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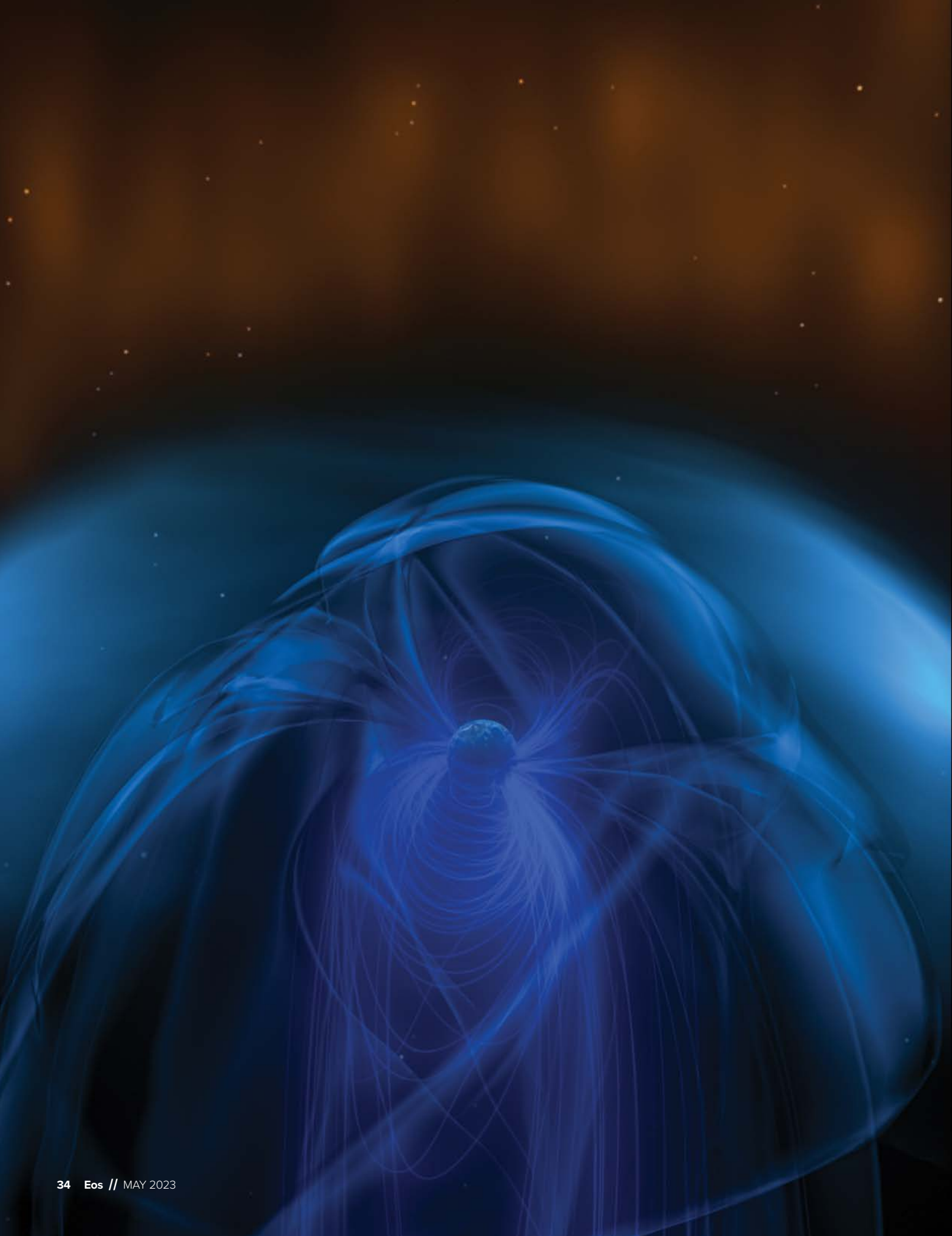
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SPACE RAINDROPS SPLASHING ON EARTH'S MAGNETIC UMBRELLA

