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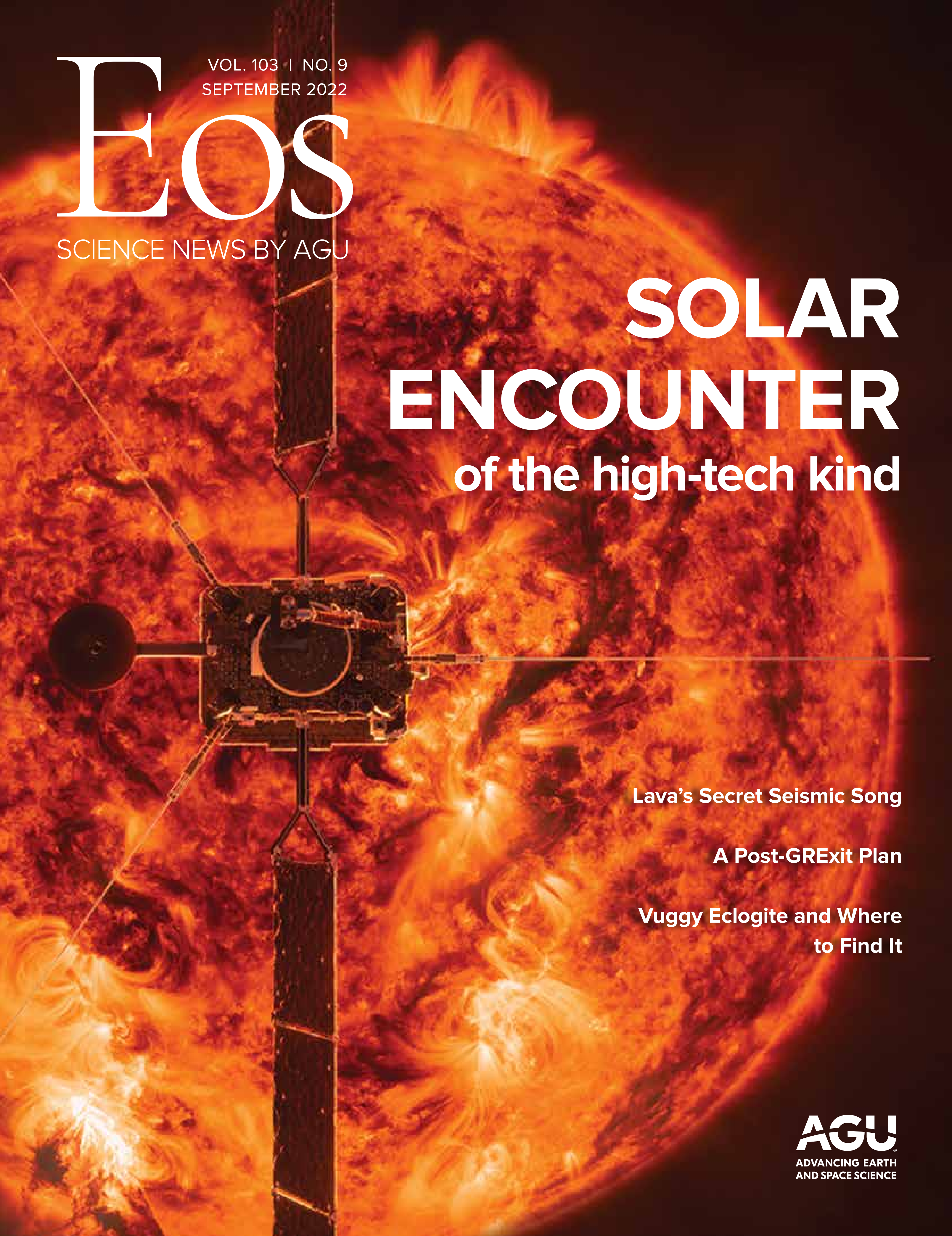

