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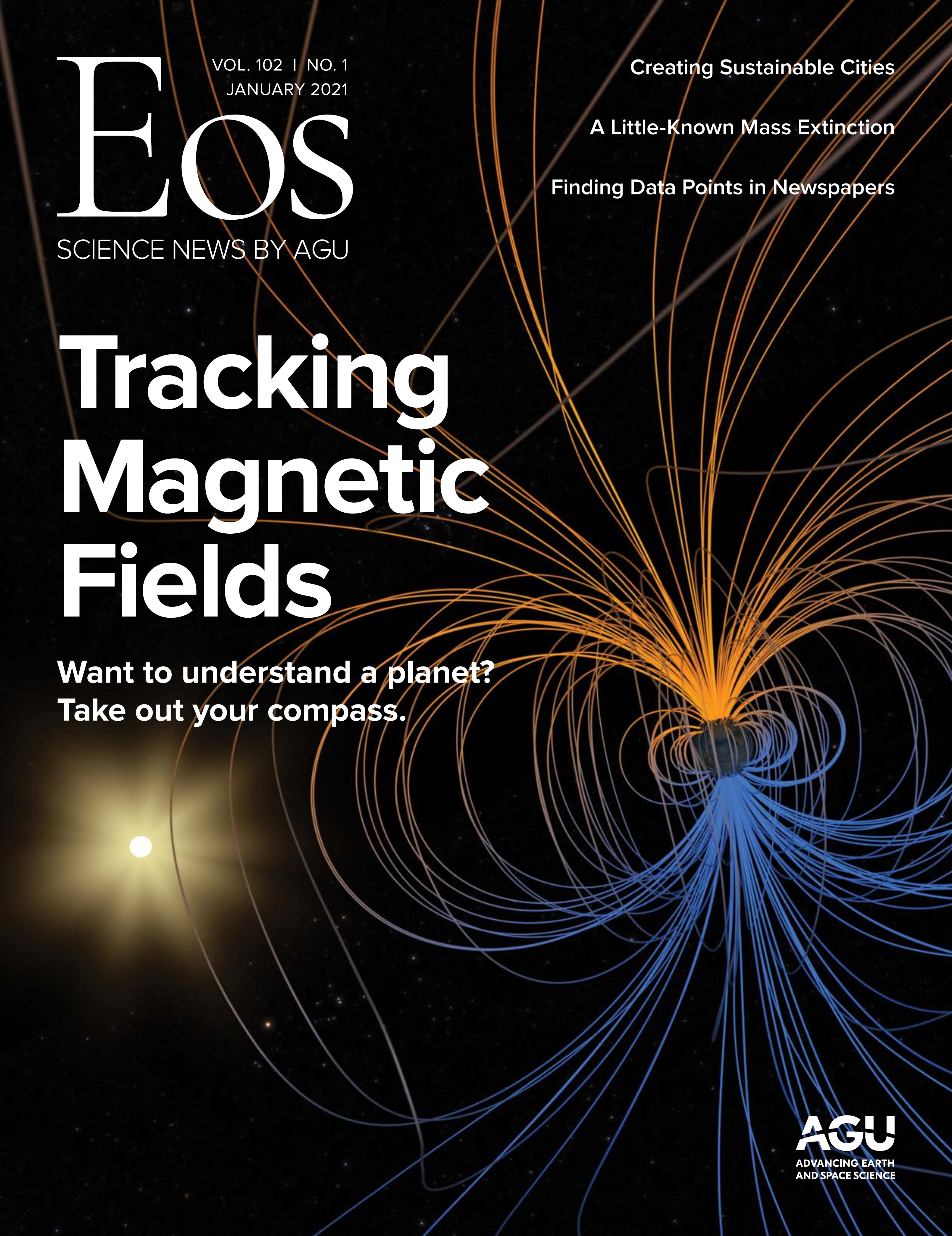