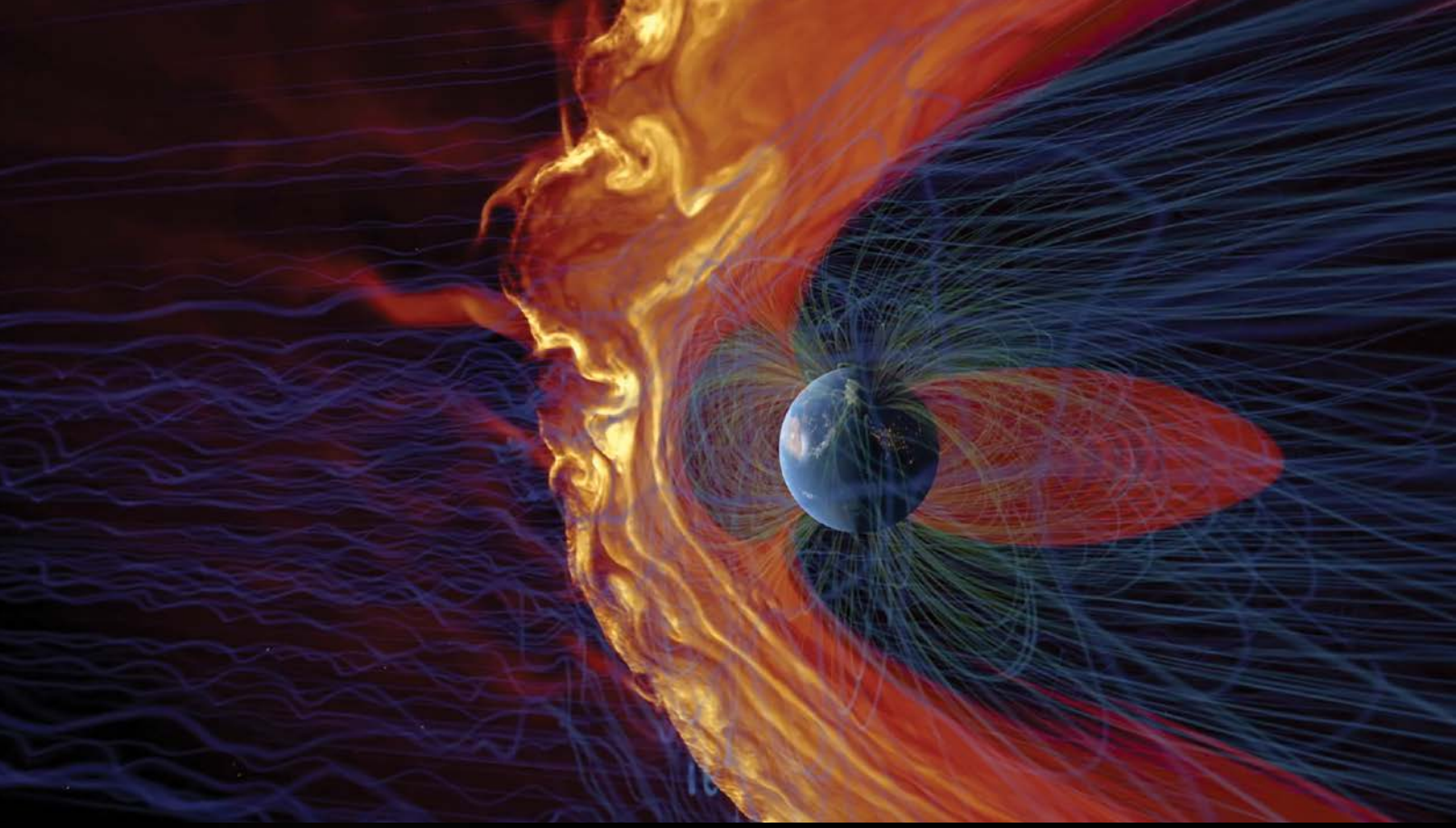
Though not as damaging as extreme space weather events, showers of fast plasma jets hit Earth's magnetic shield every day—and we're only beginning to understand their effects.

**By Laura Vuorinen, Adrian LaMoury, Emmanuel Masongsong,
and Heli Hietala**

Every few minutes, enormous “droplets” of plasma rain down from space toward Earth. Instead of crashing catastrophically to the ground, these droplets, called magnetosheath jets, are deflected by the outer reaches of Earth's magnetic field.

Despite the frequent occurrence of magnetosheath jets near Earth and their likely ubiquity across the solar system, their study is young and there is much we do not know about their origins and behavior. Specifically, their potential effects on space weather—the phenomena we experience on Earth due to the ever changing stream of plasma that flows through our solar system—are unclear and still being investigated. Therefore, these jets are currently not factored into space weather models or predictions. Here we discuss recent findings in this field and important questions that remain to be answered.

