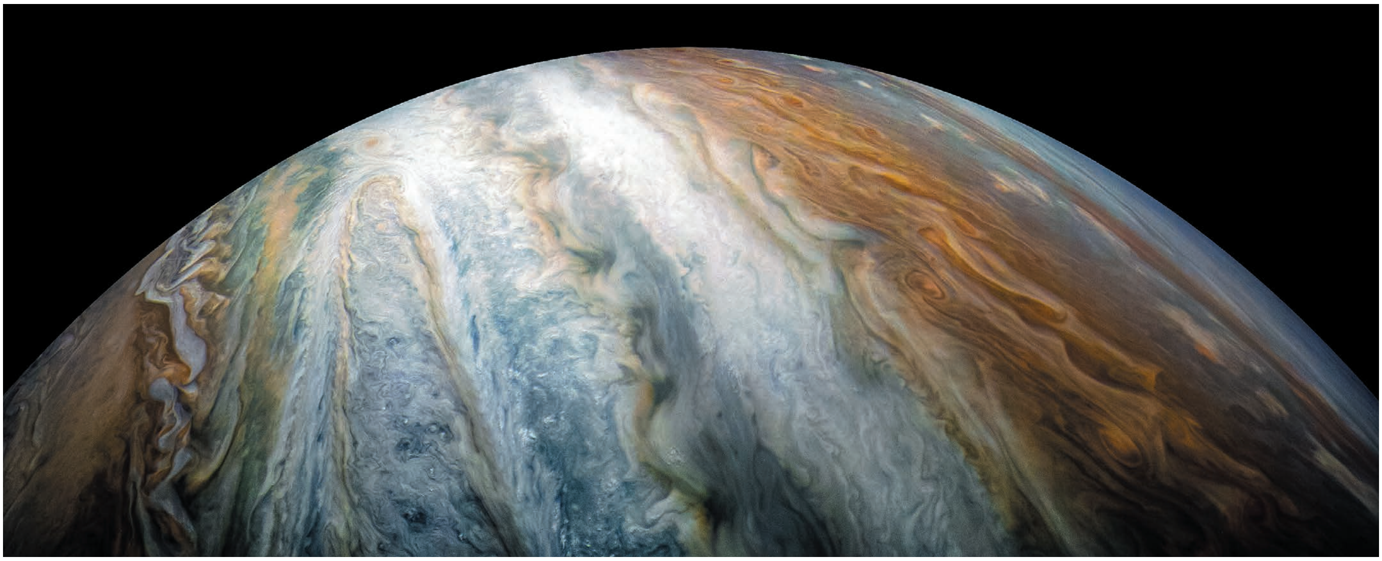

Figure 1 | The surface of Jupiter, as captured by NASA's Juno spacecraft.

PLANETARY SCIENCE

A deeper look at Jupiter

NASA's Juno spacecraft has made precise measurements of the gravitational field of Jupiter. The data reveal details of the structure and dynamics of the planet's interior. See Letters p.220, p.223 & p.227

JONATHAN FORTNEY

The surface of a planet typically reveals little about the processes at work in the planet's interior. Jupiter's surface consists of alternating bright and dark bands of gas that harbour powerful winds. These winds flow in opposite directions and can reach speeds of more than 100 metres per second. But what happens in the depths below that cannot be seen? In particular, is the planet's interior as dynamic as its surface? In three papers[1–3] in this issue, scientists have used small signatures in the gravitational field of Jupiter to address these questions and to potentially revolutionize our understanding of the internal dynamics of such gas-giant planets.

Jupiter's interior is a dense fluid that comprises a mixture of hydrogen and helium. Energy loss from the interior drives convection currents inside the planet that reach up to the surface. However, neither work in the past few decades on the physics of hydrogen and helium under high pressure, refined measurements of Jupiter's gravitational field from spacecraft nor improved methods to model the planet's structure have been able to determine the mechanics of how the convection operates and whether convective flows in the interior are related to the banded appearance of the surface (Fig. 1).

