about whether plasmonic excitation can have a non-thermal role in catalytic reactions[4,5,9].

The authors' results demonstrate that the search for plasmonic catalysts based on Earth-abundant metals should not be guided by the many decades of research into thermally driven catalysis. The findings also suggest that this search should focus on cheap catalytic materials from which molecular desorption is hindered — such desorption could be activated by light when the catalysts are combined with a plasmonic material. More specifically, plasmonic DIET triggered by LED illumination of Earth-abundant catalysts is a potential strategy for the development of sustainable industrial chemical processes, because it would avert the need for extensive heating (thereby reducing fuel consumption and potentially achieving zero carbon emissions), while avoiding the use of precious metals.

Indeed, Yuan and co-workers demonstrate that they can produce gram quantities of hydrogen (up to about 18 g per day) using their copper–iron catalyst in a small commercial reactor fitted with LEDs, without heating. This suggests that plasmonic catalysis with LEDs could be a viable strategy for reaching a major goal in this field: the development of a process that enables one kilogram of hydrogen to be made at a cost of US$1. However, there are many challenges to be overcome, other than lowering the cost, before this approach can be used for the industrial production of green hydrogen.

First, reactors will need to be engineered to ensure that large volumes of reaction solutions can be illuminated uniformly by LEDs. Second, a process for the sustainable, large-scale synthesis of ammonia is required. Currently, ammonia is manufactured by reacting hydrogen with nitrogen, and the hydrogen is obtained from an energy-intensive reaction (steam methane re-forming) that consumes a large amount of fossil fuels. As a result, ammonia production is responsible for the highest fraction of CO_2 emissions from the chemical industry (see go.nature.com/3r4ufgm). Electrically driven processes for ammonia production might solve this problem, but it seems unlikely that sustainable processes for making ammonia and hydrogen will be scaled up for industrial use in the short term.

Nevertheless, Yuan and colleagues' LED-driven method for producing hydrogen from ammonia is a nice proof of concept that could be combined immediately with emerging approaches for the small-scale electrified synthesis of ammonia. The production of small quantities of green hydrogen at some industrial sites might not be too far away.

The third challenge is economic: the cost of using LEDs to drive industrial reactions must be lower than the cost of burning fuels to heat equivalent thermally activated reactions. In this regard, a highly detailed analysis[10] has shown that sunlight can generate electricity to power LEDs that have electrical-to-optical power efficiencies of about 90% in most cases, thereby providing 'cheap photons' for catalysis. Moreover, the idea of using LEDs (which produce powerful light at a fixed energy) to activate plasmonic catalysts removes the constraints of using sunlight directly — a strategy requiring materials that can absorb the low-intensity, broad spectrum of photons emitted by the Sun. Industrial processes driven by sunlight-powered LEDs could thus become a cheap replacement for some current energy-intensive and high-carbon-emitting processes.

In the next decade, it is to be hoped that the chemical industry will shift towards using more-sustainable processes. In this context, the combination of sunlight-powered LEDs with Earth-abundant catalysts, such as that reported by Yuan *et al.*, might help plasmonic catalysis to transition from the laboratory scale to the industrial scale. We need more such examples to speed our way to a sustainable future.

Emiliano Cortés is at Nano Institute Munich, Faculty of Physics, Ludwig-Maximilians University of Munich, Munich 80539, Germany.
e-mail: emiliano.cortes@lmu.de

1. Yuan, Y. *et al. Science* **378**, 889–893 (2022).
2. Yin, F., Xu, B. Q., Zhou, X. P. & Au, C. T. *Appl. Catal. A* **277**, 1–9 (2004).
3. Boisen, A., Dahl, S., Nørskov, J. K. & Christensen, C. H. *J. Catal.* **230**, 309–312 (2005).
4. Camargo, P. H.C. & Cortés, E. (eds) *Plasmonic Catalysis: From Fundamentals to Applications* (Wiley, 2021).
5. Zhou, L. *et al. Science* **362**, 69–72 (2018).
6. Frischkorn, C. & Wolf, M. *Chem. Rev.* **106**, 4207–4233 (2006).
7. Bonn, M. *et al. Science* **285**, 1042–1045 (1999).
8. Yin, S. F., Xu, B. Q., Wang, S. J., Ng, C. F. & Au, C. T. *Catal. Lett.* **96**, 113–116 (2004).
9. Dubi, Y. & Sivan, Y. *Light Sci. Appl.* **8**, 89 (2019).
10. Schroeder, E. & Christopher, P. *ACS Energy Lett.* **7**, 880–884 (2022).

The author declares no competing interests.
This article was published online on 1 February 2023.