The interaction of solar wind plasma with Earth's umbrella-like magnetosphere creates regions in space known as the foreshock (brown shading) and bowshock (curved area of light blue shading). Credit: NASA/GSFC



Solar wind plasma interacts with Earth's magnetic field in this computer-generated visualization. Credit: Advanced Visualization Lab, National Center for Supercomputing Applications, University of Illinois, Urbana-Champaign (National Science Foundation award 1445176)

Earth's Umbrella

We live under a protective umbrella, or bubble, called the magnetosphere (Figure 1). This is the region where Earth's magnetic field shields us from the solar wind—the constant stream of plasma that flows from the Sun. The solar wind drags the Sun's magnetic field far into interplanetary space, where it clashes with other objects in the solar system. Were it not for Earth's own magnetic field, the solar wind would strip away our atmosphere, leaving our planet a barren rock like Mars.

The solar wind blows at hundreds of kilometers per second (~1 million miles per hour), squashing Earth's magnetosphere on the side nearest the Sun and dragging it out like a wind sock on the other side. The surface over which the competing pressures of the solar wind and the magnetosphere are balanced—the surface of the bubble, in other words—is called the magnetopause. The solar wind is highly variable, with its speed and magnetic field orientation constantly changing, and as the wind ebbs and flows, this surface compresses and expands to maintain the balance without bursting the bubble.

The solar wind is supersonic, and analogous to what happens when an airplane flies at supersonic speeds through the atmosphere, a shock wave—called the bow shock—forms outside the magnetosphere on the Sun-facing side. At this shock front, solar wind plasma is slowed, heated, and compressed, creating a turbulent layer known as the magnetosheath, and it is here that we find fast plasma jets.

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Space Weather Big and Small

We experience space weather because of our planet's interaction with the solar wind. Large and dramatic space weather events, such as explosive solar flares and coronal mass ejections, can have potentially catastrophic effects on modern civilization.

The famed Carrington event of 1859, the strongest coronal mass ejection ever observed, produced auroras as far south as Mexico and Cuba, with many people reporting the night sky to be as bright as day. The massive compression of the magnetosphere during the event caused severe and widespread damage to telegraph systems, resulting in the electrocution of operators and outbreaks of fires.

If such an event were to happen today, the disruption to our technology and infrastructure would be profound, with costs estimated to be in the trillions of dollars. From GPS failure to widespread electrical power outages, a Carrington-sized coronal mass ejection could bring the world to a standstill. It's hard to imagine a world where telephone and Internet communications are suddenly cut off, let alone one without power to charge devices.

Fortunately, events of this intensity are very infrequent compared with a human lifespan. They are among the least common natural disasters—the superhurricanes or giant earthquakes of the space weather world. Yet we experience less extreme forms of space weather every day, exemplified by the dazzling auroras at high northern and southern latitudes, which are consequences of solar wind interacting with our magnetosphere.

Forecasting occasional major hurricanes is crucial for public safety and survival, but on a regular basis, most people are more interested in whether their local forecast calls for rain. Similarly, while space weather scientists urgently look to forecast major events, we are also constantly monitoring the more mundane types of space weather activity and their fundamental effects. This is important both in space, to protect satellites and astronauts who are vulnerable to energetic particles, and on Earth, where the induced currents from magnetic field disturbances can cause gradual degradation in power transformer stations and other infrastructure, such as pipelines and rail lines.

Magnetosheath Jets: Space Rain

Magnetosheath jets rain on Earth's magnetosphere every day [Plaschke *et al.*, 2018]. As the solar wind is processed, slowed down, and compressed at the bow shock, jets can sporadically emerge, influenced by the structure of the shock itself.

The global-scale geometry of the bow shock is important. The bow shock's curvature and the orientation of the interplanetary magnetic field carried by the solar wind determine the structure of the shock and how it processes the solar wind. Zooming in, spacecraft observations and model simulations show us that shock regions where the interplanetary magnetic field is perpendicular to the shock surface look completely different from regions where the magnetic field is almost aligned with the shock surface (Figure 1).

In regions where the magnetic field is perpendicular to the shock surface, the shock transition is extended and the shock surface is corrugated, as opposed to the more abrupt transition and simpler structure where the magnetic field and the shock surface are more closely aligned.

