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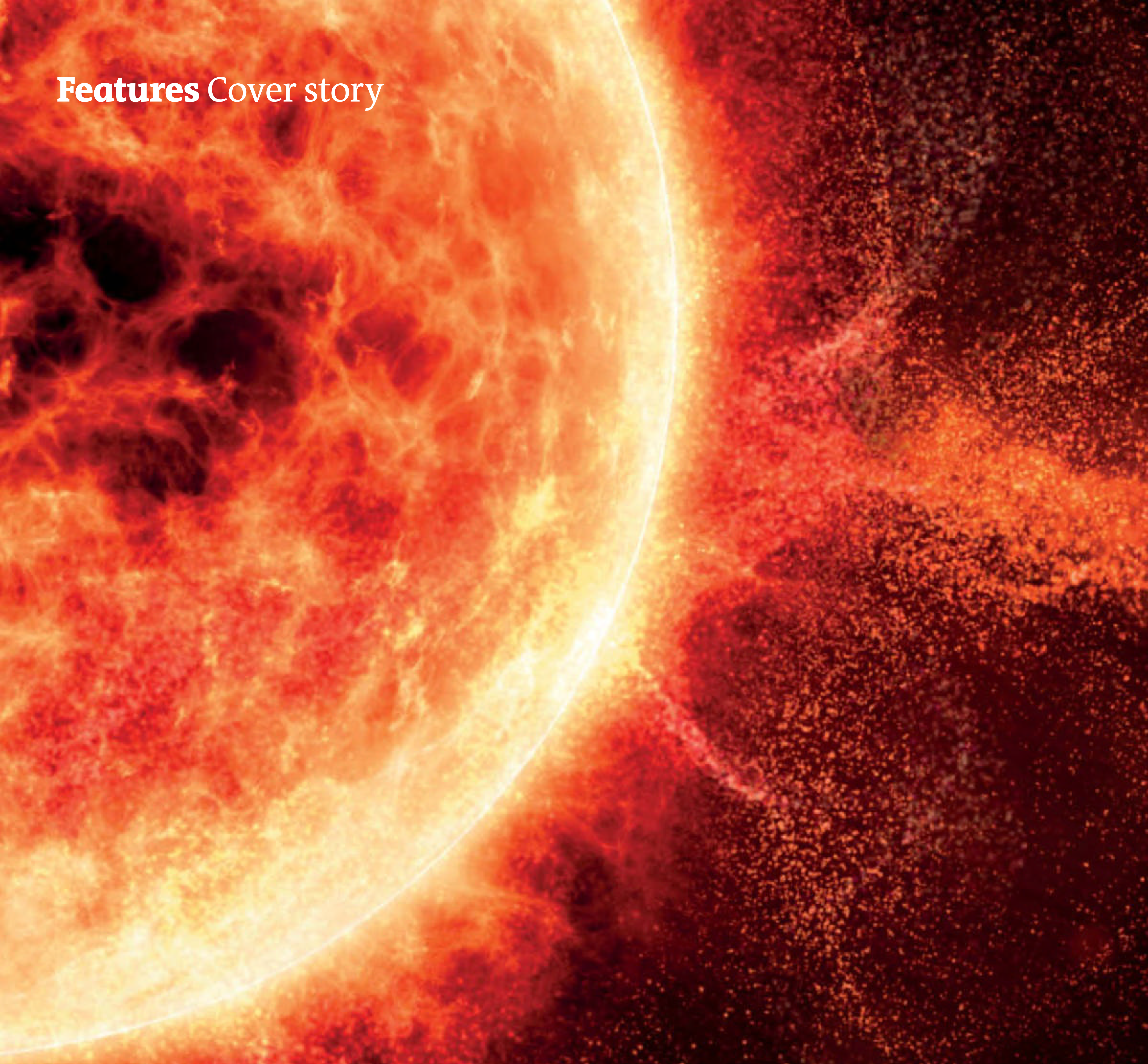

Solar surprise

Solar storms can wreak havoc on Earth, but we usually see them coming. Now physicists fear the sun will strike with no warning at all, finds **Stuart Clark**

TROUBLE brewed on 30 January 2022, although no one knew how bad it was going to be. If they had, SpaceX wouldn't have launched 49 Starlink satellites into low Earth orbit a few days later.