One possibility is that the bands are merely a surface phenomenon and that convection in the interior follows an entirely different pattern from convection at the surface. Alternatively, what is seen at the surface could be an extension of deep-seated convective flows that transport energy out of the interior. In both frameworks, sophisticated models have been developed to explain the structure of the bands[4,5]. A main goal of the NASA Juno mission to Jupiter — Earth's nearest gas-giant planet — is to determine which of the frameworks is correct. Because such planets are now known to be common in the Galaxy[6], achieving this goal would have far-reaching implications for our understanding of this class of astrophysical object.

Iess *et al.*[1] (page 220) tracked the acceleration of the Juno spacecraft in its close elliptical orbit around Jupiter by monitoring the change in frequency, known as the Doppler shift, of radio waves sent back to Earth. Tiny anomalies in these signals revealed details about the mass distribution of Jupiter. Such tracking of Juno was no trivial feat: the authors had to take into account other small accelerations of Juno, including those caused by the absorption and re-radiation of sunlight. They achieved this by using a sophisticated model of the spacecraft's incoming and outgoing energy.

Iess and colleagues' most stunning finding is that there is a component of Jupiter's gravitational field that does not show north–south symmetry — a peculiar observation for such a fast-rotating gas-giant planet. Kaspi *et al.*[2] (page 223) show that this feature is the result of latitudinal asymmetry in the speed of the winds at the surface. The only way that these winds could affect the planet's gravitational field is if they were relatively deep and involved a substantial amount of mass. This implies that Jupiter's bands are not just a surface phenomenon, thus answering the long-standing question.

Kaspi and co-workers show that the magnitude of the winds decays slowly with depth until about 3,000 kilometres below Jupiter's surface (roughly one-twentieth of the planet's radius), a point at which the pressure is about 100,000 times that of the atmosphere at Earth's surface. The volume of Jupiter in which these winds occur represents about 1% of the planet's mass.

Guillot *et al.*[3] (page 227) confirmed the 3,000-kilometre depth reported by Kaspi and colleagues using the symmetrical component of Jupiter's gravitational field. They demonstrate that, below this depth, the planet's interior rotates as a solid body, despite its fluid nature. This is in accordance with the prediction that hydrogen ionizes to produce free-moving protons and electrons in such a high-pressure environment. These particles generate strong drag forces that suppress winds flowing in opposite directions[7].

The three studies confirm previous suggestions that high-precision measurements of a planet's gravitational field can be used to answer questions of deep planetary dynamics[8,9]. In terms of future work, scientists could use the Juno spacecraft to measure the depths of storms on Jupiter such as the Great Red Spot, or to observe the planet's response to tides raised by its large moons. Such analyses would provide a further window into Jupiter's interior.

The work demonstrated here is extremely robust, perhaps unlike other inferences made using data from Juno, including the mass and density of Jupiter's primordial core[10], that are somewhat model-dependent and rely on our imperfect understanding of the physics of hydrogen under extreme pressure. I do not foresee another leap in knowledge on Jupiter's interior after the Juno mission ends unless astronomers are able to study the planet's internal oscillations[11], as has been done for the Sun[12].

Given the inherent complexity of planets, comparative planetary science has become an essential framework through which to study these astrophysical objects. Thankfully, Jupiter has a sibling, the gas-giant planet Saturn. NASA's Cassini mission to Saturn, which ended in 2017, provided a Juno-like data set for Saturn's gravitational field that is now being analysed[13]. Because Saturn has a lower internal pressure than has Jupiter, its atmospheric winds should be able to extend much deeper into its interior before hydrogen ionization and the associated drag forces take control. If a consistent physical picture could be put together for the two gas giants of the Solar System, it would go a long way towards solidifying our understanding of the internal dynamics of this class of astrophysical object. ■

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HUMAN BEHAVIOUR

Simple moral code supports cooperation

The evolution of cooperation is a frequently debated topic. A study assessing scenarios in which people judge each other shows that a simple moral rule suffices to drive the evolution of cooperation. **SEE LETTER P.242**

CHARLES EFFERSON & ERNST FEHR

The evolution of cooperation hinges on the benefits of cooperation being shared among those who cooperate[1]. On page 242, Santos *et al.*[2] investigate the evolution of cooperation using computer-based modelling analyses, and they identify a rule for moral judgements that provides an especially powerful system to drive cooperation.

