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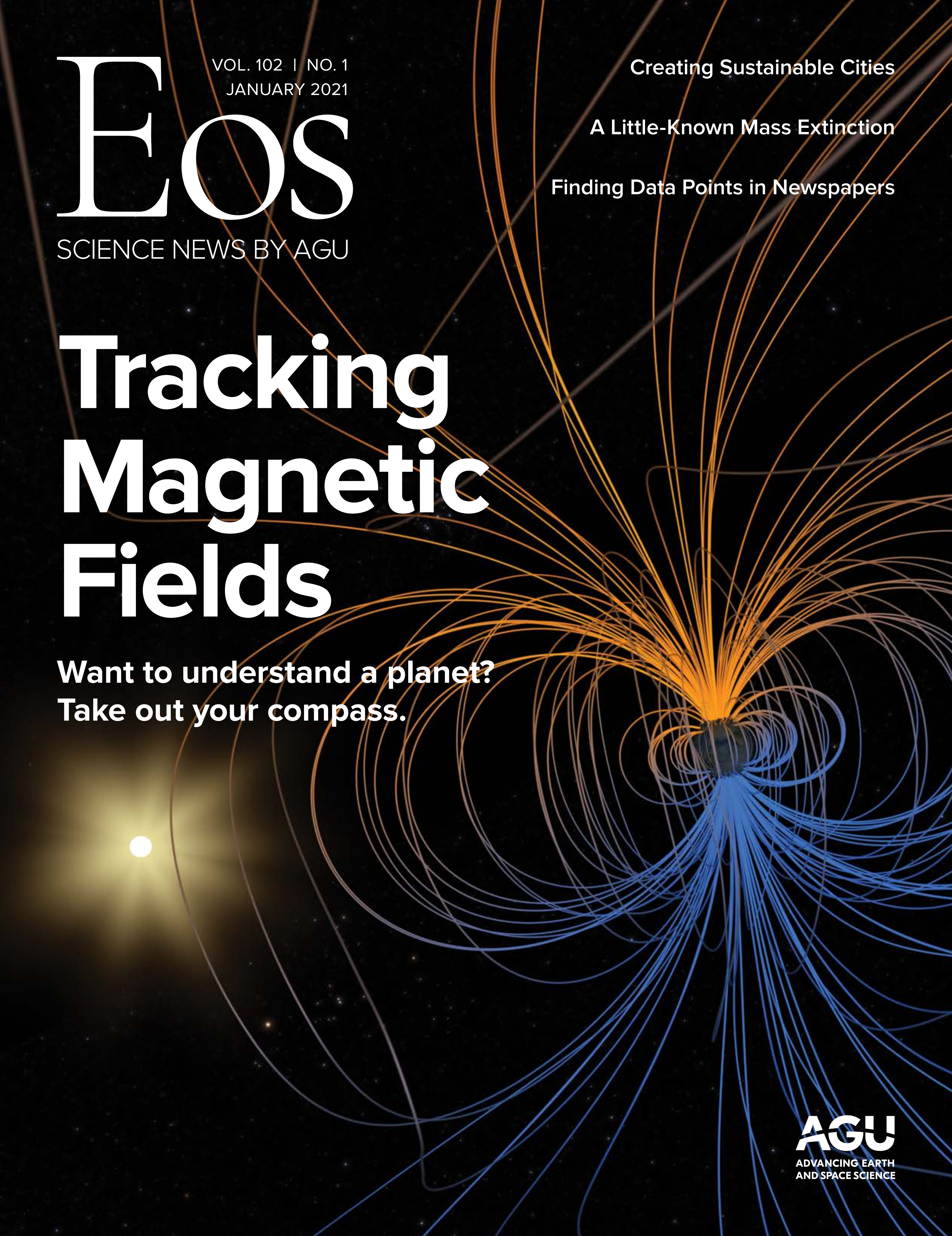

Tracking Magnetic Fields

Want to understand a planet? Take out your compass.