It began as a giant cloud of magnetised gas, called a coronal mass ejection, hurled in our direction from the sun. That wasn't a big concern. Sure, solar storms can heat Earth's atmosphere, causing it to expand and drag on low-flying satellites, but all measurements suggested only mild consequences. Power grids and satellites might glitch a little and skywatchers at high latitudes might notice aurorae, but nothing serious.

Soon after the Starlink satellites launched from Florida's Kennedy Space Center,

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however, it was clear something was up. When they reached Earth's upper atmosphere, the satellites experienced much more drag than expected for the storm's magnitude. In the end, nothing could be done. Controllers watched as 40 of the satellites were dragged down, burning up in the atmosphere in a demonstration of the sun's capricious power.

Down here on Earth, we enjoy the benefits of energy and light from the sun. We couldn't live without it. But we are also exposed to a constant barrage of solar wind, charged particles coming from our star. Most of the time, these only make themselves known in colourful displays of aurorae.

Every so often, however, the sun spits out a lot more material, endangering satellites and infrastructure on Earth. Usually, these come with the warning of a solar flare a day or two before they reach us. But recent research suggests some storms could appear with no warning at all.

Compared with what the sun is capable of, the storm that hit Starlink was a minnow. To truly understand what is possible, we must turn the clock back to 2 September 1859. On that day, Earth was engulfed by a gargantuan coronal mass ejection (CME). Huge bursts of electrically charged particles were thrown out from the sun's surface. These particles made their way to Earth, where they overwhelmed the barrier created by the planet's magnetic field. But no one knew what this was at the time – CMEs weren't discovered until the 1970s. What happened next appeared to come completely out of nowhere.

Brilliant displays of the aurora, or northern lights, filled the night skies across much of the world, caused by the particles interacting with gases in our atmosphere. The global telegraph system failed as electrical currents surged through the wires, sending sparks flying and starting fires in offices. At least one telegraph operator was stunned unconscious by phantom electricity jumping from equipment. Compasses spun uselessly as Earth's usually steady magnetic field writhed under the assault. Global communication and navigation was brought to a standstill.

That storm and its aftermath became known as the Carrington event, named after Richard Carrington, the British astronomer who witnessed the enormous solar flare on 1 September that, unbeknownst at the time, set the CME in motion. Although CMEs happen regularly, something as big as the Carrington event still hasn't come our way since. If it did, it would be a very different story.

"We're doing so much more in space," says Jonathan Eastwood, who runs a research group at Imperial College London dedicated to modelling space weather with the aim of developing forecasting tools. Today, we are much more reliant on electricity, and grids are vulnerable to the storms. We have satellites and, potentially, people in orbit. A solar storm could even disrupt the internet (see "Deep-fried internet", page 40). "We need to know what the space weather is," says Eastwood, "in the same way that we need to know what the weather on the high seas is – or anywhere on the surface of the Earth."

CMEs are typically launched from the sun in some kind of explosive magnetic event, which sets off a solar flare that we can see from Earth. The ejected particles take a day or two to reach us. So, the basic idea behind space weather forecasting is that you look for the bright flash of a solar flare, usually at ultraviolet wavelengths, and then look for any resultant CME in cameras called coronagraphs that block out the blinding light from the sun. If you see a CME approaching, ›

Deep-fried internet

How long could you live without the internet? As the sun's activity ramps up towards its next maximum, predicted for 2025, you might well find out.

Last year, Sangeetha Abdu Jyothi, a computer scientist at the University of California, Irvine, published an analysis of how solar activity might affect internet infrastructure. She suggested the long fibre-optic cables that lie across ocean floors are particularly vulnerable. That is because they require long wires to link "repeater" stations, devices that keep the optical signals from accruing errors. During a significant solar storm, magnetic fields could induce huge electrical currents in the wires linking the repeaters. According to Jyothi's analysis, 80 per cent of fibre-optic undersea cables could fail in an extreme event.

When Facebook, Google and other internet big hitters are sending most of their data from North America to Europe via fibre-optic cables that run at solar storm-vulnerable northerly latitudes, that is a disaster-in-waiting, says Jyothi.

