The sun as you've never seen it before

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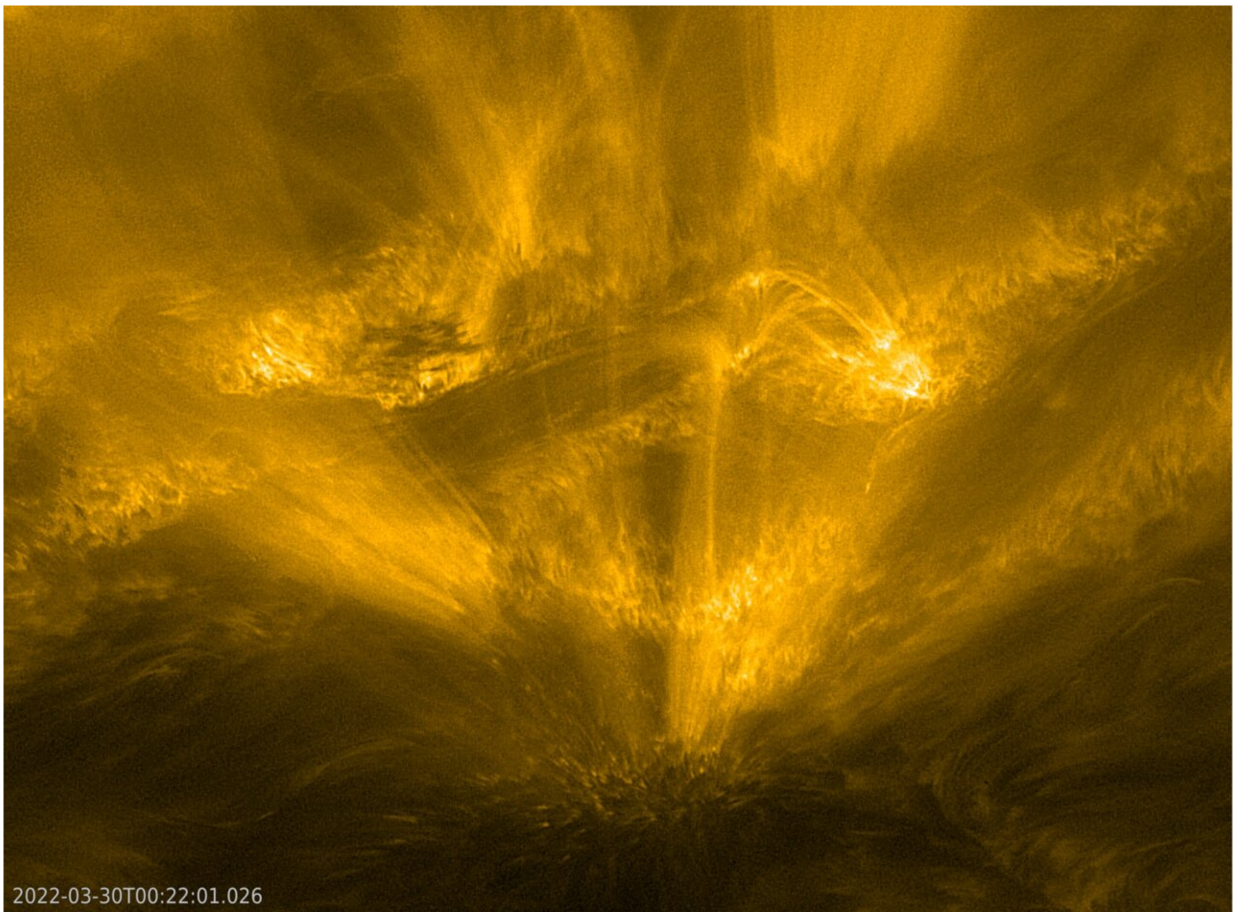


The intriguing feature in the bottom third of the image, below the centre, has been nicknamed the solar hedgehog. At present no one knows exactly what it is or how it formed in the sun's atmosphere. The image was captured on 30 March 2022 by the Extreme Ultraviolet Imager (EUI) at a wavelength of 17 nanometres. Just days earlier, Solar Orbiter had passed through its first close perihelion. At just 32 percent the distance of the Earth from the sun, this placed the spacecraft inside the orbit of the inner planet Mercury. Being closer to the sun than any previous solar telescope has allowed EUI to take exquisitely detailed images of the solar atmosphere. These are revealing the sun as never before, and have shown a multitude of intriguing features such as the hedgehog, which although classed as a small-scale feature still measures some 25 000 km across, making it around twice the diameter of the Earth. The gases shown in this image have a temperature of around one million degrees. The image has been colour coded because the original wavelength detected by the instrument is invisible to the human eye. Watch movies of the solar hedgehog here and here. Credit: ESA & NASA/Solar Orbiter/EUI Team

