

unstable and dangerous environments^{4,5}. Until recently, robots designed for such places all had wheels, which neatly offer huge differences in the friction in the fore-and-aft and side-to-side directions. Hu and colleagues' investigations¹ provide guidance on the types of material that might be used to manufacture a robot belly

that offers similar frictional properties to those of snakes. As a form of locomotion, the slither has a lot going for it.

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PLANETARY SCIENCE

Io's escape

Gerald Schubert

According to the latest study, our witnessing of the volcanic splendour of Jupiter's moon Io might just be a lucky circumstance. The odds are that the satellite will become quiescent on its escape from orbital custody.

Jupiter's moon Io is about the same size as our Moon, but the similarities end there. Its motion around Jupiter is tightly constrained by its gravitational interactions with the giant planet and with two of Jupiter's other moons, Europa and Ganymede. Io's orbital imprisonment is the cause of its spectacular volcanism¹.

But Lainey and colleagues², on page 957 of this issue, provide evidence that Io is loosening the bonds that hold it in its unexpectedly elliptical path around Jupiter. If it eventually breaks free, the most volcanically active object in our Solar System will become dormant.

Io's intense volcanism is driven by tidal heat

created as Jupiter's differential gravitational pull causes the satellite to deform continuously and repeatedly as it orbits the planet: Io's surface probably moves up and down by more than 10 metres over an orbit. Jupiter's varying gravitational pull and the resulting oscillations in the tides on Io occur because the satellite is in an elliptical orbit. If Io were an isolated satellite, tidal heat would circularize its orbit. But Io's orbit is elliptical, a circumstance dictated by the moon's gravitational interaction with Europa and Ganymede (an interaction referred to as a Laplace resonance). Although Io's spin and orbital periods still have equal values, Jupiter oscillates back and forth in Io's sky as Io is alternately closer and more distant from the planet.

It requires energy to tidally deform a body, and part of this energy is eventually dissipated as heat by frictional processes within the body. The energy for Io's tidal heating ultimately comes from the energy of Jupiter's rotation. Figure 1 sketches the gravitational tidal interaction of the planet and its moon. The interaction is two-way, with the planet raising tides on the moon (Fig. 1a) and the moon raising tides on the planet (Fig. 1b). These tides influence the orbital motion of the moon in opposite ways.

The tide raised on Jupiter by Io is carried ahead of the line that connects the two objects — the Io–Jupiter line — because Jupiter spins faster than Io orbits Jupiter. The gravitational attraction of the part of Jupiter's tidal bulge that is closest to Io pulls Io forward in its orbit, whereas the attraction of the part of the tidal bulge farthest from Io retards the moon's orbital motion (Fig. 1b). The effect of the part of the bulge closest to Io dominates simply because it is nearer to the moon. As a result, Io gains orbital energy and moves away from Jupiter, whereas Jupiter loses rotational energy. This is the same interaction that is responsible for the Moon receding from Earth as Earth's rotation rate decreases over time.

However, there is another effect taking place that causes Io to spiral inward towards Jupiter. The planet tidally deforms Io as shown in Figure 1a at the instant that Io passes perihelion (its orbital point closest to Jupiter). The tidal deformation lags behind the Io–Jupiter line because, at perihelion, Io's orbital rotation is faster than its spin. The gravitational pull on the part of Io's tidal bulge nearest to Jupiter acts to increase the satellite's spin to match its orbital rotation. The opposite effect occurs at aphelion (Io's orbital point farthest from Jupiter), but