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A FIELD GUIDE TO THE MAGNETIC SOLAR SYSTEM

Not all planets move the needle. But whatever planet you take a magnetic compass to, it's sure to point out clues to secrets underfoot.

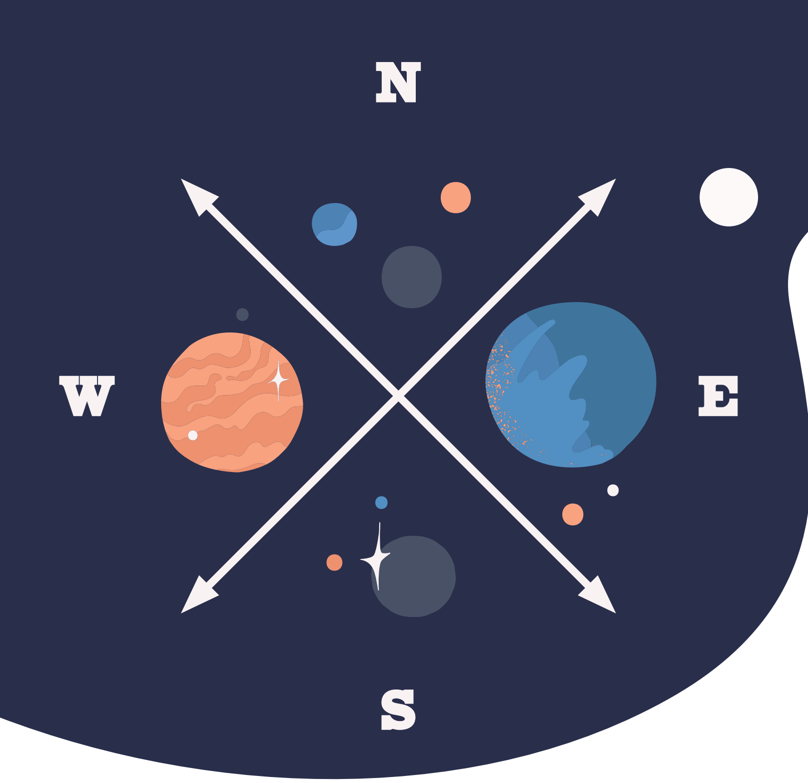
By Bas den Hond

Congratulations! With the IP9, the new interplanetary model in *Eos*'s signature line of magnetic compasses, you've chosen a travel companion that will serve you as best it can on the many GPS-challenged bodies of our solar system—be your plans a hike on Mercury, a ride on Mars, or a glide over Neptune.

Before you start using your compass, please note that your warranty is voided when you drop your IP9 onto a hard surface or into a high-pressure or high-temperature environment, or store it unshielded from magnetic fields during extended periods of interplanetary travel.

Other warnings and pointers, specific to select extraterrestrial destinations, are as follows.

Good Studio/stock.adobe.com



Destination: Mercury

On Mercury, using the compass will be straightforward. The structure of Mercury's magnetic field is much like Earth's, so your compass will behave approximately as if a huge bar magnet rests at the planets center, aligned with its rotational axis. Or—a bit closer to the mark—as if electric currents are girding that axis.

Do give your needle time to adjust. Mercury's magnetic field, which was measured by the MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging) spacecraft that orbited the planet from 2011 to 2015, is only 1.1% the strength of Earth's.

And pay attention to space weather: "Because Mercury is much closer to the Sun," said Sabine Stanley, a professor in the Department of Earth and Planetary Sciences at Johns Hopkins University, "and because the planet's magnetic field is much weaker than Earth's field, there are times when the solar magnetic field gets really important, even very close to the planet. Your compass may actually measure fields in the magnetosphere of Mercury that are caused by interaction with the solar wind. We call them external magnetic fields because they are due to currents flowing outside of the planet, not inside of it."

In rocky planets like Mercury and Earth, any such internal electric currents flow in the iron cores they obtained when they were young and hot, and their materials separated out according to density.