The explanation for this difference is rooted in geometry. At shock regions where the solar wind magnetic field is perpendicular to the shock, solar wind particles can reflect off the shock and travel far back away from Earth along incident magnetic field lines. These reflected particles collectively form a turbulent region—the foreshock—because of their interaction with the incoming solar wind. The adjacent shock region is also affected, becoming corrugated and rippled.

When the solar wind flows through such a ripple at the shock, it is not slowed as much as the surrounding solar wind is. Thus, fast magnetosheath jets can emerge when the solar wind flows through a rippled shock. In

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addition, plasma structures from the turbulent foreshock can cross the shock, emerging as jets. Because the formation of jets is linked to the foreshock, jets are most often observed when the solar wind magnetic field lines are pointed directly from Earth to the Sun, known as radial interplanetary magnetic field conditions. During these conditions, the foreshock is present at the nose of Earth's bow shock.

Once jets have formed, they travel through the magnetosheath toward Earth, plowing through the surrounding slower plasma with dynamic pressure comparable to the upstream solar wind. Some jets dissipate along the way, but many of them survive the journey across the whole magnetosheath and eventually collide with high

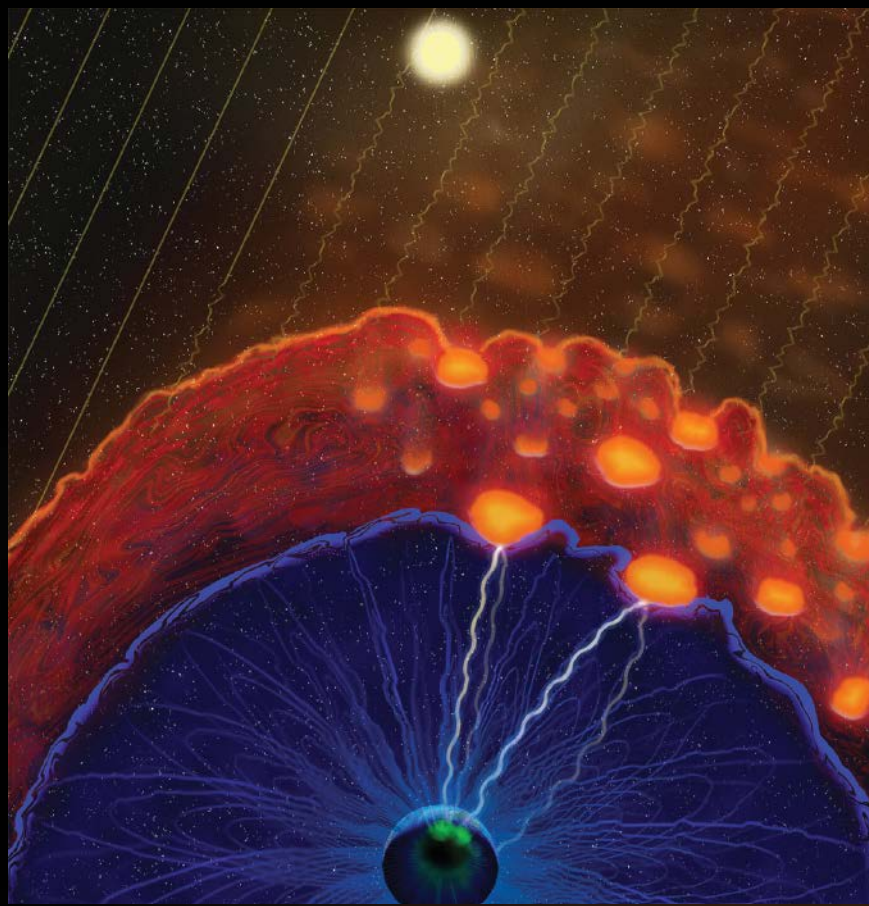


Fig. 1. The solar wind with its interplanetary magnetic field (yellow lines) flows from the Sun and forms a shock wave called the bow shock (bright orange line) where it meets Earth's magnetic field upstream of the planet. At the bow shock, the solar wind is slowed, except for fast plasma jets (orange globules) emerging from where the shock wave is corrugated, adjacent to the turbulent foreshock region (brown shading at top right). Jets travel through the magnetosheath (red swirls), and eventually, some of them hit the magnetopause (bright blue line), the outer edge of Earth's magnetosphere (blue shading). Earth's magnetic field (faint blue lines) and an aurora in Earth's ionosphere are also represented. Credit: E. Masongsong, H. Hietala, L. Vuorinen, A. LaMoury

momentum into the boundary of Earth's magnetosphere, the magnetopause (Figure 2).