SOLAR ENCOUNTER

of the high-tech kind

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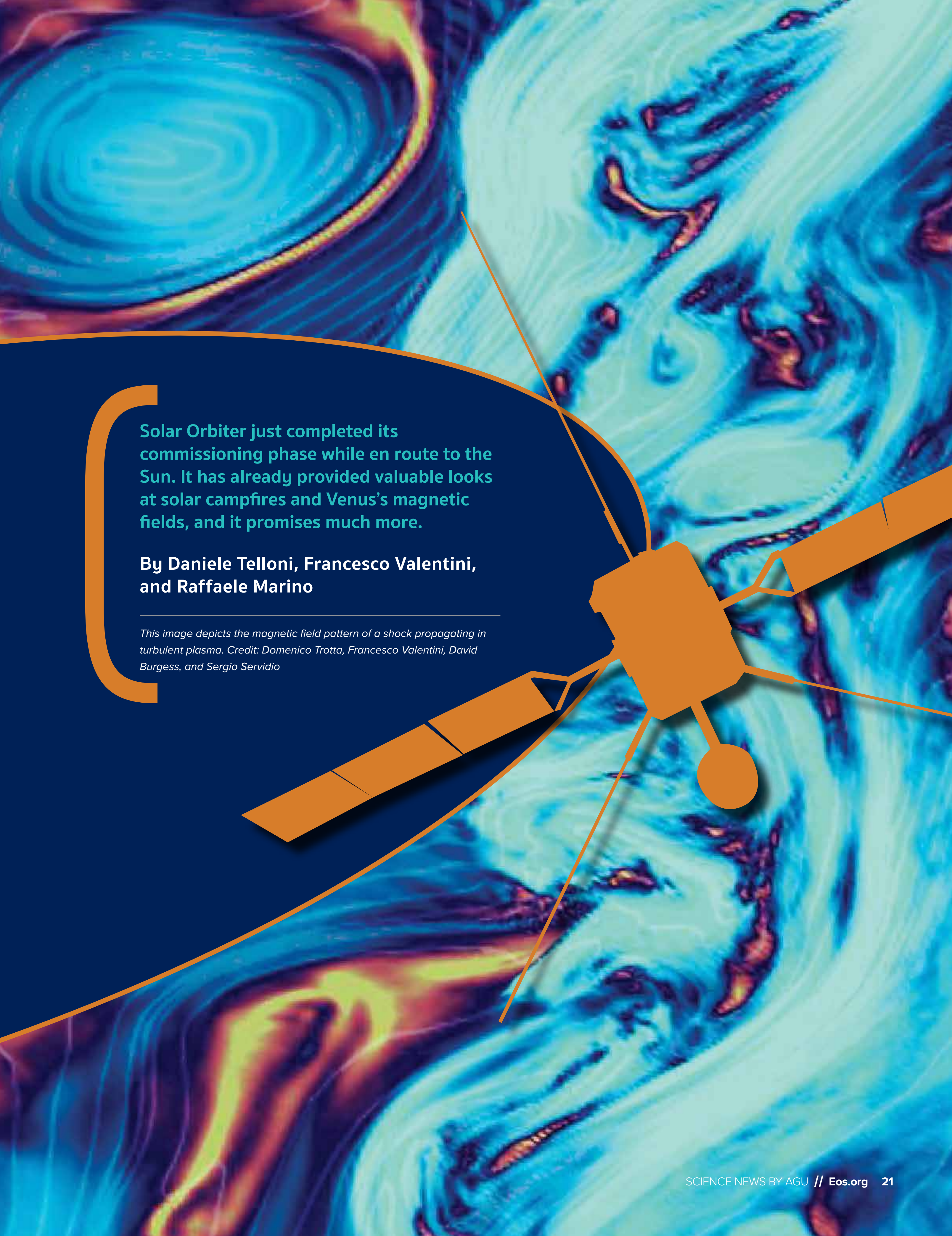
ADVANCING EARTH
AND SPACE SCIENCE

A NEW JOURNEY AROUND (AND AROUND) THE SUN



Solar Orbiter just completed its commissioning phase while en route to the Sun. It has already provided valuable looks at solar campfires and Venus's magnetic fields, and it promises much more.

By Daniele Telloni, Francesco Valentini, and Raffaele Marino

This image depicts the magnetic field pattern of a shock propagating in turbulent plasma. Credit: Domenico Trotta, Francesco Valentini, David Burgess, and Sergio Servidio

The Sun is one of billions of stars forming the Milky Way, which is, in turn, one of the billions of galaxies populating the universe. Yet to us, the Sun is not simply one of many stars. It is the most important celestial body, both sustaining life on Earth and posing persistent hazards in the form of damaging radiation. It is also the only star we have direct access to by means of robotic probes—or by the observations of our own eyes.

> **Among the groundbreaking observations that Solar Orbiter has made already are those of short-lived, small-scale flickering bright spots, nicknamed "campfires," in the solar corona.**

Indeed, generations of scientists, since Galileo Galilei in the 16th and 17th centuries and even before, have used observations of the Sun to investigate a large variety of astrophysical phenomena, from the formation of stars to the origins of stars' self-sustained magnetic fields. These fields are responsible for violent, impulsive events on our star, such as flares and coronal mass ejections (CMEs), which sometimes direct bursts of high-energy ionized particles, or plasmas, toward our planet.

