Superflares

Astronomers have discovered many Sun-like stars that unleash titanic flares. Could our Sun produce such a flare? Has it already?

Monica Bobra

The largest solar flare in modern history happened only 12 years ago. On November 4, 2003, a sunspot group on the western limb of the Sun hurtled a massive blast of particles in a direction away from Earth. A week before, the same sunspot group had cranked out eruptions that spawned auroras as far south as Florida. This flare was likely as big as the first one ever recorded, using ink and paper, in 1859.

But both these eruptions, monsters by our standards, are tiny compared with *superflares* — flares roughly tens to thousands of times more energetic than the largest solar flare ever observed. In fact, many yellow, middling-mass *G*-type stars like the Sun produce superflares. Astronomers wonder why this is. As such, they're beginning to ask: Could a superflare ever occur on the Sun?

That, it turns out, is a controversial question.

Flare Mechanics

The story of a solar flare begins deep inside the Sun. There, energy from the seething, boiling interior gets converted into magnetic energy, giving rise to the solar magnetic field. When strongly concentrated bits of field poke out of the solar surface (called the *photosphere*), they choke the motion of the photosphere's hot gas, making those locations appear dark. We call these dark features sunspots. In most cases, sunspots travel in pairs. Each pair acts like a tiny bar magnet worming its way across the solar disk, with one spot leading while the other follows.

Like long stalks of grass swaying in the breeze, the magnetic field is anchored firmly to sunspots but moves freely in the upper solar atmosphere, or *corona*. There, the field can twist, snap apart, and fuse back together, and when it does it releases energy. We call this burst of energy a flare.

To happen, solar flares need a magnetic field that's both freely moving and strong. That's why flares release most of their energy in the corona (where the field moves like billowing meadow grass), directly above sunspots (where the field is strongest).

During a flare, particles from the Sun head every which way. Some travel out into space. Under the right conditions, they flow seamlessly from the solar to terrestrial magnetic field, hit our ionosphere, and create auroras.

But our Sun's flares are nothing compared with superflares. In 2012, Hiroyuki Maehara (then at Kyoto University, Japan) and colleagues discovered 365 superflares on 148 solar-like stars, using data from NASA's Kepler space telescope in a landmark study of the largest sample of superflares compiled for these stars. The Kepler satellite, which observed more than 100,000 stars on a fixed patch of sky over a four-year period, was designed to detect exoplanets, but astronomers soon discovered that careful processing could uncover thousands of superflares. (The signal from an average-size solar flare is too faint for Kepler to detect.)

While Kepler cannot directly image these distant stars, it can detect how brightly a star shines over time. Astronomers compile this information in diagrams called light curves. By analyzing peaks in these light curves, Maehara's team and, soon after, many others discovered hundreds of superflares on solar-like stars.

In addition, from dips in these same light curves, Maehara's team also inferred that these stars' surfaces are marred with massive starspots, the likes of which we've never seen on the Sun. These starspots cover huge swaths of the stellar surface and can survive for months on end.

This summer, Yuta Notsu (Kyoto University) and colleagues used the 8.2-meter Subaru Telescope atop the summit of Mauna Kea to track down some of the stars reported in Maehara's study. In particular, they looked at the stars' spectra in the ionized calcium (Ca II) and