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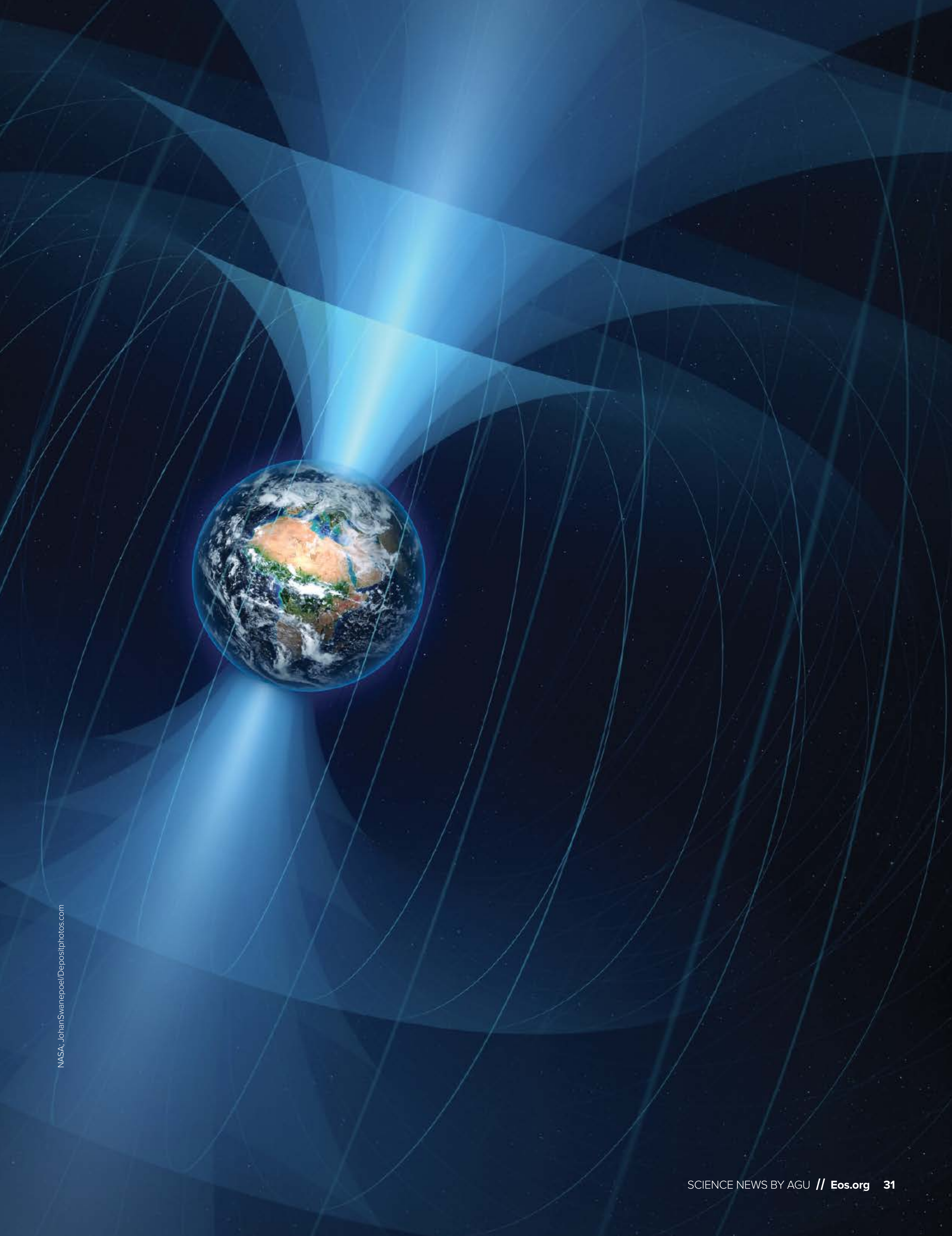
ADVANCING EARTH AND SPACE SCIENCE

THE HERKY-JERKY WEIRDNESS OF EARTH'S MAGNETIC FIELD

Dented, erratic, and wandering, our field is constantly changing its mind.

By Jenessa Duncombe


NASA, JohanSwanepoel/Depositphotos.com

Most people don't know that Earth's magnetic field has a weak spot the size of the continental United States hovering over South America and the southern Atlantic Ocean.