"The biggest thing Mercury's field tells you is it has an iron core, and that core is still partly liquid and moving around," said Stanley. "Before we can really understand what the field tells us about the planet, we need to understand what the composition is of the core, what's mixed in with the iron, what are the temperatures. We learn a little bit about that from the composition of the surface."

Those assumptions about composition eventually go into modeling, which is what Stanley does. The goal is to predict how an iron core, wholly or partially fluid, sheds its primordial heat. If this happens fast enough, convection will occur. As swirls of electrically conducting fluid both create and are moved around by magnetic fields, they become a self-sustaining source of such fields: a dynamo. But modeling that process realistically is not really possible just yet, said Stanley. "Because the viscosity of the iron is so low, the flows are turbulent at a small scale, so in our simulation we would really need high resolution, a lot of grid points."

Bruce Buffett, of the Department of Earth and Planetary Science at the University of California, Berkeley, agreed. Models, he said, are characterized by how the friction forces associated with viscosity compete with the Coriolis forces associated with the rotation of the planet. "When we first started [modeling], the viscous forces were about 1,000 times less important than the Coriolis forces. In a realistic model, they are 10^{15} times less. In our current models, 10^5 or 10^6 is possible."

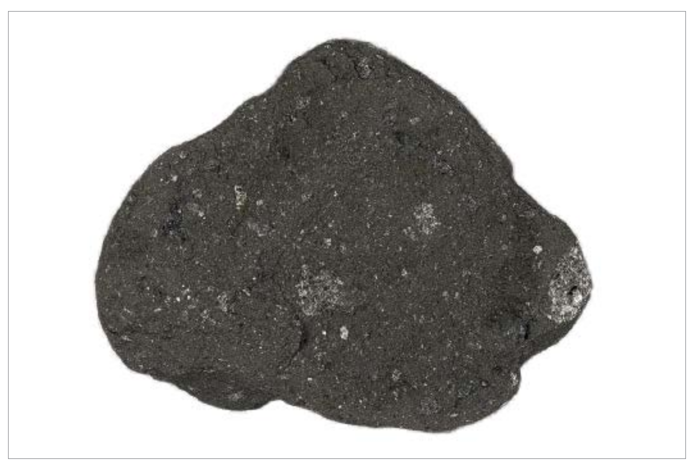
Achieving realistic conditions means that modelers like Buffett and Stanley need computers that are about 2,000 times faster than what they can currently get their hands on. If Moore's law, which says computer power doubles roughly every 2 years, keeps working, scientists will get those computers in 11 years.

In the meantime, researchers studying Mercury's magnetic field have to work with approximations, which "do produce magnetic fields," said Buffett. "There are some people who believe that if you go to lower viscosity, you stay in the same dynamical regime, and others say there could be something different, a change of phase almost. I'm not sure who's right. But the results that we are getting now are useful."

Destination: The Moon

Although all major rocky bodies in our solar system have iron cores, your IP9 compass is unfortunately not suitable for use on Venus and the Moon and is of only limited use on Mars.

The time when the Moon had a global magnetic field is long past. Your compass will at most pick up remanent magnetization in some lunar rocks.



Rocks like the Contingency Sample, above, the very first sample picked up from the Moon, provide clues to the Moon's magnetic past. Credit: NASA/Astromaterials 3D

That the field is absent tells us that the lunar core is fairly quiescent, said Sonia Tikoo, an assistant professor of geophysics at Stanford University.

The ages of magnetized rocks constrain the time when a dynamo was active inside the Moon. But there are large uncertainties to those constraints, due to the limited samples of rocks that Apollo astronauts brought back to Earth.

"At least prior to 3.5 billion years ago, the field appears to have been as strong as Earth's," Tikoo said. "After that it was an order of magnitude weaker. It lasted at least until 1.9 billion years ago, and very likely was turned off by 0.9 billion years ago."