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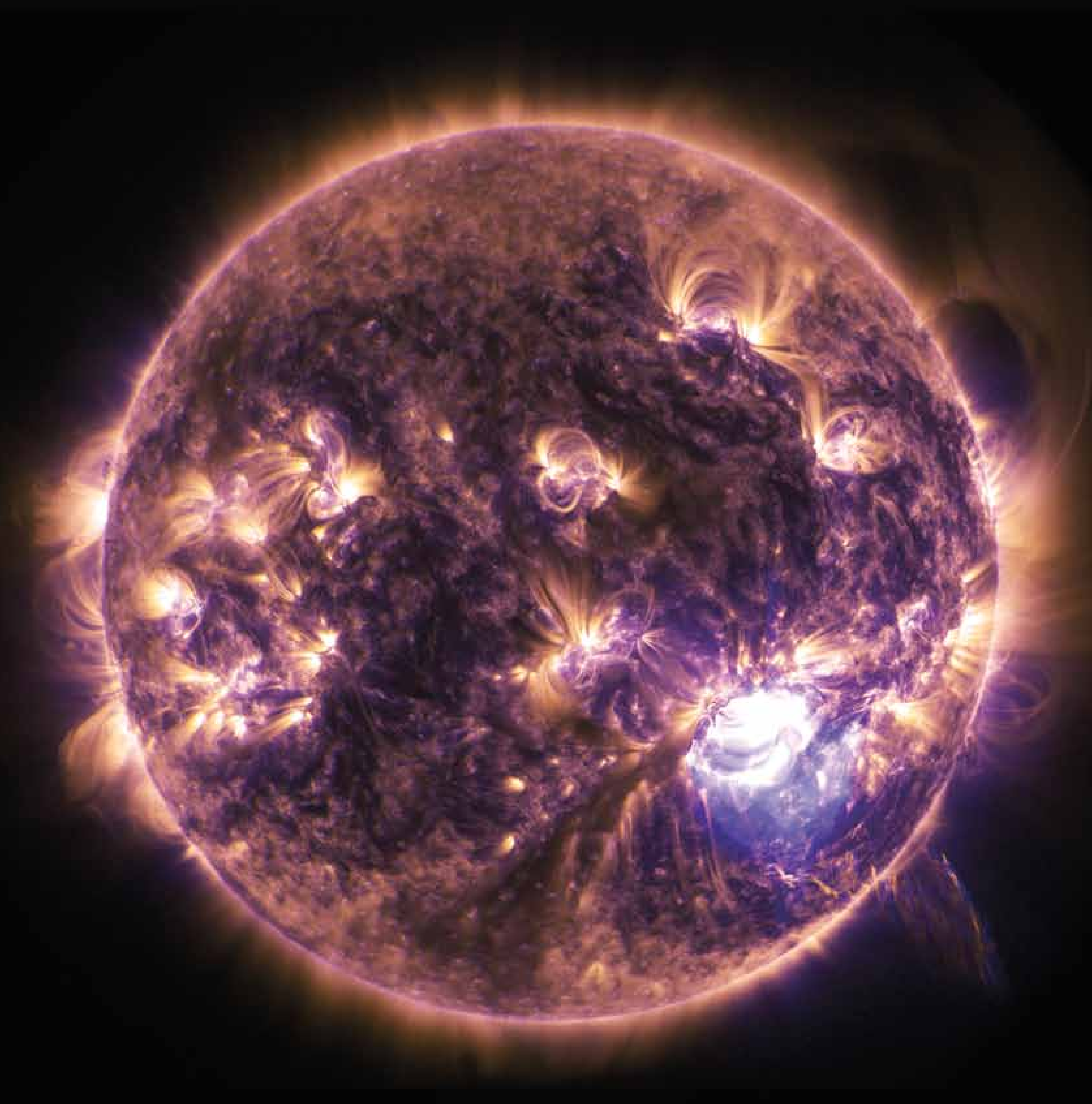
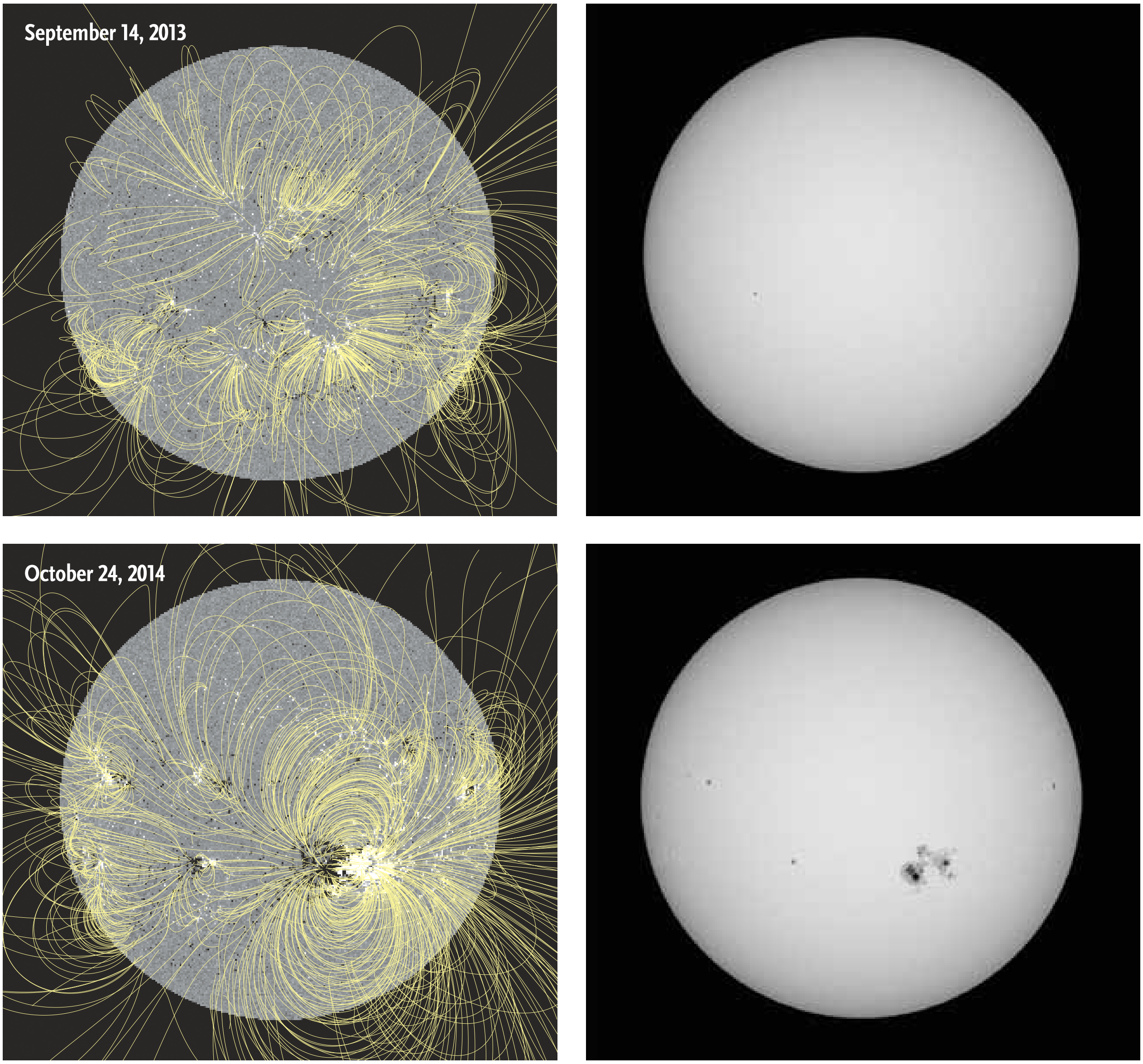