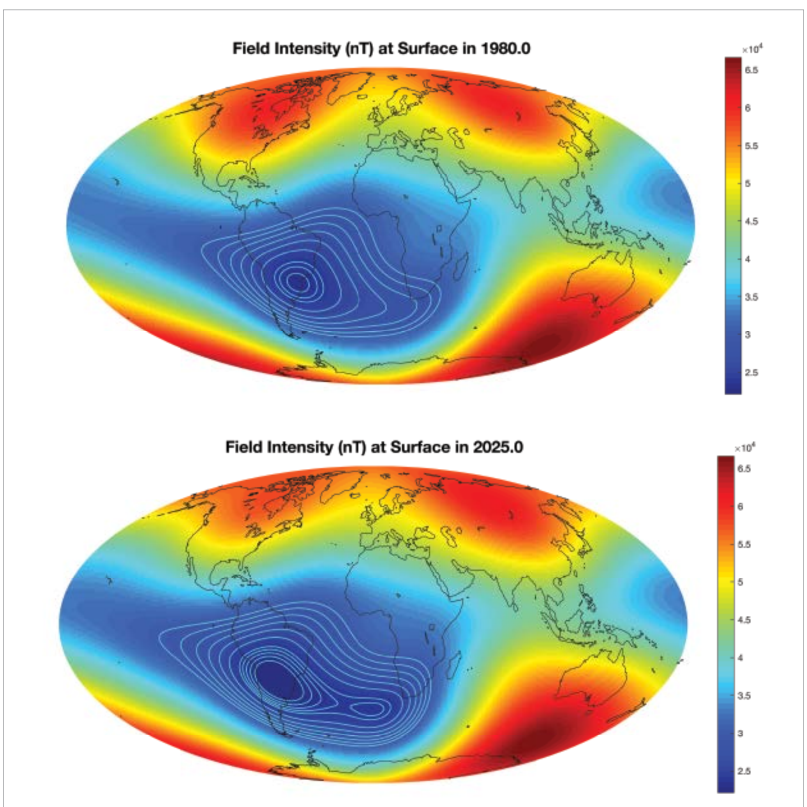
We're safe from any effects on the ground, but our satellites aren't so lucky: When they zip through this magnetic anomaly, they are bombarded with radiation more intense than anywhere else in orbit. There is reason to believe that this dent in the magnetic field, called the South Atlantic Anomaly, is only getting bigger.

This anomaly is far from the only unusual feature of Earth's magnetic field.

Hundreds of times in Earth's history, our magnetic field has reversed, switching north and south in a planetary flip-flop. Earth's magnetic North Pole keeps drifting too, stumbling around the Arctic in a chaotic dance. And scientists have detected pulses of Earth's magnetic field—called geomagnetic jerks—that can undermine our navigation systems.

Yet forecasting these changes remains a challenge. "Just like weather forecasts, you can't predict the evolution of the core beyond a few decades," said Julien Aubert, a researcher at the Paris Institute of Earth Physics.

But scientists want to know how Earth's magnetic field will change further into the future than that. Without a magnetic field, satellites could be lost, and tools that rely on careful magnetic models for navigation could go askew.



The South Atlantic Anomaly currently covers parts of southern Africa, much of the southern Atlantic Ocean, and South America. In 5 years, the region is forecast to grow and bifurcate. Credit: Weijia Kuang and Terence Sabaka/NASA GSFC

The answers can't come soon enough. The magnetic field protects Earth's atmosphere from harmful radiation emitted from the Sun. Scientists are learning that the Sun is capable of emission events—solar flares—even more destructive than we ever thought possible, and understanding our magnetic field strength and variation is vital for knowing how at risk we could be from the next big solar storm.

THE IRON HEART

The puppeteer that drives the magnetic field is Earth's core, the superheated heart of our planet, which burns as hot as the surface of the Sun.

In the core, molten metals are constantly in motion as hot buoyant plumes of lighter material rise outward. At the very center lies a small hardened inner core that has been growing as Earth cools.