These numbers pose hard questions for modelers. The early magnetic field seems too strong to have been generated by the sort of dynamo the Moon's heat budget could sustain. "So people are looking at alternatives that are mechanical in nature," Tikoo said.

One possible energy source is precession, with the core and mantle, and perhaps a liquid outer core and a solid inner core, rotating around different axes. "That can generate turbulence in the fluid core and power a dynamo," said Tikoo. "But what is missing is any magnetohydrodynamic simulation. Nothing yet has been published that says, 'Yes, you can do this.'"

Destination: Venus

For Venus, information about any past magnetic field is even scarcer. "We don't know what we would see your compass do," admitted Joe O'Rourke, an assistant professor in the School of Earth and Space Exploration at Arizona State University. "One possibility is that it would do nothing, because there never was a magnetic field of any kind. The second is that it would occasionally behave erratically as you encounter regions of the crust that are magnetized."

Such regions would prove that Venus did have a magnetic field and that it was preserved in rocks. But whether those rocks exist is anyone's guess. "The mission that provided the tightest constraints on the magnetism of Venus was the Pioneer Venus Orbiter, which launched in the late '70s," said O'Rourke. "All we really know is that if there is a magnetic field at Venus, it has to be 100,000 times weaker than Earth's magnetic field."

The most likely explanation for the absence of a magnetic field now, according to O'Rourke, is that the Venusian lithosphere is not broken up into wandering continental plates. "Because there is no plate tectonics, [Venus's] silicate mantle probably cools down slowly, and the mantle is what is insulating the core. So Venus could have a core that is exactly the same size, exactly the same composition, as Earth, but cooling down more slowly over time."

Venus could also differ from Earth in radical ways that would reduce the strength of its magnetic field or prevent it from having one at all. A chemical gradient in the core, for instance, or an insulating ocean of molten rock surrounding the core may prevent convection in the planet's interior.

If Venus never had a magnetic field at all, it would be a very special planet indeed. Research on the remanent magnetism of meteorites suggests that even some planetesimals, the building blocks of planets like Earth and Venus, had iron cores that for a time produced dynamos.

Stanley has studied a class of very old meteorites called angrites. "They're dated very close to the beginning of the solar system," she said, "and they have a magnetic signature in them that seems to suggest they formed on a body that had a dynamo. Nothing else, like solar wind or flares, is strong enough [to form the magnetic signature]. And the field has to be very stable, for about tens of thousands of years, because rocks cool very slowly, and they imprint an average field over that time."

"So we did some modeling to ask the question, Could a planetesimal, something that's maybe 100 kilometers to a few hundred kilometers in radius, generate a dynamo?" Stanley continued. "And we found that yes, in certain circumstances you could have enough power available to generate those motions you need in the cores of these planetesimals."

That power would have come from a radiogenic isotope of aluminum, Al-26. "It has a very short half-life," said Stanley, "so all of it has already decayed today, but very early in the solar system it was an available heat source."

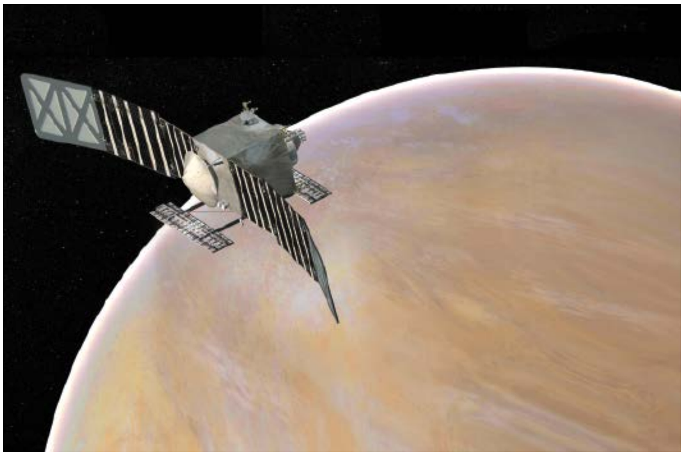
The decay of Al-26, according to Stanley's calculations, could completely melt a planetesimal, allowing an iron core first to form in its center and then to cool down through convection, creating a short-lived dynamo.