Powerful flares, breathtaking views across the solar poles, and a curious solar "hedgehog" are among the haul of spectacular images, movies and data returned by Solar Orbiter from its first close approach to the sun. Although the analysis of the new dataset has only just started, it is already clear that the ESA-led mission is providing the most extraordinary insights into the sun's magnetic behavior and the way this shapes space weather.

Solar Orbiter's closest approach to the sun, known as perihelion, took place on 26 March. The spacecraft was inside the orbit of Mercury, at about one-third the distance from the sun to the Earth, and its heatshield was reaching around 500°C. But it dissipated that heat with its innovative technology to keep the spacecraft safe and functioning.

Solar Orbiter carries ten science instruments—nine are led by ESA Member States and one by NASA—all working together in close collaboration to provide unprecedented insight into how our local star "works." Some are remote-sensing instruments that look at the sun, while others are in-situ instruments that monitor the conditions around the spacecraft, enabling scientists to "join the dots" from what they see happening at the sun, to what Solar Orbiter "feels" at its location in the solar wind millions of kilometers away.

When it comes to perihelion, clearly the closer the spacecraft gets to the sun, the finer the details the remote sensing instrument can see. And as luck would have it, the spacecraft also soaked up several solar flares and even an Earth-directed coronal mass ejection, providing a taste of real-time space weather forecasting, an endeavor that is becoming increasingly important because of the threat space weather poses to technology and astronauts.

Introducing the solar hedgehog

"The images are really breathtaking," says David Berghmans, Royal Observatory of Belgium, and the Principal Investigator (PI) of the Extreme Ultraviolet Imager (EUI) instrument, which takes high-resolution images of the lower layers of the sun's atmosphere, known as the solar corona. This region is where most of the solar activity that drives space weather takes place.

The task now for the EUI team is to understand what they are seeing. This is no easy task because Solar Orbiter is revealing so much activity on the sun at the small scale. Having spotted a feature or an event that they can't immediately recognize, they must then dig through past solar observations by other space missions to see if anything similar has been seen before.

"Even if Solar Obiter stopped taking data tomorrow, I would be busy for years trying to figure all this stuff out," says David Berghmans.

One particularly eye-catching feature was seen during this perihelion. For now, it has been nicknamed "the hedgehog." It stretches 25,000 kilometers across the sun and has a multitude of spikes of hot and colder gas that reach out in all directions.

Joining the dots

Solar Orbiter's main science goal is to explore the connection between the sun and the heliosphere. The heliosphere is the large "bubble" of space that extends beyond the planets of our Solar System. It is filled with electrically charged particles, most of which have been expelled by the sun to form the solar wind. It is the movement of these particles and the associated solar magnetic fields that create space weather.

To chart the sun's effects on the heliosphere, the results from the in-situ instruments, which record the particles and magnetic fields that sweep across the spacecraft, must be traced back to events on or near the visible surface of the sun, which are recorded by the remote sensing instruments.

This is not an easy task as the magnetic environment around the sun is highly complex, but the closer the spacecraft can get to the sun, the less complicated it is to trace particle events back to the sun along the "highways" of magnetic field lines. The first perihelion was a key test of this, and the results so far look very promising.

On 21 March, a few days before perihelion, a cloud of energetic particles swept across the spacecraft. It was detected by the Energetic Particle Detector (EPD). Tellingly, the most energetic of them arrived first, followed by those of lower and lower energies.