This planetary anatomy sets the stage for an active magnetic field. The core's constant need to cool itself, and thus convect, drives our planet's electric generator. The generator produces a self-sustaining magnetic field through a process called the geodynamo. The mathematics of the geodynamo are so messy that Albert Einstein did not believe the theory when one of its founders, Walter M. Elsasser, proposed it to him.

The geodynamo works because the natural convection of the liquid core pushes metals through a weak existing magnetic field, exciting an electric current. Because of the relationship between electricity and magnetism, the current produces a second magnetic field, and the process repeats. This process has been self-sustaining for most of Earth's history.

Although the core sits thousands of kilometers beneath our feet, the magnetic field it produces stretches far into space, surrounding the planet like armor. But our planet's armor isn't perfect, and the results can be heartbreaking.

A CHINK IN EARTH'S ARMOR

On an early spring day in 2016, teams of engineers in Japan watched as their prized satellite spun out of control.

The teams behind Hitomi, a satellite launched just 5 weeks earlier, had hoped the spacecraft would observe black holes, galaxy clusters, and other high-energy features. The satellite even had a prized X-ray calorimeter, a triumph of 3 decades of engineering.

But a cascade of events that began with encountering the South Atlantic Anomaly seemed to spell doom for Hitomi. Passing through the anomaly, the onboard system that controlled the satellite's orientation glitched while it was pivoting to observe a new star cluster. The maneuver kicked off a series of software errors that left Hitomi spinning madly. Before long, the satellite broke into 11 pieces.

"It's a scientific tragedy," Richard Mushotzky, an astronomer at the University of Maryland in College Park, told *Nature* at the time.

Other spacecraft have fallen prey to the South Atlantic Anomaly. The magnetic field intensity at the altitude of many satellites is half as strong in the anomaly compared with elsewhere, and the weak field does not repel radiation as effectively. The inner Van Allen radiation belt, a doughnut-shaped disk of radiation around Earth that traps high-energy particles, hugs much closer to the surface at the anomaly because of the weakened field.

Any satellite in near-Earth orbit—a common altitude for Earth observing satellites—must travel through the anomaly. The Hubble Space Telescope spends 15% of its life in the region—and routinely shuts down its light-sensitive cameras to avoid damage. Some instruments, like NASA's Ionospheric Connection Explorer, power down electrical components of an ultraviolet photon detector every time they pass through. In the early days of the International Space Station, the anomaly would crash astronauts' computers.

But sometimes a satellite is just unlucky. Ashley Greeley, a postdoctoral scholar at NASA Goddard Space Flight Center, recalled a CubeSat that died shortly after launch. During start-up checks and the commissioning phase, "we think that an energetic particle hit it in the wrong place at the wrong time, and we never got data, unfortunately," she said.

A GROWING ANOMALY

Researchers discovered the South Atlantic Anomaly in 1958 when satellites first began measuring radiation in space. Now the region shows up prominently in most models, said NASA's Terence Sabaka. "Everybody is pretty much in agreement on its size, shape, and strength." Although it's still a matter of speculation, there is some evidence that the anomaly has been around since the very early 19th century and maybe even earlier.

The real debate surrounds what the anomaly will do next.

Greeley took her first look at the anomaly during her doctoral work. Peering through 20 years of satellite data, she calculated the extent of the anomaly during each pass of the Solar Anomalous and Magnetospheric Particle Explorer. Satellites in low Earth orbit pass through the region every week or so, and the transit lasts for several minutes, she said.

Over time, Greeley found that the South Atlantic Anomaly is moving westward (at about 1° longitude every 5 years) and ever so slightly northward. Eventually, "the bulk of it will be over land," she said. The bull's-eye of the anomaly will pass over Argentina, Bolivia, Brazil, Chile, and Paraguay.

A forecast from NASA scientist Weijia Kuang and University of Maryland, Baltimore County professor Andrew Tangborn shows that in addition to migrating westward, the anomaly is growing in size. Five years from now, the area below a field intensity of 24,000 nanoteslas (about half the normal magnetic strength) will grow by about 10% compared with 2019 values. The dent may also be splitting, Kuang said, or perhaps another weak spot is emerging independently and biting into it.