Many planetesimals are still around, for instance, as Kuiper belt objects, and two have been visited by a spacecraft: the contact binary Arrokoth and the dwarf planet Pluto. When New Horizons came calling, however, it didn't bring a magnetometer. Its designers didn't think such an instrument would measure anything while passing Pluto. Pluto's small size and slow rotation—its day takes almost an Earth week—work against any dynamo activity. Stanley is quite sure: "Pluto does not have a magnetic field."

Whether Venus ever had a dynamo can be established only by a new magnetometer-equipped mission.

O'Rourke hopes the recent discovery of phosphine in the Venusian atmosphere will be an impetus to go there again. "Just the fact that we don't understand fundamental things about Earth's nearest neighbor is humiliating to our attempts to claim that we understand anything about planetary evolution.

"IF THERE IS A MAGNETIC FIELD AT VENUS, IT HAS TO BE 100,000 TIMES WEAKER THAN EARTH'S MAGNETIC FIELD."



The VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) orbiter, seen here in an artist's rendering, is one of many proposed missions to Venus.

There have been many great mission proposals for Venus that are technically ready, they're scientifically valuable. NASA just has to pick one."

In the early days of the space program, O'Rourke said, "Venus and Mars shared the glory. The first successful interplanetary flyby mission went to Venus.... The Soviet Union sent landers to Venus. But in recent decades, Venus has absolutely been neglected and Mars stole the show."

THE NEXT MARS MISSION WILL ARRIVE IN FEBRUARY WITH A ROVER, PERSEVERANCE, BUT WITHOUT A MAGNETOMETER.

Destination: Mars

We have a clearer picture of Mars's magnetic properties because it has been the subject of so many recent missions.

According to Jennifer Buz, a postdoctoral scholar in the Department of Astronomy and Planetary Science at Northern Arizona University, travelers to Mars may want to avoid the northern hemisphere if they are going to rely on a compass. "Most of the north is unmagnetized, [so] it wouldn't do much," she said. "But as you go south, there is a region where the crust is really strongly magnetized, in alternating fashion. Some people think it's like the magnetic seafloor stripes that we have on Earth. If you were to traverse significant lengths of the southern hemisphere [on Mars], the compass would completely switch direction multiple times."

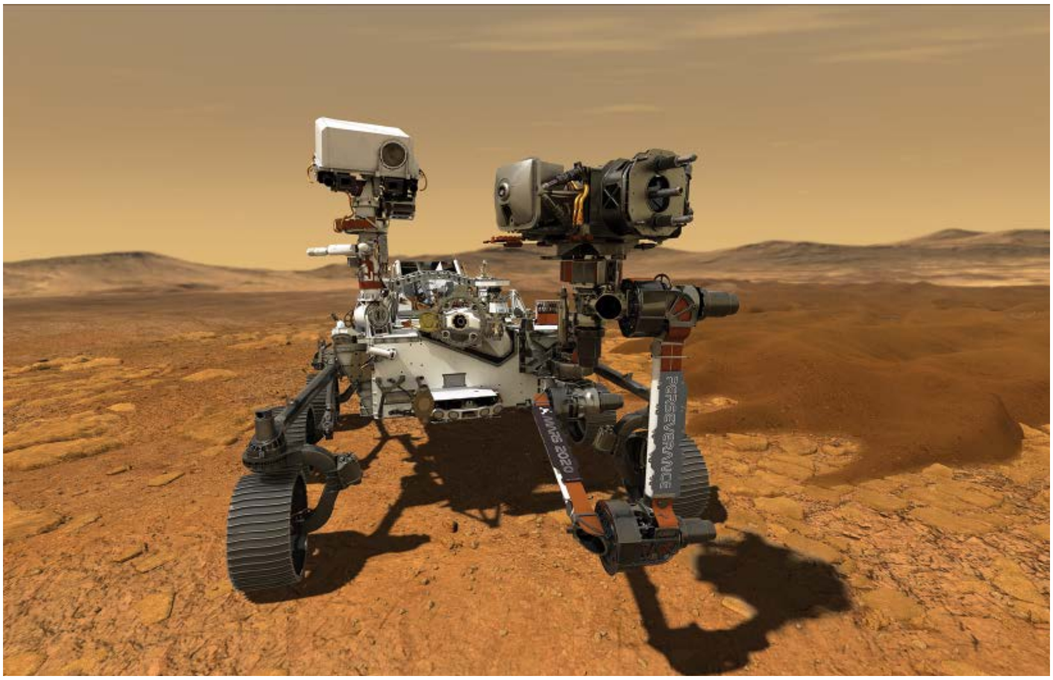
These anomalies indicate that Mars once had a core dynamo and suggest that its magnetic field was strong for its size, about as strong as Earth's. "But there are ways to explain that," said Buz. "Mars has a lot more iron, so it could have a more significant core. And then because Mars is smaller, the field at the surface is closer to the core."