Astronomy

A planetary ring in a surprising place

Matthew M. Hedman

An object in the distant Solar System has been shown to have a ring that is unusually far from its host — prompting speculation about how the ring material has avoided clumping together to form moons. **See p.239**

Planetary rings are disks containing many small chunks of ice and other materials that are in orbit around a larger object[1]. Most rings are found within a critical distance of their host, known as the Roche limit, where the gravitational pull of the host prevents this material from accreting into objects. But on page 239, Morgado *et al.*[2] report the discovery of a ring that doesn't follow this rule: it lies far outside the Roche limit of its host and is thus at odds with our current understanding of how such rings are maintained.

Saturn has the most famous ring system, with rings so large and bright that they can even be seen with small telescopes. But all the other giant planets (Jupiter, Uranus and Neptune) are surrounded by rings too, and these can be seen with sufficiently powerful telescopes, such as the Keck Telescope in Hawaii or the James Webb Space Telescope. Narrow rings have also been found around a few non-planetary bodies in the outer Solar System, such as Chariklo and Haumea[3,4]. The ring discovered by Morgado and colleagues surrounds an object called Quaoar, which lies beyond Neptune's orbit.

This ring is too small and narrow to be detected directly — even with large telescopes. Instead, the authors used multiple telescopes to monitor the brightness of stars as Quaoar passed in front of them. The ring material around Quaoar caused a temporary dip in the stars' apparent brightness by blocking some of the starlight from reaching the telescopes. And different telescopes observed dips of different shapes and intensities, indicating that the ring's opacity varies along its length. Similar variations have been observed in rings surrounding Saturn[5] and Neptune[6]. However, the position of Quaoar's ring is very different from that of any comparably opaque ring, and therefore poses a challenge to standard models of planetary rings.

Rings that have sufficient opacity to block detectable amounts of starlight are so dense that their component particles collide with neighbouring particles on timescales comparable to their orbital periods (that is, hours to days). In principle, these collisions could result in the particles sticking together, bouncing off each other or breaking apart — with sticking

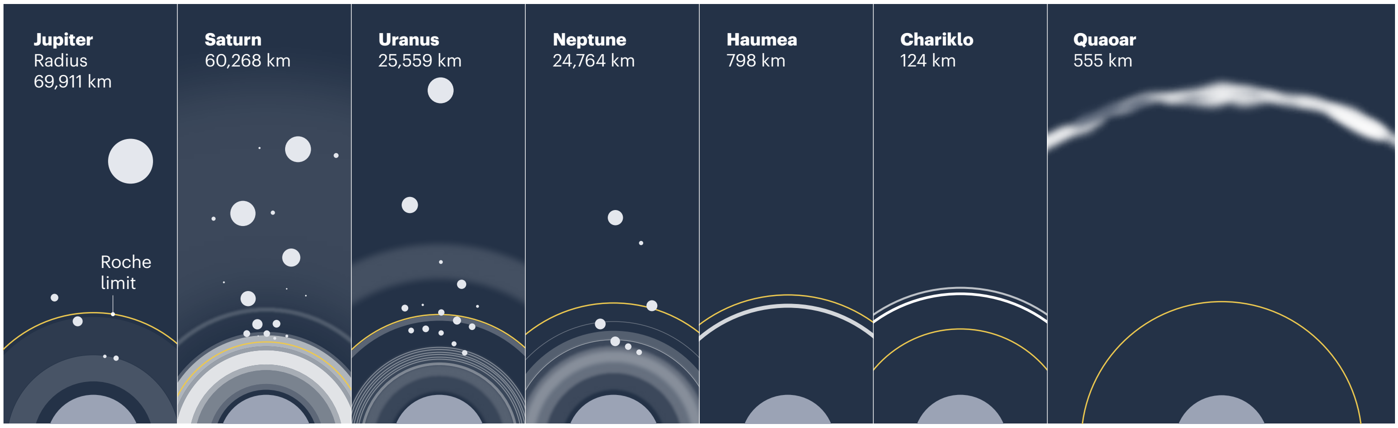

Figure 1 | Rings around planets. The Roche limit is the distance from a planet at which its gravitational field tends to prevent material in orbit around it from aggregating into moons. Rings around the giant planets (Saturn, Jupiter, Uranus and Neptune) are all mostly within this limit, shown here for ring material with density comparable to that of porous water ice (0.5 g cm^{-3}). The rings of Chariklo and Haumea (non-planetary objects in the outer Solar System) are close to the limit. Haumea has an elongated shape that is not shown here. Known moons that are close to the planets are shown, although not to scale with their planets. Morgado *et al.*[2] discovered a ring around Quaoar, another object in the outer Solar System, which is much farther from its host than its Roche limit, in a region where moons typically form in other systems – posing a challenge for standard models of planetary rings.

being more likely for lower-speed collisions and fragmentation more likely for higher-speed collisions. However, because all these collisions dissipate energy, the relative speeds of the colliding particles naturally tend to decrease over time. If nothing counteracts this trend, the collisions eventually become slow enough for the ring material to aggregate into larger objects, such as moons[7].

