What are the chances of a hazardous solar superflare?

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On March 1, 2010, the Kepler space telescope spotted a distant star brighten slightly. Compared with the ferocious intensity of a supernova or gamma-ray burst, this event was feeble. It was merely a stellar flare, and by no means the most powerful flare ever seen. Nevertheless, it was ominous.

The star, known as KIC9944137, lies more than 1800 light-years away between the constellations Cygnus and Lyra. It closely resembles our Sun: about the same size, about the same temperature, about the same rotation rate. Yet the flare was at least 10 times as powerful as anything recorded on the Sun.

Kepler has detected many more such superflares on sunlike stars. In May this year, a team of astronomers led by Yuta Notsu of Kyoto University in Japan published a study confirming that many of these stars share our Sun's composition and other properties (1).

This raises the prospect of superflares on the Sun, perhaps one every few centuries. Such events could have serious consequences for society. But other evidence for these events is strangely lacking. They should deposit much more radioactive material on Earth and the Moon than researchers have found thus far. Either our Sun is subtly different from these superflare stars, or a superflare is possible in the foreseeable future.

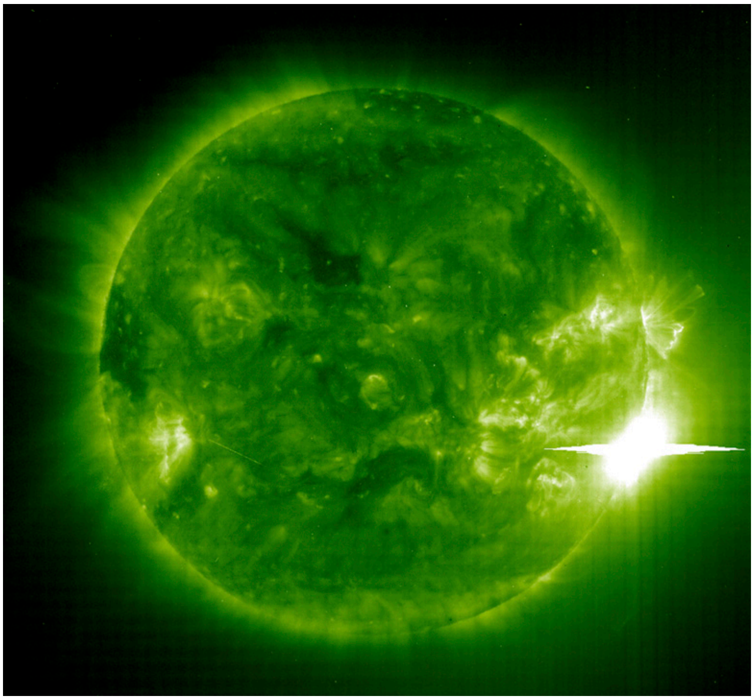

Fig. 1. One of the largest flares ever seen on the Sun—captured here in extreme ultraviolet light by the Solar and Heliospheric Observatory—erupted in November 2003. Classed as an X28 flare, it had greater energy than any other flare seen in the space exploration era but still falls far short of a superflare. Image credit: SOHO/EIT (ESA and NASA).

Magnetic Catapult

Flares happen because of convulsions in the Sun's magnetic field. The field stretches out through the solar atmosphere and into deep space. Electromagnetic forces fuse the field to the electrically charged plasma that makes up the body and atmosphere of the Sun, and the churning motions of that plasma stretch and twist the field into complex shapes.

Strong concentrations of the field form sunspots, and when two spots with opposite polarity come close together they can create a flare. Tens of thousands of kilometers above the spots, in the solar corona, opposing field lines squeeze close together, until eventually the field snaps into a lower-energy configuration. This process, known as reconnection, whips electrons up to high energy. They spiral down the field lines and collide with ions in the lower atmosphere of the Sun, generating a flash of X-rays and other forms of electromagnetic radiation. Sometimes a flare heralds another kind of solar eruption called a coronal mass ejection (CME) when the reconnection process also unleashes a ball of plasma that races away from the Sun.

One of the most powerful solar flares ever seen, the Carrington Flare of 1859, was accompanied by a CME that hit Earth and buffeted the planet's magnetic field, generating electric currents strong enough to melt telegraph wires. The flare energy is estimated at around 5×10^{25} joules, equivalent to 10 billion megatons of TNT. During the past few decades, spacecraft have kept a close eye on the Sun. The strongest flare yet seen, in November 2003, was about 3×10^{25} joules (2) (see Fig. 1).