It would be possible to study the core by observing seismic waves traversing the planet from several locations simultaneously. But there is only one working seismometer on the planet, brought there on the 2018 Mars InSight Mission.

The InSight lander also had a magnetometer on board. "And from that single data point, where that probe landed, we were able to validate a lot of the global mapping from orbit," Buz said. "When it landed, [we found that] the field was a lot stronger than we had modeled."

But here, too, data from one instrument at one location are limiting. "It would be really great if we could have a magnetometer on one of the rovers," said Buz. "To see the minute changes in the magnetization as the magnetometer traverses the planet would shed a lot of light on why [Mars has] such variable crustal magnetization."

NASA's next Mars mission will arrive in February with a rover, Perseverance, but without a magnetometer. But it looks like Buz's wish will be fulfilled by a Chinese mission that launched in the same month, July 2020. Tianwen-1 (the name means "Heavenly Questions") will also arrive in February, and put a rover down in May. This rover carries the Mars Surface Magnetic Field Detector, which will measure the field to an accuracy of better than 0.01 nanotesla. That's less than a millionth of the field strength of Earth. "Historically, it's been hard to access data from Chinese missions," Buz said, "but it looks like this mission has a lot of international collaboration. I'm excited for their results."



The next Mars mission will arrive in February with a rover, Perseverance, but without a magnetometer. Credit: NASA/JPL-Caltech

Destination: Gas Giants

If you're the kind of traveler who is slightly annoyed that your magnetic compass doesn't quite point to the geographic North Pole on Earth, then Saturn is your magnetic Shangri-la, while you may give Jupiter a pass.

"Saturn's field is unique: It's almost perfectly axisymmetric," said Stanley. But on the other gas giant of the solar system, the compass is tricked by flux patches not far from the poles, where additional field lines emerge.

The flows of conducting material that a dynamo needs are not located in the metal cores of gas giants—if the planets even have them.

Instead, scientists think the flows arise at higher levels, where the hydrogen that makes up the bulk of these planets is hot and pressurized enough to become metallic.

Modelers can produce a field like Jupiter's, but as for Saturn, "it's really hard to generate a dynamo that produces a symmetric field," said Stanley. "You have to do something special in the interior."

This would perhaps be some kind of shielding layer around the dynamo. "As you go deeper into Saturn and the hydrogen becomes metallic...the helium that is mixed in with the hydrogen doesn't transition [to metal], and it can actually rain out of the hydrogen." The result is a helium-depleted layer covering the dynamo region. "It could act as a shield that gets rid of any of the nonaxisymmetric fields that we otherwise might see at the surface."

Destination: Galilean Moons

While you're in the neighborhood of the gas giants, it seems a shame not to have a quick visit to some of the Galilean satellites. "They're really interesting," said O'Rourke.