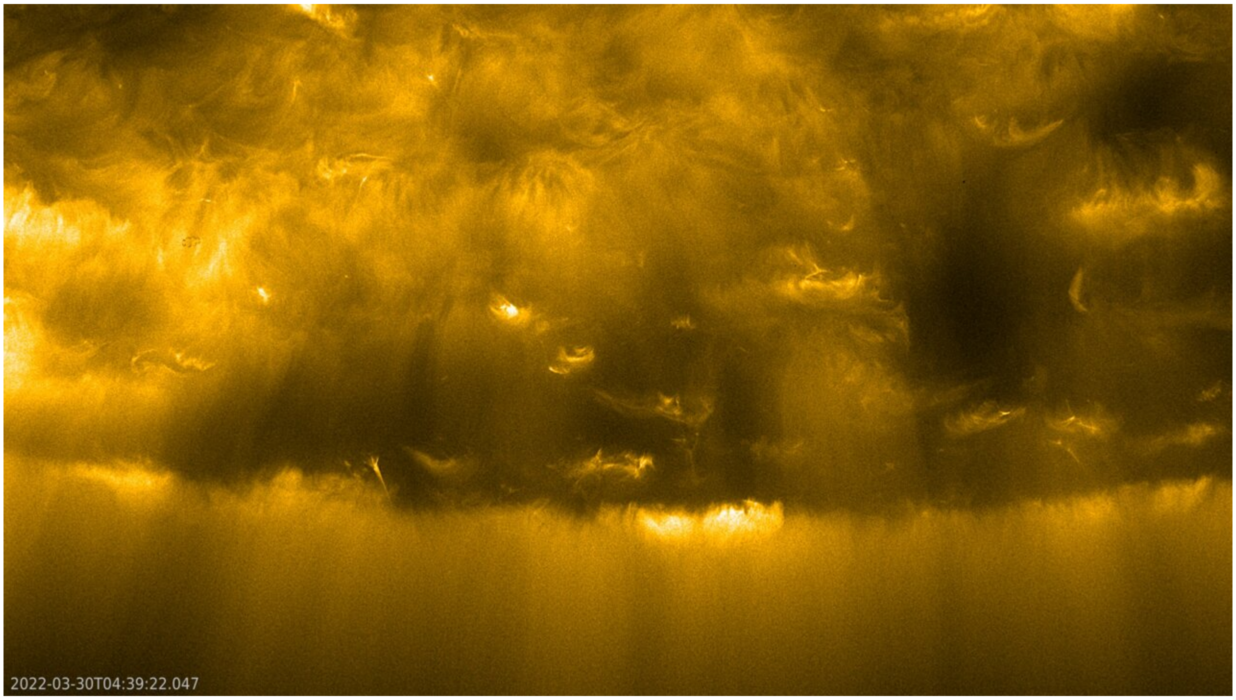
"This suggests that the particles are not produced close to the spacecraft," says Javier Rodríguez-Pacheco, University of Alcalá, Spain, and EPD's PI. Instead, they were produced in the solar atmosphere, nearer the sun's surface. While crossing space, the faster particles pulled ahead of the slower ones, like runners in a sprint.

On the same day, the Radio and Plasma Waves (RPW) experiment saw them coming, picking up the strong characteristic sweep of radio frequencies produced when accelerated particles—mostly electrons—spiral outwards along the sun's magnetic field lines. RPW then detected oscillations known as Langmuir waves. "These are a sign that the energetic electrons have arrived at the spacecraft," says Milan Maksimovic, LESIA, Observatoire de Paris, France, and RPW PI.

Of the remote sensing instruments, both EUI and the X-ray Spectrometer/Telescope (STIX) saw events on the sun that could have been responsible for the release of the particles. While the particles that stream outwards into space are the ones that EPD and RPW detected, it is important to remember that other particles can travel downwards from the event, striking the lower levels of the sun's atmosphere. This is where STIX comes in.

While EUI see the ultraviolet light released from the site of the flare in the atmosphere of the sun, STIX see the X-rays that are produced when electrons accelerated by the flare interact with atomic nuclei in the lower levels of the sun's atmosphere.

Exactly how these observations are all linked is now a matter for the teams to investigate. There is some indication from the composition of the particles detected by EPD that they were likely accelerated by a coronal shock in a more gradual event rather than impulsively from a flare.