Early warning of a storm might allow us to isolate the repeaters from such currents. "If we can detect the changes and break the circuit in some way, that could help," says Jyothi. However, such early warnings won't always be possible (see main story). And repairing submarine cable damage is costly and time-consuming, so an outage is a distinct possibility. "We could reroute data, but available capacity will be much less elsewhere," says Jyothi.

There is some good news, though. Although significant solar storms could cause internet outages, it isn't yet agreed that the impact would be as severe as Jyothi predicts. Mike Hapgood at the Rutherford Appleton Laboratory in Oxfordshire, UK, says the currents induced in the repeaters will be much lower than Jyothi's analysis suggests. "These cables are designed to be resilient to such extra currents," he says.

Milton Mueller, who researches the resilience of our infrastructure at the Georgia Institute of Technology in Atlanta, say that in such extreme circumstances, the electrical infrastructure is likely to fail first, so there will be no currents anyway and hence no surges in repeaters. "Internet outages may be secondary or tertiary concerns if the breakdown is severe."

Michael Brooks

you issue warnings, just as you would for a looming hurricane.

While simple in principle, in practice, this is anything but. Lots can change in the CME while it is en route, which sometimes makes it nearly impossible to know what is truly going on. And the consequences of getting it wrong are not only expensive but potentially deadly.

Eastwood is part of a team at the Rutherford Appleton Laboratory in Oxfordshire, UK, that works for the UK government on a continual appraisal of space weather consequences. The researchers take the Carrington event as a "reasonable worst-case scenario", studying the effects such a geomagnetic storm would have. In 2019, Eastwood and his colleagues found that power stations were particularly vulnerable. The surging electricity could overwhelm and burn out transformers, potentially interrupting the power supply for millions of people for weeks or even months.

Extreme space weather has been on the UK National Risk Register since 2011. Current estimates suggest a major event could cost the country between £100 million and £1 billion in lost revenue and claim up to 200 lives, in accidents mostly derived from the loss of power. In the US, one study predicted blackouts for around 130 million people and said the damage could take up to 10 years to remedy. Another, by researchers in New Zealand, said it could cause a global catastrophe.

Food supplies could be disrupted for weeks. There could be accidents at road junctions no longer controlled by traffic lights or failures on the rail network. People connected to life-support systems could die when backup generators fail, and in remote places, those reliant on GPS could become lost. There is even a chance that a severe solar storm could trigger some kind of violent event, in a similar way to the apparition of comet Hale-Bopp in 1997, which led 39 members of the Heaven's Gate cult to die by suicide.

In the past few years, new risks have been added. NASA is planning to send people once more to the moon, where there is no magnetic field to protect them. For those astronauts, a major solar storm could be fatal. Back on Earth, the exponential rise in satellite constellations and the near ubiquitous use of global navigation satellite systems (GNSS) mean losing them for a couple of days could be severe. "GNSS is more and more ingrained in all of our everyday services, more so than two or three years ago, and certainly more than five years ago," says Eastwood. "But we haven't scoped out all the consequences yet."

So far, so scary. The one saving grace is the warning signs we get from the sun. After

NUTEXZLES/GETTY IMAGES

witnessing a big solar flare, we know a CME is coming. We have a day or two to prepare, which is crucial. But, unfortunately, it might not be so simple. Over the past few years, solar physicists have begun to suspect that some CMEs sneak up on Earth, launching themselves without an observable ultraviolet signature. They call such wraiths stealth CMEs.

Not so long ago, if a CME appeared in a coronagraph, but no triggering event could be seen, researchers tended to assume the eruption had taken place on the far side of the sun, blooming out into space in the opposite direction to us. Even then, some geomagnetic storms appeared to come out of nowhere. It was as if Earth was being struck by a CME, while the sun appeared calm. These enigmas were known as "problem geomagnetic storms".

Researchers, including Jennifer O'Kane from the UK government's Defence Science and Technology Laboratory, set out to investigate what was going on, using missions such as NASA's Solar Terrestrial Relations Observatory project (STEREO). Launched in 2006, STEREO consisted of two spacecraft that drifted away from Earth in opposite directions – one eastwards, the other westwards. This allowed

"This time, there was no warning sign at all"

Solar wind particles interact with gas in the atmosphere to cause aurorae

us to study the space between the sun and Earth sideways on. "It was only when we got these different viewpoints that the stealth CMEs really came to light," says O'Kane.