No one would call these superflares—although the term is not precisely defined. Notsu and colleagues use superflare for anything above 10^{26} joules. Astrophysicist Karel Schrijver, based at Lockheed Martin's STAR Labs in Palo Alto, CA, puts the threshold at 10^{27} joules. "It is a matter of taste," says Schrijver.

Superflares do happen on yellow stars with around the same size and temperature as our Sun but mostly ones that rotate rapidly, and thus, have stronger magnetic fields and much more violent magnetic activity. Stars similar to the Sun, with its sedate 25-day rotational period, are not expected to flare up in this way.

A Flare for Destruction

But KIC9944137 did. In 2012, Notsu and his colleagues analyzed data from the Kepler telescope on solar-type stars and found 365 flares of more than 10^{26} joules. As expected, the researchers found that the faster-spinning stars are more likely to generate the biggest flares. But some superflares showed up on slower spinners (3). "It was a very big surprise for us to find superflares on slow-rotating stars," says Notsu.

The statistics from Kepler imply that solar-type stars with 25-day periods will produce a superflare (by Notsu's definition) every 500 to 600 years. When the team added more stars to the analysis, the prediction showed that every few thousand years such stars could produce even larger flares of around 5×10^{27} joules—100 times as powerful as the Carrington flare (4). Although we have not seen such large flares on the Sun, the potential may be there. The total magnetic energy in the largest observed sunspot groups exceeds 10^{27} joules, according to a 2017 calculation (5).

If a solar superflare ever strikes Earth, the first thing to hit us will be an intense flash of X-ray and ultraviolet radiation. This would disrupt the ionosphere, scrambling the satellite navigation signals needed in critical services and infrastructure. The burst of radiation would heat the outer layers of Earth's atmosphere making them expand, increasing drag on satellites so much that some might be lost.

A wave of high-energy protons, accelerated by shockwaves in the Sun's atmosphere, would hit Earth a few minutes later. These could cripple satellites, compromising global communications. "High-energy particles can permanently damage processors," says Schrijver. If the flare also spawns a supersize CME that happens to be aimed at Earth, it could cause a violent geomagnetic storm, inducing electric currents that could be strong enough to paralyze even modern power grids. A 9-hour blackout in Quebec in March 1989 was caused by a much more modest CME.

Superflare Signatures

Researchers have looked for the mark of past superflares on Earth. Flares and CMEs both generate high-energy protons, which create radioactive isotopes carbon-14 and beryllium-10 in Earth's atmosphere. The former can be detected in tree rings; the latter in the ice caps of Greenland and Antarctica.

Ice cores and ancient tree rings do show a few spikes in these isotopes, marking extreme solar particle storms in the past. The strongest took place in 774 CE (6). Although it is not simple to convert the strength of solar particle storms into the flare energy, one study (7) puts the 774 CE flare at about 2×10^{26} joules, at the lower end of Notsu's superflare range. The overall statistics show that such an extreme event occurs at most once in several millennia, much more rarely than the few centuries implied by Kepler, and there is no evidence of huge 10^{27} joule superflares. Rocks from the Moon, which accumulate radioisotopes, provide a similar constraint. "This leaves us in a quandary," says Schrijver. "Stellar data on flares don't match the statistics of solar energetic particles."

It may be that the Kepler superflare stars are not really sunlike. For example, they could be in binary systems, where the gravity of a companion would boost magnetic activity in the main star. To find out, Notsu and his colleagues looked closely at 64 superflare stars using the 3.5-meter telescope at the Apache Point Observatory in Sunspot, NM. They found that 21 superflare stars were indeed part of a binary system, but that still left 43 single stars.

Some of the apparently sunlike stars could also be subgiants, with similar spectra but at a later stage of evolution than the Sun and much larger in size. Notsu's team used data from the European Space Agency's Gaia space observatory to work out the distances to stars and their radii. They found that only about 40% of the 64 stars are subgiants. So plenty of single, sunlike stars generating superflares that are apparently much bigger than anything coming from our own Sun.