Although the dent is projected to grow in the next 5 years, it's impossible to make predictions further into the future, said Kuang. Fluid movement in Earth's core is so turbulent that a small perturbation to the system could lead to a cascade of outcomes that we can't foresee. The further you go in time, the more runaway situations abound.

Although the future is uncertain, studying the anomaly "provides a very good window for us to understand not only the core dynamics," said Kuang, but also "the regional properties of this area."

Luckily, the anomaly can't hurt life on the surface, said Kuang. "But if it continues to weaken over time, this may eventually impact us." The hole in our field would expose us to high-energy particles that could surge power grids and eat away at protective gases in our atmosphere.

> Jerks may illuminate the core's thermal properties, a hotly debated topic that affects our ideas about everything from the age of the core to the onset of plate tectonics.

MAGNETIC SHUDDERS AND A WANDERING POLE

Chengli Huang's daughter would often hear a familiar story at bedtime.

One day, four blind men decided to go to the zoo to visit an elephant. They'd never met one before, and they wanted to know what it looked like. The first man approached the elephant, felt its trunk, and declared it a "curved paddle." The second touched its tail and concluded it was like a stick. The third man gingerly patted the body and pronounced that the animal looked like a wall, whereas the fourth felt its leg and said it was like a pillar.

Separately, the four men understood only one part of the elephant. But together, they had a clearer picture of the elephant's true nature.

Huang tells this story to colleague Pengshuo Duan, too. As astronomers peering into Earth's interior, there is no way for them to "feel" the true nature of the core. But they can probe different aspects and collaborate and compare with others to make a more complete picture.

Scientists have long been on this quest, sometimes with fatal consequences. Explorers of old perished trying to set up monitoring stations in far-flung locales, like the doomed English explorer Sir John Franklin, whose expedition to take magnetic observations of the North Pole in 1845 ended with 129 men dead and two ships lost.

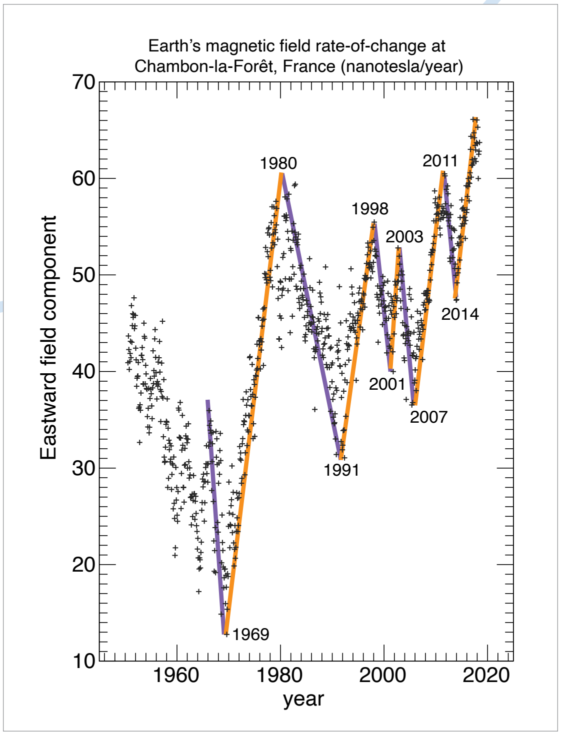
As soon as long-lasting ground observatories sprung up around the world, scientists noticed strange deviations in the field, including for example, that our magnetic North and South Poles roam freely around the planet. It's true that the poles sit off-kilter to Earth's rotational axes because of the uneven and turbulent flow in the core, but they also drift gradually as the core's dynamics swirl field lines. Last century, the magnetic North Pole paraded through the Canadian Arctic, and since the 2000s, it's been sauntering across the Arctic Ocean.

But occasionally, this gradual movement accelerates seemingly at random, and the drift of Earth's magnetic field skirts in another direction. These diversions are called geomagnetic jerks.

The dent may be splitting, or perhaps another weak spot is emerging and biting into it.

Scientists also call the jerks "V-shaped" events based on their appearance in plots of the field's rate of change over time. The events usually last between 1 and 3 years, and the first documented case was recorded in 1902. Dozens of jerks have happened since.