The sun's south pole as seen by the ESA/NASA Solar Orbiter spacecraft on 30 March 2022, just four days after the spacecraft passed its closest point yet to the sun. These images were recorded by the Extreme Ultraviolet Imager (EUI) at a wavelength of 17 nanometers. Watch movie version here. Many scientific secrets are thought to lie hidden at the solar poles. The magnetic fields that create the great but temporary active regions on the sun get swept up to the poles before being swallowed back down into the sun where they are thought to form the magnetic seeds for future solar activity. The lighter areas of the image are mostly created by loops of magnetism that rise upwards from the solar interior. These are called closed magnetic field lines because particles find it hard to cross them, and become trapped, emitting the extreme ultraviolet radiation that EUI is specially designed to record. The darker areas are regions where the sun's magnetic field lies open, and so the gasses can escape into space, creating the solar wind. Starting in 2025, Solar Orbiter will use the gravitational pull of Venus to gradually crank up the inclination of its orbit. This will allow the spacecraft's instruments to investigate the solar poles from a more top-down viewpoint. The colour on this image has been artificially added because the original wavelength detected by the instrument is invisible to the human eye. Credit: ESA & NASA/Solar Orbiter/EUI Team

"It could be that you have multiple acceleration sites," says Samuel Krucker, FHNW, Switzerland, and PI for STIX.

Adding another twist to this situation is that the Magnetometer instrument (MAG) did not register anything substantial at the time. However, this is not unusual. The initial eruption of particles, known as a Coronal Mass Ejection (CME), carries a strong magnetic field that MAG can easily register, but energetic particles from the event travel much faster than the CME and can rapidly fill large volumes of space, and therefore be detected by Solar Orbiter. "But if the CME misses the spacecraft, then MAG will not see a signature," says Tim Horbury, Imperial College, U.K., and MAG PI.

When it comes to the magnetic field, it all begins at the sun's visible surface, known as the photosphere. This is where the internally generated magnetic field bursts into space. To know what this looks like, Solar Orbiter carries the Polarimetric and Helioseismic Imager (PHI) instrument. This can see the north and south magnetic polarity on the photosphere, as well as the rippling of the sun's surface due to seismic waves traveling through its interior.

"We provide the magnetic field measurements at the surface of the sun. This field then expands, goes into the corona and basically drives all the sparkle and action you see up there," says Sami Solanki, Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany, and the PI for PHI.

Another instrument, the Spectral Imaging of the Coronal Environment (SPICE), records the composition of the corona. These "abundance maps" can be compared to the contents of the solar wind seen by the Solar Wind Analyser (SWA) instrument.

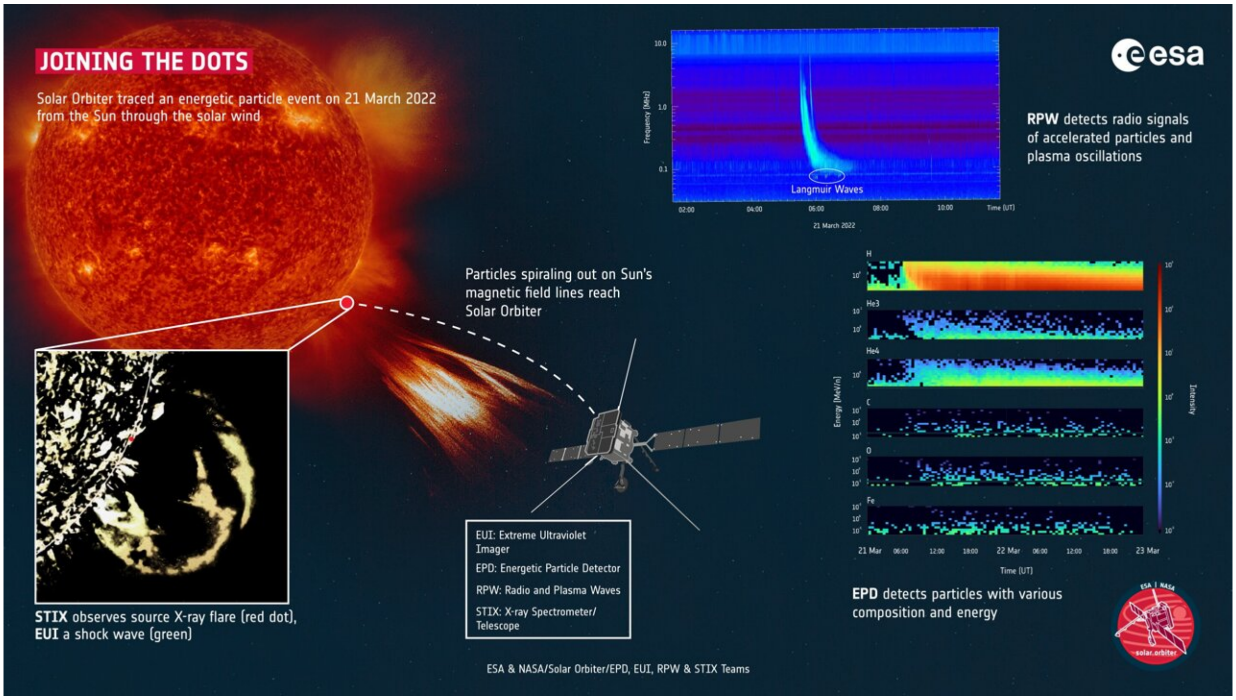
"This will track the evolution of the composition of the solar wind from the sun to the spacecraft, and that tells us about the mechanisms responsible for the acceleration of the solar wind," says SPICE PI Frédéric Auchère, Institut d'Astrophysique Spatiale, France.