Of Jupiter's Galilean moons—Io, Europa, Ganymede, and Callisto—the first three are thought to have iron cores, based on their gravitational pull on the Galileo spacecraft that cruised around the Jovian system from 1995 to 2003. Only one of them, though, Ganymede, has a core with an active dynamo, producing a strong dipole field.

Why the others don't is a puzzle O'Rourke is working on. "It could be related to the amount of tidal heating in these worlds. Io, of course, is super close to Jupiter—it is being violently heated by tides, and if the rocky part of Io is superhot, maybe even liquid, that would insulate the metal core. Whether or not that process also works on Europa is totally unclear."

Not having a dynamo doesn't mean a Galilean moon can't be an interesting place to bring a compass. Near Europa and Callisto, for example, Galileo measured perturbations of the magnetic field of Jupiter. Instead of dynamos, these moons are thought to be the solar system's induction coils. Stimulated by changes they experience in the magnetic field of Jupiter as it rotates, electric currents flow inside the moons, and these in turn bring about magnetic fields that counteract the changes. The existence of the fields is taken as evidence that hidden under the surfaces of Europa and Callisto are salty oceans. Compass readings on these moons will be hard to interpret without detailed knowledge of where the satellite is in its orbit.

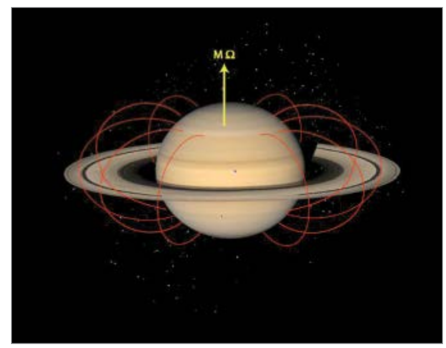
INSTEAD OF DYNAMOS, THESE MOONS ARE THOUGHT TO BE THE SOLAR SYSTEM'S INDUCTION COILS.

Destination: Ice Giants

Great caution is advised when magnetically navigating Uranus and Neptune. The magnetic fields of the solar system's two ice giants are not dipolar but multipolar, said Stanley. "They have lots of places where field lines come out of the planet and go into the planet. So you never know where your compass is going to be pointing."

The poles of our solar system's ice giants may not even be fixed. "The only data we have [are] from a single flyby of both planets by the Voyager II spacecraft in the late '80s," said Stanley. "So all we have is a snapshot in time of the field. We think they move around. But we don't know at what speed."

Uranus and Neptune consist of water, ammonia, and methane ices, which may contribute to the planets' magnetic potential. "When you're thinking about dynamos and magnetic field generation," said Stanley, "you have to ask: Where in the planet can I get a material that is going to be fluid, and a good electrical conductor? For Uranus and Neptune, as you descend into the planet, water—as you keep putting it under higher and higher pressure—becomes ionic. The bonds in the molecules break, and you have OH^{-s} and H^{+s} ions of water. And those can carry electric charges, creating a current. So we think the dynamos in Uranus and Neptune happen in the ionic water layers. We don't know how deep the dynamo region goes, and we really don't understand what happens to the water."



Saturn's magnetic field lines (red) are symmetric, and the planet's dipole axis (M) and its rotation axis (Ω) are nearly perfectly aligned. Credit: NASA/JPL-CaltechDQ: Your compass may actually measure fields in the magnetosphere of Mercury that are caused by interaction with the solar wind.

Some Final Pointers

Clearly, tourist excursions in the solar system are not for the fainthearted—and at present, travel insurance is available only for the rocky planets, with deductibles varying from very reasonable (the Moon) to quite steep (Venus). This may well change as further data become available and magnetohydrodynamic models improve. Those who have an itch to go farther afield should follow the Earth science journals for the latest developments and, of course, Eos, *proudly your companion in all your interplanetary adventures.*

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