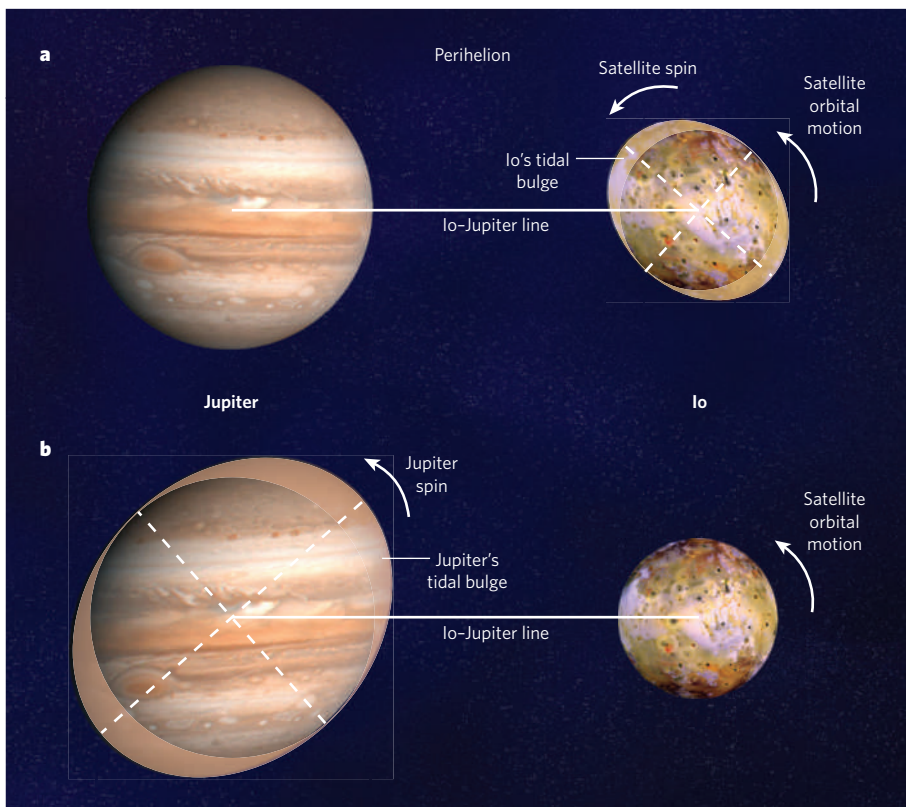


Figure 1 | Jupiter–Io tidal interaction. **a**, The tide raised on Io by its parent planet Jupiter — indicated by the exaggerated elliptical distortion of the body — lags behind the Io–Jupiter line at perihelion (the moon's orbital point closest to Jupiter) because Io's orbital rotation is faster than its spin at this position in its orbit. The gravitational torque exerted by Jupiter on Io's tidal bulge tends to increase Io's spin at the expense of its orbital energy, and forces Io to move inward. **b**, The tide raised on Jupiter by Io leads the Io–Jupiter line because Jupiter rotates faster than Io orbits the planet. The Jovian planet's tidal bulge pulls Io forward in its orbit and, as a result, the moon gains orbital energy and moves outward from Jupiter. Lainey and colleagues² show that the effect of the tide raised on Io by Jupiter wins out, so Io is moving in towards Jupiter. (Both panels depict the tidal interaction looking from above the orbital plane of Io.)

the interaction at perihelion dominates. As a result, Io's spin tends to increase at the expense of its orbital motion; Io loses orbital energy, its orbital period decreases, and it moves inward towards Jupiter.

So, is Io moving towards or away from Jupiter? Which of the above effects wins out? Lainey *et al.*² carry out a numerical integration of Io's orbital dynamic motion and constrain their computation by astronomical observations of the innermost Galilean moons (Io, Europa and Ganymede) acquired over the 116-year period between 1891 and 2007. They conclude that Io is moving in towards Jupiter and that Europa and Ganymede are moving away from the planet. Others^{3,4} have attempted the same calculation in the past, but with poorly constrained — and often contradictory — results, probably owing to approximations made in their orbital dynamical models.

The consequences of Lainey and colleagues' results² are manifold. First, the present global heat loss from Io can be accounted for by tidal dissipation in the moon — that is, Io is in an approximate thermal steady state, in which its radiative heat loss is being balanced by the tidally driven, frictional production of heat. Io's thermal state has until now been uncertain, with suggestions that its thermal behaviour could involve oscillatory periods of activity⁵.

Second, Io, Europa and Ganymede are moving out of resonance. (The Laplace resonance is a special orbital configuration in which Europa's orbital period is twice that of Io, and Ganymede's orbital period is twice that of Europa.) Lainey *et al.* predict the rate at which the satellites' orbital periods are moving away from the 2:1 ratio (Europa:Io and Ganymede:Europa), but they do not estimate at what point the Laplace resonance will be effectively broken. If this occurs on a short timescale, say 10^8 years or less, then we have been lucky to see Io in its volcanic glory, because dormancy will be the fate of Io when the resonance is broken (S. Peale, personal communication).

Finally, the estimated tidal dissipation in Jupiter is close to the upper-bound value associated with the expansion of the orbits of Io, Europa and Ganymede from positions in the past that were closer to Jupiter to their present orbital locations. The physical mechanisms of tidal dissipation in giant planets are not well understood, and the authors' estimate, if correct, would be an important constraint on these mechanisms. ■

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INFLAMMATION

Wound healing in zebrafish

Paul Martin and Yi Feng

What is the first signal that directs the rapid influx of immune cells to a wound to stave off potential infection? A study in the zebrafish reveals an unusual but well-qualified candidate.