Studying how our Sun interacts with the surrounding region it influences, called the heliosphere, has further allowed us to investigate physical processes that are ubiquitous in the universe. One such process, magnetic reconnection, involves the breaking and rejoining of oppositely directed magnetic field lines that occur during various phenomena, including CMEs, and can release tremendous amounts of energy. Another is turbulence (famously called by Richard Feynman the most important unsolved problem of classical physics), which contributes to the acceleration of particles in space and plays an important role in the dynamic and energetic processes of the solar environment.

It is therefore not surprising that some of the most important missions of the space exploration era have focused on observing the Sun and the solar wind, the plasma flow that continuously expands from the Sun's outer atmosphere, or corona, into the heliosphere. Now a new mission, Solar Orbiter, is set to advance our understanding further—in fact, it is already doing so.

The Closest Look Yet at the Sun

Solar Orbiter, a joint mission of the European Space Agency (ESA) and NASA, was successfully launched from Kennedy Space Center in Florida on 10 February 2020 [*Müller et al.*, 2020]. The mission is one of the most technologically advanced and recent assets in a series of large ground-based and space-based solar observatories, with the latter group including Skylab, Solar Maximum Mission, Solar and Heliospheric Observatory, Parker Solar Probe, and others.

Solar Orbiter's main purpose is to help us achieve a better understanding of how the Sun creates and controls the heliosphere and why solar activity changes with time. The spacecraft is the first to carry both remote sensing and in situ instruments (10 in total) so close to the Sun—about 42 million kilometers away, or one third of the Earth-Sun distance, at its closest. With each orbit of the Sun and with gravitational assists from Venus, it will gradually lift out of the orbital plane (ecliptic) of the planets in our solar system, potentially reaching orbital planes with inclinations of up to about 33° from the ecliptic.

Thanks to its unique payload and the range of tilted orbits it will cover, Solar Orbiter will observe the Sun from different perspectives and take the closest images of the star ever. It will also observe, for the first time, the solar magnetic poles, regions where most of the so-called fast solar wind originates and the polarity of the Sun's magnetic field reverses periodically [*Zouganelis et al.*, 2020]. The synergy of remote sensing and in situ observations collected by Solar Orbiter will enable scientists to connect transient magnetic events and the continuous solar wind to their sources on the Sun.

Campfires on the Sun, Magnetic Fields on Venus

Solar Orbiter's data production routine officially started on 27 November 2021 after more than a year and a half of commissioning as the spacecraft was en route toward its first production orbit. Even before then, however, it had revealed new discoveries about the Sun. Several of these results have been collected in a special issue of *Astronomy and Astrophysics* (bit.ly/solar-orbiter-first).

Among the groundbreaking observations that Solar Orbiter has made already are those of short-lived, small-scale flickering bright spots, nicknamed "campfires," in the solar corona. These tiny flares, which had eluded observation by previous spacecraft, were first imaged in May 2020 by the Extreme Ultraviolet Imager (EUI) on board Solar Orbiter [*Berghmans et al.*, 2021].

From the recent images, scientists found that these fine structures cover the entire solar surface and occur far more frequently than larger flares. And they are now thought to contribute significantly to the extreme heating of the corona, although exactly how is not clear. The corona, where temperatures can rise to upward of 1 million degrees Celsius, is much hotter than the material below it—a seeming paradox that has puzzled solar physicists for many years. Campfires may be the missing piece of the puzzle, explaining how energy is released, transported, and eventually converted into heat in the corona.

Although Solar Orbiter's main objective is to shed new light on unsolved mysteries of the Sun, the mission has also offered insights into our neighboring planet Venus. During its first Venus flyby in December 2020, Solar Orbiter revealed new details of the planet's unusual magnetic configuration [*Allen et al.*, 2021]. In particular, scientists verified that Venus's magnetosphere, which is generated by the interaction of the solar