"This leaves us in a quandary. Stellar data on flares don't match the statistics of solar energetic particles."
—Karel Schrijver

To find out whether the physics behind superflares is the same as that of solar flares, Anne-Marie Broomhall at the University of Warwick in the United Kingdom studies flares that wax and wane with a rough rhythm—so-called quasiperiodic pulsations (QPPs). Astronomers often see slow QPPs on other stars with periods of several minutes. QPPs on the Sun tend to be rapid, with periods of seconds or less, which hinted that different mechanisms may be at play. But when Broomhall and her colleagues studied a powerful solar flare from September 2017, they found two QPPs: one with a Sun-typical period of several seconds and the other around 4 to 5 minutes (8), more characteristic of the superflare stars. "QPPs suggest that the same physics is going on," says Broomhall. Hence, the quandary regarding our Sun's paucity of superflares remains.

Lost in Transportation

Schrijver suggests three resolutions for that quandary. It may be that the Sun and its kin occasionally change their magnetic activity: sometimes quiet, sometimes in superflare mode. "We know that the Sun can change its behavior on time scales of a century or so," explains Schrijver, pointing to the Maunder Minimum, a lull in sunspots between 1645 and 1715. If activity can change more radically, that could mean that the Sun is a superflare star in some eras—just not for the past 11 millennia.

Or it may be that the Sun's superflares don't leave much of a radioactive trace on Earth. One theory is that a really powerful blast of energetic protons from a superflare could create magnetic waves strong enough to then scatter the protons, preventing most of them from reaching us, reducing the radioactive fallout (9).

It's also possible that researchers have missed some subtle difference between the Sun and those sunlike superflare stars. "The answer will come by looking at a lot more stars," says Schrijver. NASA's new Transiting Exoplanet Survey Satellite, already in orbit, should soon turn up many more superflare stars, enabling astronomers to look for more patterns in the data.

Eventually, a better understanding of the phenomenon could help warn us of an impending solar superflare. The growth of a very large area of sunspots might be one giveaway, in which case we would get about a week's warning of a possible superflare, says Notsu. Particular motions in the solar plasma could be important too. Studying the big September 2017 flare, a team led by Paolo Romano at the Catania Astrophysical Observatory in Italy saw nearby streams of plasma moving in opposite directions (10). Perhaps such motions could help to forecast superflares.

Today the Sun is quiet, at a lull in its 11-year magnetic cycle. But even now a few largish flares are likely to punctuate the solar calm, giving astronomers a chance to test their ideas and work out just what our star's limits might be.

1 Y. Notsu *et al.*, Do Kepler superflare stars really include slowly rotating sun-like stars?—Results using APO 3.5 m telescope spectroscopic observations and Gaia-DR2 data. *Astrophys. J.* **876**, 58 (2018).

2 M. Kretzschmar, The Sun as a star: Observations of white-light flares. *Astron. Astrophys.* **530**, A84 (2011).

3 H. Maehara *et al.*, Superflares on solar-type stars. *Nature* **485**, 478–481 (2012).

4 Y. Notsu *et al.*, Superflares on solar-type stars observed with Kepler II. Photometric variability of superflare-generating stars: A signature of stellar rotation and starspots. *Astrophys. J.* **771**, 127–136 (2013).

5 S. Toriumi *et al.*, Magnetic properties of solar active regions that govern large solar flares and eruptions. *Astrophys. J.* **834**, 56–74 (2017).

6 I. G. Usoskin *et al.*, The AD775 cosmic event revisited: The Sun is to blame. *Astron. Astrophys. Lett.* **552**, L3–L6 (2013).

7 E. W. Cliver, A. J. Tylka, W. F. Dietrich, A. G. Ling, On a solar origin for the cosmogenic nuclide event of 775 A.D. *Astrophys. J.* **781**, 32–35 (2014).

8 D. Y. Kolotkov, C. E. Pugh, A. Broomhall, V. M. Nakariakov, Quasi-periodic pulsations in the most powerful solar flare of Cycle 24. *Astrophys. J. Lett.* **858**, L3–L10 (2018).

9 D. V. Reames, C. K. Ng, Streaming-limited intensities of solar energetic particles on the intensity plateau. *Astrophys. J.* **723**, 1286–1293 (2010).

10 P. Romano *et al.*, Homologous white light solar flares driven by photospheric shear motions. *Astrophys. J. Lett.* **852**, L10–L17 (2018).