These collisions may indent the magnetopause, perturbing the outer edge of the magnetosphere and setting in motion a chain of events spanning from the magnetosphere all the way to the ionosphere. The magnetopause surface can rebound, for example, vibrating like the skin of a drum and launching plasma waves into the magnetosphere. Jet impacts also have been linked to observations of the aurora. To forecast the potential space weather effects of jets, we must understand the conditions under which they occur and when they will hit the magnetopause at the highest rates.

When It Rains, It Pours

Our knowledge of magnetosheath jets relies on data captured by spacecraft surveying the near-Earth electromagnetic environment. Launched in 2007 and still going strong, NASA's THEMIS-ARTEMIS five-satellite mission in particular has greatly enhanced our understanding of many areas of space and space weather, from the solar wind and its interactions with Earth's magnetic field to the aurora and even plasmas around the Moon.

In a recent study using THEMIS data, researchers observed that the frequency of jets reaching the magnetopause is highly dependent on the properties of the solar wind at the bow shock [LaMoury *et al.*, 2021]. They found that when the solar wind's magnetic field is nearly radial, jets are expected to hit the magnetopause every few minutes—that is, more than 17 times more often than when the solar wind's magnetic field reaches Earth at an oblique angle. They also found that more jets arose during intervals of “fast” solar wind (which travels about twice the normal velocity). These intervals vary with the 11-year solar cycle, so the number of jets hitting the magnetopause may exhibit the same periodic dependence.

In addition to controlling the structure of different bow shock regions, the orientation of the solar wind magnetic field influences what happens at the magnetopause. Zooming in on this boundary where the solar wind magnetic field meets Earth's magnetic field, we see that geometry comes into play once again.

Namely, if the solar wind magnetic field is oriented southward, opposite to Earth's northward magnetic field, erosion of the magnetopause can occur via a process known as magnetic reconnection (Figure 2). Reconnection is a key process in plasma physics, in which the connectedness of magnetic field lines is fundamentally changed and energy stored in the magnetic field is explosively released.

In the case of the magnetopause, antiparallel field lines of the solar wind connect with those of Earth, peeling them away from the Sun-facing side of the magne-

to-sphere. This has the effect of weakening Earth's magnetic shield, allowing solar wind plasma and energy to enter Earth's magnetosphere. Thus, one of the most critical aspects of forecasting space weather is monitoring the solar wind magnetic field orientation far upstream of Earth.

Although measuring the north-south component of the solar wind magnetic field before it arrives at Earth (together with solar wind speed and density) can help us prepare for space weather storms, it does not give us the full picture of how space weather evolves at Earth. Much more frequent rain showers (i.e., jets) may play a role that, until recently, was not considered to control magnetic reconnection, sparking debate in the magnetospheric physics community. Jets, because of their high dynamic pressure, have been observed compressing the magnetopause boundary, which helps initiate reconnection, as opposite magnetic fields are being pushed together more efficiently [Hietala *et al.*, 2018].

In addition, researchers have suggested that the magnetic field orientation in jets may be different from field orientations in the surrounding magnetosheath. Nykyri *et al.* [2019] observed jets with