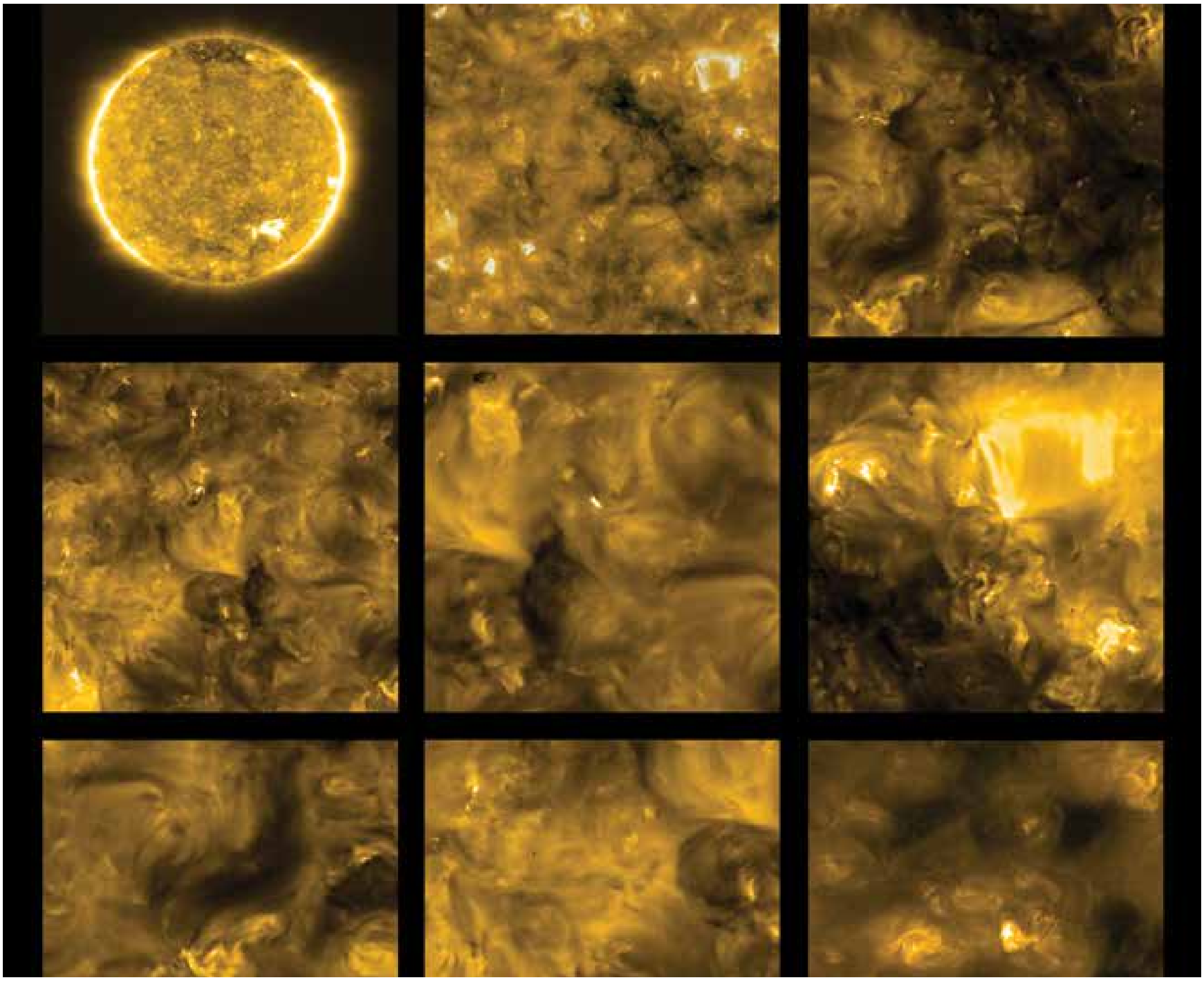
The Solar Orbiter spacecraft approaches the Sun in this artist's illustration. Credit: European Space Agency wind with the planet's ionosphere, protrudes behind the planet to form a magnetotail up to 300,000 kilometers long. Scientists already knew about Venus's unusual magnetosphere from previous missions in the 1960s and 1980s; however, they didn't know until now how far an induced magnetosphere could extend before it falls apart.

Using measurements from the Energetic Particle Detector (EPD) aboard the spacecraft, Solar Orbiter also found that Venus's magnetosphere is able to accelerate plasma particles to millions of kilometers per hour through multiple mechanisms, including wave-particle interactions, turbulence, and current sheet crossings (which involve electrical currents confined to a surface). These findings allowed researchers to speculate about the formation and evolution of exoplanet magnetospheres outside our solar system, which cannot be observed directly with current technologies. To this end, it is crucial to confirm and corroborate measurements made by modern spacecraft with modeling of poorly accessible astrophysical objects and phenomena. State-of-the-art numerical simulations are an indispensable tool in this regard because they can realistically reproduce the dynamics and physical conditions of interplanetary plasmas.