The rapid recruitment of white blood cells to a wound site after tissue damage is essential to prevent the entry of microorganisms into the breach and to help to coordinate wound closure. These immune cells perform other functions at wounds as well, such as clearance of cell and tissue debris during the repair process. However, overenthusiastic inflammation can be damaging¹, so understanding how immune cells are recruited to a wound and how the inflammatory response resolves is crucial. A complex series of temporally overlapping signalling molecules, including the well-studied chemokine proteins, are known to attract immune cells to a wound site. But the identity of the initial chemoattractant generated at the site of tissue damage has, so far, remained elusive. A study published in this issue by Niethammer *et al.*² (page 996) now indicates that this earliest 'danger' signal originates from a surprising source — a gradient of hydrogen peroxide (H_2O_2) emanating from the wound.

Neutrophils are the first white blood cells to arrive at a wound site. If blood vessels are damaged by wounding, these cells spill out of the circulation and form part of the clot. In addition, neutrophils migrate to the wound from small blood vessels near the site of tissue damage. To do this, they adhere to the luminal surface of activated endothelial cells lining the blood vessels and then transmigrate either between, or through, endothelial cells into the extravascular space³. Subsequently, they move towards the wound by extending projections (pseudopodia) from the cell and retaining those pseudopodia that by chance are directed towards the wound signal⁴. The first cells arrive within minutes of tissue damage: live imaging of fluorescently tagged neutrophils in mice⁵ shows that about a million cells have arrived at a small skin lesion 4 hours after the initial tissue insult, and after 18 hours about 5 million have arrived. If the wound is infected, then at least twice this number of neutrophils will be recruited.

The initial signal that instigates rapid neutrophil influx to a wound must fulfil certain criteria: it cannot feasibly be upregulated by increased gene transcription, or by increased protein production through messenger RNA translation, because such forms of modulation are too slow. In line with this, several potential candidates have been mooted as first danger signals, including ATP⁶, uric acid⁷, the chromatin protein HMGB1 (ref. 8) and various

growth factors⁹ — all of which can be released immediately from ruptured cells at the wound site, and each of which has been shown to have some capacity for chemoattraction in tissue-culture experiments. But Niethammer *et al.*² provide convincing evidence that, at least in wounds in wet epithelia, the first danger signal is the reactive oxygen species (ROS) H_2O_2 .

The authors study a relatively new model in the immunity field, the zebrafish larva, which because of its translucency and the availability of several lines with fluorescently tagged neutrophils^{10–12} offers unrivalled opportunities for imaging the dynamic behaviour of immune cells (Fig. 1, overleaf). Compared with the millions of neutrophils drawn to even the smallest nick in humans, only 20 to 30 cells are drawn to a wound in the larval zebrafish fin — and each of these cells can be tracked with fine spatial and temporal precision.

Niethammer and colleagues² use a genetically encoded, fluorescent intracellular H_2O_2 sensor, HyPer, to reveal the wound-triggered gradient of H_2O_2 . The gradient initiates at the wound margin, extends 200 micrometres from the wound — far enough to reach the nearest vessels — and is established within 5 minutes of wounding, just preceding the movement of the first neutrophils towards the wound. Although it is often presumed that there are spatial gradients of chemoattractants in tissues, they are exceedingly difficult to visualize, and so watching the gradient as it becomes established and then dissipates with a spatial and temporal profile that befits its postulated function is a rare treat. (See Movie 1 in Supplementary Information to ref. 2.)

The authors use a combination of genetic and pharmacological experiments to identify possible sources of the H_2O_2 signal. The most likely physiological source is one of the NADPH oxidase enzymes that generate ROS during the course of standard metabolic processes¹³. There are several such enzymes in zebrafish larval tissue, and bathing the larvae in drugs that inhibit all NADPH oxidases both prevents the establishment of the H_2O_2 gradient and markedly inhibits neutrophil migration to the wound. To pinpoint the specific NADPH oxidase that generates H_2O_2 at the wound margin, Niethammer *et al.*² perform a series of knockdown experiments using small molecules called morpholinos, which prevent the translation of specific mRNAs into proteins. They find that knocking down mRNA translation of a specific NADPH oxidase, Duox,