X-CLASS FLARE On December 19, 2014, a powerful flare erupted on the Sun. This composite image from NASA's Solar Dynamics Observatory blends two wavelengths of extreme ultraviolet light, 17.1 nm (gold) and 13.1 nm (purple). Scientists rate flares according to their X-ray intensity; this flare (bright region, center right) they rated as X1.8, which puts it in the most intense category, X. The largest flare ever observed unleashed at least 15 times as much energy — fortunately, that one wasn't pointed at Earth.



C. SCHRIJVER / SDO / NASA (4)

SUN IN KNOTS Shown is the Sun on September 14, 2013, and October 24, 2014. In white light, we see only sunspots (or lack thereof). But solar physicists can use spectral-line observations to infer the photospheric magnetic field. From this map of the surface field, they can then model the coronal field *(left images)*. There's no strong concentration of field apparent on September 14th, when the Sun was nearly spotless. Conversely, on October 24th, almost all of the coronal magnetic field originates from the giant sunspot group AR 12193.

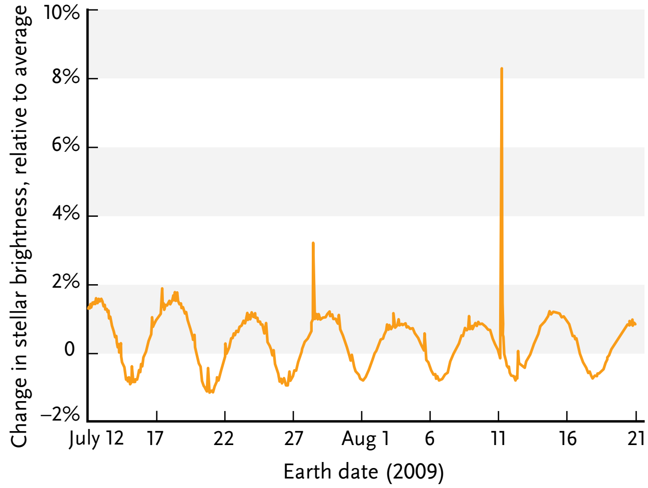
hydrogen-alpha wavelengths, which are better indicators of magnetic activity than Kepler's white-light observations. And they learned what makes these stars so special: superflaring stars have stronger Ca II and hydrogen-alpha signals than the Sun. In other words, these stars generate much stronger magnetic fields.