For example, recent numerical experiments explained how the interaction of shocks and plasma turbulence in the magnetosphere of Venus can accelerate particles and play a role in the process of plasma heating [*Trotta et al.*, 2021], thus supporting analyses of observational evidence from Solar Orbiter. The synergistic use of measurements and numerical modeling is central to the exploitation of the unprecedented observations made by Solar Orbiter.

Pairing with Parker

Companion observations made by Solar Orbiter and NASA's Parker Solar Probe [*Fox et al.*, 2016] offer unique opportunities for comprehensive study of our star and its environment [*Velli et al.*, 2020], as well as of how this environment evolves with



In May 2020, the Extreme Ultraviolet Imager (EUI) on board Solar Orbiter spotted tiny flares in the Sun's corona called "campfires." These features are visible as small bright spots in these images acquired at a wavelength of 17 nanometers. Credit: Solar Orbiter/EUI Team/ESA and NASA; CSL, IAS, MPS, PMOD/WRC, ROB, UCL/MSSL distance from the Sun and with solar activity. These opportunities arise because of the complementary trajectories covered by Solar Orbiter and Parker Solar Probe as they orbit around the Sun. Thanks to seven Venus flybys, Parker Solar Probe will gradually shrink its orbit around the Sun, coming as close as 6.16 million kilometers to the Sun, about 7 times closer than any spacecraft has come before.

When the angular separation between the two spacecraft is 90°, with the Sun at the vertex of the angle, the coronal sources of local plasma phenomena—observed in situ by Parker Solar Probe—can be determined using the remote sensing instruments aboard Solar Orbiter. The first such "quadrature" configuration, which occurred in January 2021, allowed scientists to track, for the first time, the same plasma volume as it expands from the extended corona to the very inner heliosphere. It also allowed them to infer crucial quantities in the wind acceleration region along the coronal current sheet, such as the flow-aligned magnetic field, the Alfvén radius (where the speeds of the solar wind and Alfvén waves are equal), and the bulk kinetic energy flux density of the solar wind [*Telloni et al.*, 2021b].

Similarly, radial alignments of the two spacecraft (i.e., when they are simultaneously in line with each other and the Sun) are key for investigating how plasma parcels in the solar wind evolve as they propagate outward. Analysis of the first such radial alignment, which occurred in September 2020, revealed that the solar wind evolves from a less developed turbulent state, dominated by Alfvénic fluctuations near the Sun, to a state of fully developed turbulence dominated by intermittent events in locations closer to Earth [*Telloni et al.*, 2021a].

Along with Parker Solar Probe, Solar Orbiter will also improve our capability to trace and forecast the propagation of the most powerful perturbations produced by solar activity, including coronal mass ejections, throughout the interplanetary medium, as well as to forecast impacts of these perturbations on the geospace environment. Monitoring heliospheric space weather in the short term and predicting how the Sun may affect power grids, as well as space-related technologies for telecommunication, transportation, and other applications, are of paramount importance given our increasing reliance on this infrastructure.

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Revealing Solar Secrets

People always have looked at the Sun with hope, wonder, and awe. A symbol of rebirth and the cyclical nature of life, an inspiration to poets, and an object of worship in ancient times, the Sun also has guarded secrets of the cosmos dating back to the origin of the universe.

> **Just as Prometheus stole fire—a symbol of knowledge—and gave it to humans, so Solar Orbiter will provide future generations with new knowledge about our star.**

Just as Prometheus stole fire—a symbol of knowledge—and gave it to humans, so Solar Orbiter will provide future generations with new knowledge about our star, offering a deeper understanding of how it operates and how it affects life for better and worse. But even if the mission results in the Sun holding fewer secrets—and even though, amid the vast universe, the Sun is a tiny yellow dot like the zillions of other bright dots sparkling in the sky—it will remain a beautiful source of wonder for us here on Earth.

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Author Information

Daniele Telloni (daniele.telloni@inaf.it), Astrophysical Observatory of Torino, National Institute for Astrophysics, Pino Torinese, Italy; **Francesco Valentini,** Department of Physics, University of Calabria, Rende, Italy; and **Raffaele Marino,** Laboratoire de Mécanique des Fluides et d'Acoustique, École Centrale de Lyon, Centre National de la Recherche Scientifique, Écully, France

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