For most dense rings, differences in the central body's gravitational pull keep the ring material from assembling into moons. Particles at different distances from the planet are subject to different gravitational forces, and this causes them to orbit at different speeds[7]. These local variations in the gravitational field become increasingly important the closer they are to the central body. And inside the Roche limit, such variations are strong enough to overwhelm the mutual gravitational attraction between objects that are close to each other, tearing them apart.

All the previously known dense rings fall close to or within the Roche limit for objects with densities comparable to that of porous water ice. But the ring discovered by Morgado and colleagues is 4,100 kilometres from Quaoar's centre, whereas its Roche limit (also measured from its centre) is 1,780 km, assuming the ring particles' density is also roughly that of porous ice (Fig. 1). This means that the mutual gravitational attraction of chunks of water ice should easily overwhelm the variations in Quaoar's gravitational pull. We therefore need some other explanation for why this material hasn't aggregated into a moon.

Morgado *et al.* considered various possible explanations for the existence of Quaoar's ring. One is that the ring is made of debris that was released during a disruptive impact into a pre-existing satellite, and has not had enough time to re-accrete. However, the authors point out that it should take only a few decades for material to assemble back into a moon, which makes this option unlikely.

They therefore examined several processes that could hinder ring material from accumulating into moons so far away from Quaoar. One scenario is that the ring material is more elastic than commonly assumed, making the particles more likely to bounce apart than stick together. Another is that the ring particles are subject to external gravitational perturbations that keep their collision speeds high enough to prevent aggregation. Such perturbations could come from asymmetries in Quaoar's gravitational field; from gravitational tugs from its known moon, Weywot; or even from undiscovered moons orbiting in the vicinity of the ring.

"The ring reveals that solid particles might not always aggregate into larger bodies as quickly as one might expect."

This last option is worth considering, because a similar phenomenon might be happening in the outermost dense ring surrounding Saturn, which is known as the F ring. This lies between the orbits of the satellites Prometheus and Pandora, and is therefore in a region in which moons can exist. However, Prometheus and Pandora also strongly perturb the F ring's structure, and these perturbations could be preventing material in the F ring from accreting into another moon[5,8].

The ring reported by Morgado and colleagues not only challenges current models of planetary rings; it also reveals that solid particles might not always aggregate into larger bodies as quickly as one might expect. This could have implications for how quickly other solid objects (such as satellites) were assembled under different conditions.

Future observations of Quaoar's ring should pin down the specific mechanisms responsible for its existence. If the ring is a transient structure, it should gradually disappear as its material reaggregates. However, if the ring is long-lived, then the opacity variations along its length can be tracked over time to constrain exactly how rapidly the ring material is orbiting around Quaoar[9]. For example, the orbital period of the ring material could turn out to be a simple multiple of either Quaoar's spin period or Weywot's orbital period. If so, this would be compelling evidence that perturbations from those bodies have some role in sculpting and maintaining this ring – which would, in turn, motivate further studies of how similar resonances might affect the rates of particle aggregation in other contexts.

Matthew M. Hedman is in the Department of Physics, University of Idaho, Moscow, Idaho 83844, USA.
e-mail: mhedman@uidaho.edu

1. Tiscareno, M. S. & Murray, C. D. (eds) *Planetary Ring Systems* (Cambridge Univ. Press, 2018).
2. Morgado, B. E. *et al. Nature* **614**, 239–243 (2023).
3. Braga-Ribas, F. *et al. Nature* **508**, 72–75 (2014).
4. Ortiz, J. L. *et al. Nature* **550**, 219–223 (2017).
5. Murray, C. D. & French, R. S. in *Planetary Ring Systems* (eds Tiscareno, M. S. & Murray, C. D.) Ch. 13, 338–362 (Cambridge Univ. Press, 2018).
6. Porco, C. C., Nicholson, P. D., Cuzzi, J. N., Lissauer, J. L. & Esposito, L. W. in *Neptune and Triton* (ed. Cruikshank, D. P.) 703–804 (Univ. Arizona Press, 1995).
7. Schmidt, J., Ohtsuki, K., Rappaport, N., Salo, H. & Spahn, F. in *Saturn from Cassini-Huygens* (eds Dougherty, M. K., Esposito, L. W. & Krimigis, S. M.) Ch. 14, 413–458 (Springer, 2009).
8. Beurle, K. *et al. Astrophys. J.* **718**, L176–L180 (2010).
9. Pater, I., Renner, S., Showalter, M. & Sicardy, B. in *Planetary Ring Systems* (eds Tiscareno, M. S. & Murray, C. D.) Ch. 5, 112–124 (Cambridge Univ. Press, 2018).

The author declares no competing interests.