Forecasting space weather

By combining data from all instruments, the science team will be able to tell the story of solar activity from the surface of the sun, out to Solar Orbiter and beyond. And that knowledge is exactly what will pave the way for a future system designed to forecast the space weather conditions at Earth in real-time. In the lead-up to perihelion, Solar Orbiter even got a taste of how such a system might operate.

The spacecraft was flying upstream of the Earth. This unique perspective meant that it was monitoring the conditions of the solar wind that would hit Earth several hours later. Since the spacecraft was in direct contact with the Earth, with its signals traveling at the speed of light, the data arrived on the ground within a few minutes, ready for analysis. As luck would have it, there were several coronal mass ejections (CME) detected around this time, some of them heading directly for Earth.

On 10 March, a CME swept over the spacecraft. Using data from MAG, the team were able to predict when it would subsequently hit Earth. Announcing this news on social media allowed sky watchers to be ready for the aurora, which duly arrived around 18 hours later at the predicted time.



Joining the dots of an energetic particle event. Credit: European Space Agency

This experience gave Solar Orbiter a taste of what it is like to forecast the space weather condition at Earth in real-time. Such an endeavor is becoming increasingly important because of the threat space weather poses to technology and astronauts.

ESA is currently planning a mission called ESA Vigil that will be stationed to one side of the sun looking into the region of space leading up to the Earth. Its job will be to image CMEs traveling through this region, especially those heading for our planet. During perihelion itself, Solar Orbiter was positioned so that its instruments Metis and SoloHI could provide exactly these kinds of images and data.

Metis takes pictures of the corona from 1.7–3 solar radii. By blotting out the sun's bright disk, it sees the fainter corona. "It gives the same details as ground based total eclipse observations, but instead of a few minutes, Metis can observe continuously," says Marco Romoli, University of Florence, Italy, and PI for Metis.

SoloHI records images made of sunlight scattered by the electrons in the solar wind. One particular flare, on 31 March, made it into the X-class, the most energetic solar flares known. As yet, the data has not been analyzed because much of it remains on the spacecraft waiting to be downloaded. Now that Solar Orbiter is further from the Earth, the data transfer rate has slowed and researchers must be patient—but they are more than ready to begin their analysis when it does arrive.

"We're always interested in the big events because they produce the biggest responses and the most interesting physics because you are looking at the extremes," says Robin Colaninno, U.S. Naval Research Laboratory, Washington DC, and SoloHI PI.

Coming soon

There is no doubt that the instrument teams now have their work cut out. The perihelion was a huge success and has generated a vast quality of extraordinary data. And it's just a taste of what is to come. Already the spacecraft is racing through space to line itself up for its next—and slightly closer—perihelion pass on 13 October at 0.29 times the Earth-sun distance. Before then, on 4 September, it will make its third flyby of Venus.

Solar Orbiter has already taken its first pictures of the sun's largely unexplored polar regions but much more is still to come.

On 18 February 2025, Solar Orbiter will encounter Venus for a fourth time. This is increase the inclination of the spacecraft's orbit to around 17 degrees. The fifth Venus flyby on 24 December 2026 will increase this still further to 24 degrees, and will mark the start of the "high-latitude" mission.

In this phase, Solar Orbiter will see the sun's polar regions more directly than ever before. Such line-of-sight observations are key to disentangling the complex magnetic environment at the poles, which may in turn hold the secret to the sun's 11-year cycle of waxing and waning activity.

"We are so thrilled with the quality of the data from our first perihelion," says Daniel Müller, ESA Project Scientist for Solar Orbiter. "It's almost hard to believe that this is just the start of the mission. We are going to be very busy indeed."

Provided by European Space Agency

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