This makes sense. In general, the faster a star rotates, the stronger its dynamo, or mechanism for generating magnetic fields. Like a more powerful engine drives a more powerful car, a stronger stellar dynamo drives a stronger magnetic field. The stronger a star's magnetic field, the more spots it sports. And the greater the number of spots on a star, the more likely it is to unleash a superflare. In fact, superflaring solar-like stars could be plastered in spots. Maybe the periodic variations in a stellar light curve that we interpret as starspots (see page 25) are instead due to a singular bald patch — a small section of the photosphere that isn't covered by spots.

But while it's generally more likely for a massive spot to produce a massive flare, it's not necessary to have one to have the other. We see this on the Sun all the time. Sometimes large solar flares come from fairly innocuous-looking, decaying or small spots. And sometimes large sunspots don't produce massive flares.

In addition to differences in spot coverage among solar-like stars and the Sun, there are also differences in flare duration. On the Sun, the white-light emission from a flare usually lasts less than 10 minutes. On solar-like stars, the white-light emission from a superflare lasts for almost half a day. There is a plausible explanation for this discrepancy: perhaps the superflare is composed of many smaller — albeit still quite large — flares superimposed atop one another, creating a gargantuan signal.

This idea is not new. Observations from the Solar Dynamics Observatory and STEREO spacecraft clearly show that when the magnetic field rearranges itself during a solar flare, it can affect already-stressed magnetic fields elsewhere on the Sun. In some cases, this causes a domino effect, triggering flares that might not erupt otherwise. Recent numerical models, notably by Tibor Török (Predictive Science Incorporated) and colleagues, can reproduce such observations.



S&T: LEAH TISCIONE, SOURCE: H. MAEHARA ET AL. / *NATURE* 2012

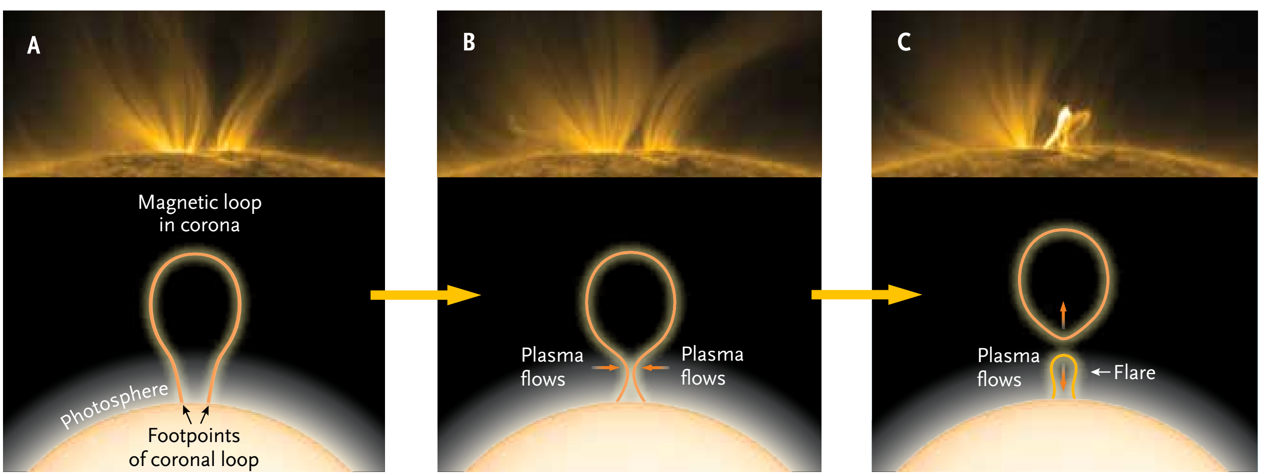
SUPERFLARE SPOTTED Hiroyuki Maehara's team used Kepler data to discover 365 superflares on Sun-like stars, including this flare on the star KIC 6034120. The superflare lasted 5½ hours and had a total estimated energy of 3×10^{35} ergs, or about a hundred times larger than the largest flare ever observed on the Sun. The team infers that the periodic variations in the light curve likely come from starspots rotating in and out of view as the star spins.