Cooperation can be defined as a behaviour that is costly to the individual providing help, but which provides a greater overall societal benefit. For example, if Angela has a sandwich that is of greater value to Emmanuel than to her, Angela can increase total societal welfare by giving her sandwich to Emmanuel. This requires sacrifice on her part if she likes sandwiches. Reciprocity offers a way for benefactors to avoid helping uncooperative individuals in such situations. If Angela knows Emmanuel is cooperative because she and Emmanuel have interacted before, her reciprocity is direct. If she has heard from others that Emmanuel is a cooperative person, her reciprocity is indirect — a mechanism of particular relevance to human societies[3].

A strategy is a rule that a donor uses to decide whether or not to cooperate, and the evolution of reciprocal strategies that support cooperation depends crucially on the amount of information that individuals process. Santos and colleagues develop a model to assess the evolution of cooperation through indirect reciprocity. The individuals in their model can consider a relatively large amount of information compared with that used in previous studies.

This increased amount of information is essential for at least two reasons. First, models of direct reciprocity show that having more information allows for many possible strategies, which can paradoxically reduce cooperation[4]. Does something similar happen for indirect reciprocity? Second, indirect reciprocity requires individuals to assess and disseminate reliable information about each other. In a real-world context, this mechanism is most convincing if the amount of information being processed is not excessive. These two considerations suggest that the most compelling models of indirect reciprocity should be simple and should support cooperation in settings in which many alternative possibilities exist.

In Santos and colleagues' set-up, social

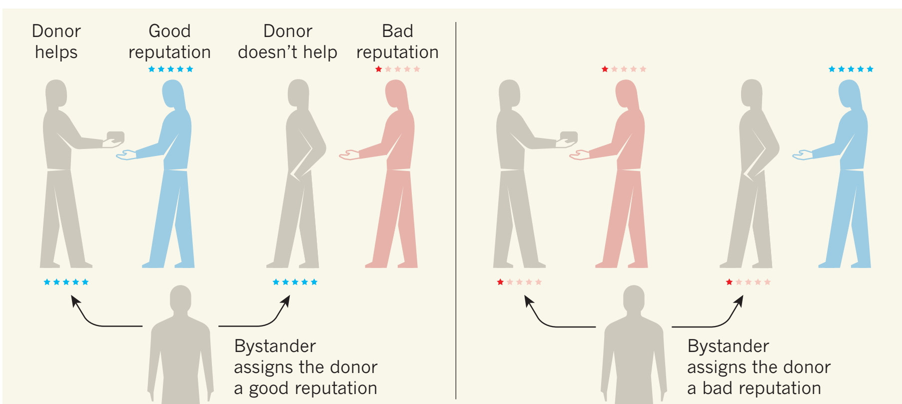

Figure 1 | The stern-judging rule. Santos *et al.*[2] used a computer-modelling approach to investigate how cooperation might evolve. They investigated scenarios in which a donor can give or refuse help to a recipient depending on the strategy that the donor uses. The donor's action is judged by a bystander who uses a rule (termed a norm) to judge the donor's action and assigns a reputation to the donor that the bystander reports to other members of the society. The authors used this system to test 65,536 different norms in terms of each norm's ability to support the evolution of cooperative strategies. The norm that stood out as being both low complexity and also highly likely to drive the evolution of cooperation is one known as stern judging. This figure shows how the stern-judging norm is used by a bystander to assess a donor's action and thereby assign the donor a good or bad reputation.