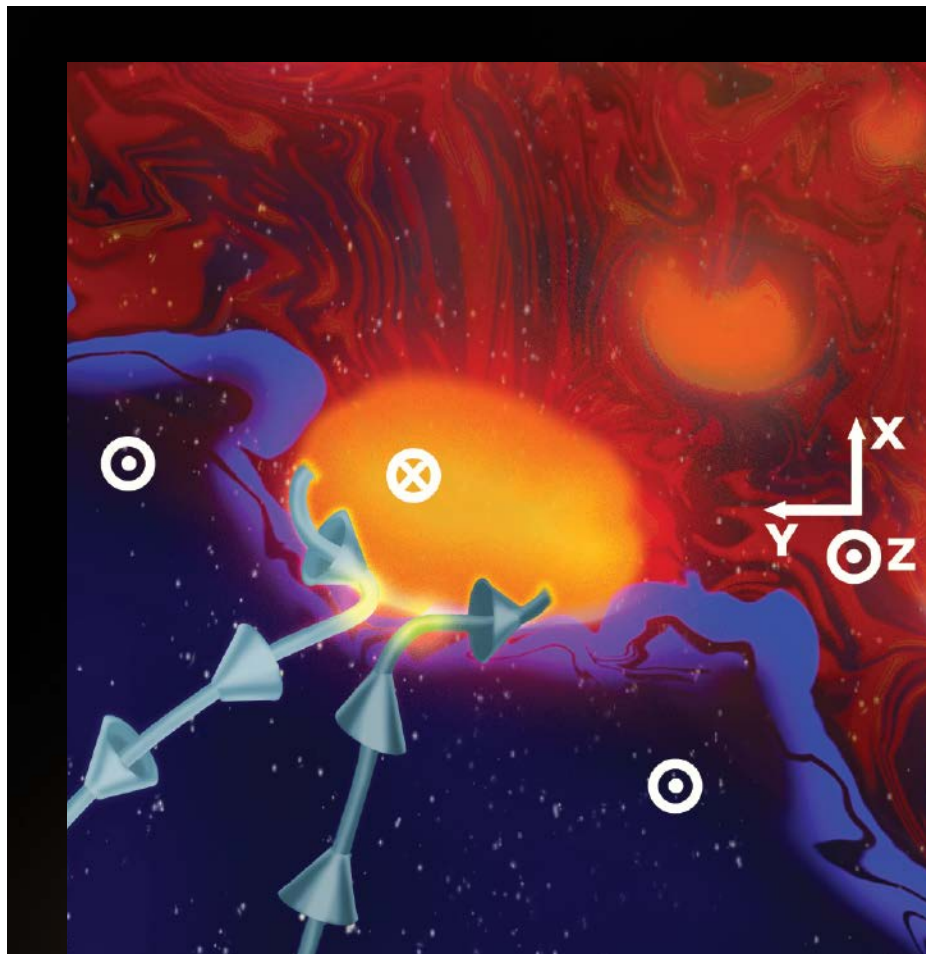


Fig. 2. Antiparallel magnetic field lines can merge during magnetic reconnection, which transforms magnetic energy into the kinetic energy of particles. At Earth's magnetopause (bright blue), this can happen when Earth's northward-oriented (⊙) magnetic field (gray curve with conical arrows) meets a plasma jet (orange globule) with southward-oriented (⊗) magnetic field. Credit: E. Masongsong, H. Hietala, L. Vuorinen, A. LaMoury, F. Beyene

southward magnetic fields propagating toward the magnetopause and triggering reconnection despite measurements at the time showing that the solar wind magnetic field was oriented northward. This was likely not an isolated occurrence, and it caused a chain of events leading to increased geomagnetic activity on the nightside of the magnetosphere, opposite from the Sun.

Vuorinen *et al.* [2021] performed a statistical study of the north–south component in jets versus the surrounding magnetosheath using THEMIS data, further confirming that jets often carry southward magnetic fields even when the solar wind magnetic field is northward. The combination of jets compressing and introducing southward fields to the magnetopause may be favorable for triggering reconnection, even during solar wind conditions when we are not typically expecting it. This result highlights the importance of studying the magnetosphere’s behavior during times of a radial interplanetary magnetic field.

Ongoing Efforts and Unanswered Questions

Thus far, we have considered jets only in Earth’s magnetosheath. However, it is very likely that jets arising from rippled shock surfaces exist elsewhere in the solar system and beyond. Therefore, by studying jets in near–Earth space, we are potentially learning about processes taking place around other planets like Venus and Jupiter, as well as at shocks driven by coronal mass ejections or even at huge astrophysical shocks such as those arising from supernovas.

Many aspects of jets are still debated. In addition to their formation at ripples in shock surfaces, other formation mechanisms have been proposed. Raptis *et al.* [2022], for example, provided evidence that pockets of fast solar wind trapped downstream of the shock can become jets as the shock surface is regenerated at a new position, in a natural cycle of shock reformation. It is not entirely clear how differ-

ent mechanisms may relate to the inherent properties of jets seen in the magnetosheath. In particular, the behavior of the magnetosphere during times of radial interplanetary magnetic field is not as well studied as the extreme cases of strong southward or northward field. As our understanding of jets increases, we expect that they will come to be considered a fundamental part of Earth’s complex magnetospheric system.

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