The last jerk was in 2016, when it jostled the field and dramatically shifted the North Pole drift. The event was rather inconvenient because scientists had just issued a 5- year model of Earth's magnetic field called the World Magnetic Model (WMM). The WMM team had to update the model ahead of schedule to avoid unacceptable navigational errors.



You can spot jerks in the V-shaped graphs of the magnetic field's change in direction over time. Credit: Julien Aubert, IPGP/CNRS from French BCMT data

Although the origin of jerks is a subject of active research, a recent study in *Nature Geoscience* by Aubert and Chris Finlay at the Technical University of Denmark suggests that jerks may originate from the push and pull of forces in Earth's interior (bit.ly/jerks-research). When a hot plume shoots up through the outer core, the delicate balance between planetary, rotational, and electromagnetic forces careens out of whack. The off-balance forces send a shudder along magnetic field lines in the form of waves.

The next jerk may already be under way. A recent analysis by Huang and Duan predicted that the next event would occur in 2020 or 2021.

If that's the case, scientists may need to update magnetic maps on which industry and government activities rely. Companies drilling for oil and gas, for example, use fine-tuned magnetic models to dig boreholes. But not all jerks cause directional changes, so time will tell what the outcome will be.

It's too soon to know whether a jerk is happening right now, however. Finlay, part of a group that publishes magnetic field models every 6 months, said it's impossible to identify geomagnetic jerks until well after they've happened because researchers must look at the data over time. It would take about 2 years to know for sure, Finlay said.

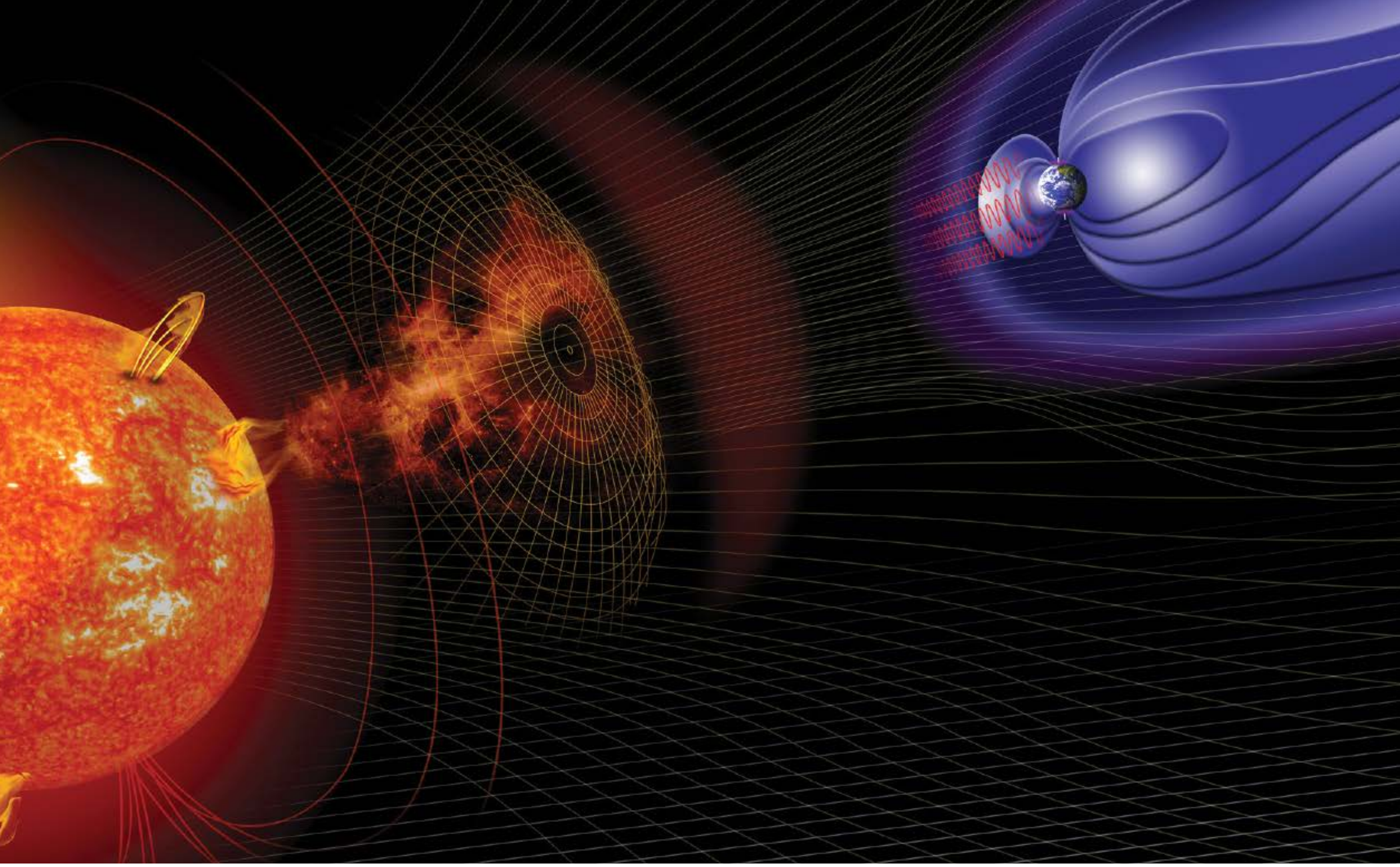
Regardless of whether the next event is upon us, geomagnetic jerks are one part of seeing the "elephant" of Earth's magnetic field. Jerks may illuminate the core's thermal properties, a hotly debated topic that affects our ideas about everything from the age of the core to the onset of plate tectonics.