Firstly, it was clear that they were exploding from the sun's Earth-facing side, not the far one. Secondly, the different viewpoints allowed astronomers to triangulate their points of origin on the solar disc. They were erupting with little or no visible warning.

During her PhD at Mullard Space Science Laboratory, University College London, O'Kane set out to determine whether stealth CMEs really were impossible to detect by studying the sun in ultraviolet wavelengths. She started by carefully analysing solar images that coincided with stealth CMEs to see if she could find any hint of the activity that had launched them. In most cases, she did find something, a blemish or an unusual pattern on the solar surface. "There was always something to indicate that maybe something was going on," she says.

But on 19 April 2020, a CME swept across the European Space Agency's (ESA) Solar Orbiter spacecraft. This time, there was absolutely no warning sign at all. Not to be beaten, O'Kane began a forensic campaign of image processing to find something – anything. Eventually, using images from STEREO, she caught a glimpse of an ultra-faint magnetic structure that gently lifted itself from the sun and began its stealthy creep into space. Working back through other images, she found the structure had existed for a while. That left an important puzzle.

"What triggered it to erupt?" says O'Kane. "We still don't know." She thinks there could be some genuinely different physics that is propelling the stealth CMEs compared with their more predictable cousins. And she isn't the only one thinking along these lines.

Nariaki Nitta at Lockheed Martin Solar and Astrophysics Laboratory in California has organised a team of researchers through the International Space Science Institute in Switzerland to investigate whether the physics launching stealth CMEs is different from that behind more normal CMEs. He recently recruited O'Kane. "The presence of stealth and stealthy CMEs presents a big challenge in space weather forecasting," says Nitta.

Maximum risk

Solar activity runs on a roughly 11-year cycle, from low to high to low again. The peaks and troughs are called the solar maximum and solar minimum. Around the solar minimum, astronomers estimate up to one-third of all CMEs are stealthy, which has implications for the efficacy of space weather forecasting. At the solar maximum, it is even worse. There is so much activity that it can be difficult to link even the ordinary flares to specific CMEs, never mind the stealthy ones.

"Space weather is a new science," says Erika Palmerio at Predictive Science in San Diego, California, who is also part of Nitta's group. "It's improving," she says. "But at every solar cycle, we have new challenges that make predictions more important and more urgent."

Like many others in this field, Palmerio is working to develop the ability to predict space weather conditions several days in advance. It is a big ask, especially when the new challenge this time is the effect on the thousands of small satellites that SpaceX and other companies plan to launch, usually to provide crucial internet services.

At present, a number of organisations offer space weather forecasts. But as the Starlink event shows, unexpected things do happen. These systems are in a constant state of improvement, and rather like weather prediction on Earth, the more stations you have collecting data, the more accurate the forecasts can be. Here, things are looking up.

Our space weather stations are the various spacecraft now circling the sun in the inner part of the solar system. There are dedicated solar missions like NASA's Parker Solar Probe and ESA's Solar Orbiter. We also have the joint European-Japanese Mercury mission, BepiColombo, which carries instruments for analysing space weather conditions. Then there are the "watchdogs" nearer Earth, such as the ESA-NASA SOHO mission or the National Oceanic and Atmospheric Administration's Deep Space Climate Observatory.

Thanks to these missions, our understanding of space weather is improving in leaps and bounds. But transforming the tools used to investigate space weather in hindsight into a system capable of reliably forecasting future events remains Herculean. "The demands are quite different," says Eastwood. "If there was a major space weather event, you need real-time information, so you can make the best decisions." To achieve this, his group is now working closely with the Met Office and ESA.

Companies such as SpaceX will no doubt be looking to improve their forecasting, too, in order to avoid a repeat of the event at the start of the year. But as Palmerio points out, the storm that brought down the Starlink satellites was only minor. "That's a kind of storm that we will see many times during the solar cycle," she says.

The last solar minimum was in December 2019. The sun is now ramping up towards an expected solar maximum in around 2025, when we will be more reliant on satellites and other vulnerable technology than ever before. All the time, the clock is ticking and the stakes are getting higher. ∎

Stuart Clark is a consultant for *New Scientist* and author of *The Sun Kings*