Solving the mystery of the jerk's origin will remove a "stumbling block" of future magnetic field predictions, said Aubert, something we'll sorely need to better understand our planet's protective armor.

AVOIDING DOOMSDAY

Vladimir Airapetian does not mince words when it comes to apocalyptic scenarios and our magnetic field.

In one grim scenario, a catastrophically massive solar flare envelops Earth and knocks out the ozone layer, exposing us to damaging ultraviolet radiation known to cause cancer. In the 6–12 months it would take to rebuild our ozone layer, we'd live like "nocturnal animals," Airapetian said.



An artist's rendering shows a solar flare leaving the Sun and hurtling toward Earth. Credit: NASA

"You'd have to go underground and go out during the nighttime," said Airapetian, a NASA scientist at the Goddard Space Flight Center. "That's the Hollywood-type scenario."

Tales of our field catastrophically failing are part of the lore of working on Earth's magnetic field. People always want to know, "When is the really, really bad stuff happening?" said Aubert.

Although the prevailing science suggests that these doomsday scenarios are possible, they are highly unlikely. Earth's magnetic field is fickle, cratered, and ever changing, but scientists have no reason to believe that the field won't protect us for decades—and most likely centuries—to come.

Even one of the most dramatic of the scenarios, a magnetic reversal, is implausible in the foreseeable future. The last reversal occurred 780,000 years ago, and over the multibillion-year lifetime of the magnetic field, researchers guess that the poles have switched hundreds of times.

But scientists have no compelling evidence to suggest that a field reversal is upon us, said Catherine Constable, a scientist at Scripps Institution of Oceanography who studies magnetic reversals. The field changes so gradually that we'll have fair warning, at least a few decades, Constable said.

Perhaps the more worrisome danger comes from space. The magnetic field is our main line of defense against the onslaughts of high-energy particles from the Sun. Recent research by Airapetian suggests that gigantic solar flares are possible in our solar system. Observations of other stars similar to the Sun reveal that our Sun may be capable of shooting out a flare of epic proportions.

The next jerk may be already under way.

Congress passed PROSWIFT (Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act) in 2020 to pour money into space weather research, which the act's authors called a matter of national security. Heliophysics is the smallest division at NASA, so Airapetian is "so excited" for the additional funding and support to discover what space hazards lie ahead.

Until then, our magnetic field will continue to do what it does best: drift, shiver, and morph into its next grand configuration.

AUTHOR INFORMATION

Jenessa Duncombe (@jrdscience), Staff Writer

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▶ **Read the article at bit.ly/Eos-magnetic-weirdness**