Signs of a Superflare?

While observations of other solar-like superflaring stars cannot provide all of the answers, there are other places to look. One place is right here, on planet Earth.

When high-energy particles impact Earth's atmosphere, they create a type of radioactive carbon called carbon-14, which is then incorporated into atmospheric carbon dioxide. During an extreme solar flare, these particles come from the Sun and bombard Earth, creating higher-than-normal levels of carbon-14. Trees ingest this carbon, preserving a historical record of the particle surge in their rings. But no such carbon-14 spikes were observed until 2012, when Fusa Miyake (Nagoya University, Japan) and colleagues unearthed a sharp increase in carbon-14 content in rings formed by Japanese cedar trees around AD 775. Since then, many groups have discovered similar increases from around the same year in bristlecone pines from the White Mountains of California, oaks from Germany, larches from northern Siberia, and, less than a year ago, kauri trees from New Zealand.

But trees aren't the only history books around. High-energy particles impacting Earth's atmosphere also



DIAGRAMS: S&T: GREGG DINDERMAN; FLARES: NASA / SDO AND THE AIA, EVE, AND HMI SCIENCE TEAMS

ONE WAY TO MAKE A FLARE Astronomers aren't quite sure of the mechanics behind solar flares, but one scenario is the pinching off of a magnetic field loop. In this scenario, the loop has its footpoints in the photosphere and extends into the corona (A). Plasma flows pinch the magnetic loop (B); these flows might be part of the natural movements in the solar atmosphere, or inherent to the plasmoid eruption's dynamics. The magnetic field lines then reconnect and the lower loop snaps back toward the photosphere (C). Plasma flows away from the reconnection point, and shock waves within the plasma heat it, creating the intense burst of emission we observe at multiple wavelengths. In simple 2D models like this one, the upper loop carries away ions and can evolve into a coronal mass ejection. But many flares don't show the pinch-off and plasma blob, leading researchers to suspect that, while magnetic knotting and reconnection are fundamental to flare creation, the loop pinch-off process is not.

Watch mesmerizing videos of solar eruptions and sunspot transformations at http://is.gd/solarflaresbpp.

FILAMENT ERUPTS Major flares can lead to coronal mass ejections (CMEs), but they're not the same thing. On August 31, 2012, this long filament erupted out into space from where it had been hovering in the corona. The CME did not travel directly toward Earth, but it did connect with Earth's magnetosphere, causing auroras on the night of Monday, September 3rd. This composite image blends observations taken at 30.4 and 17.1 nanometers by NASA's Solar Dynamics Observatory.

NASA / GSFC / SDO

create a shower of other secondary particles, notably the isotope beryllium-10. These particles fall to the ground. In cold environments, snow falls over these particles, covering them like a blanket. By drilling deep into the polar icecaps or glaciers, we can unearth yet another history. Motivated by all the tree-ring discoveries, Miyake and colleagues turned to Antarctica. There, they found 80% higher-than-average values of beryllium-10 deposits, corresponding once again to the year 775.

It's hard to know exactly what caused this massive increase in energetic particles. It's likely not a supernova, because it would have to have been a mere 52 light-years away to cause such a large carbon-14 spike, and a supernova that close should have been spotted by the naked eye at the time (and doubtless would show up in written records). It's also likely not a gamma-ray burst, which happens either when two compact objects like a neutron star or black hole merge (the short type of GRB) or when certain massive stars go supernova (the long type). Even long GRBs generally only last a few tens of seconds, and because the resulting jet is so narrow, the GRB would only have had enough time to irradiate one hemisphere of Earth. That would not explain why the increase appears in trees around the world.

And the spike isn't a solar flare of the kind we've seen before, because the 1859 flare isn't recorded in tree rings.

But it could be a superflare, some 10 to 50 times larger than the largest solar flare we've ever observed. There is no way to tell. Miyake's team has found hints of a second, smaller spike about 200 years later, but no others. The absence of other such spikes can set an upper limit on how frequently superflares might occur on the Sun.

Suggestive Sunspots

Another place to hunt for clues is, of course, our Sun. Since the advent of the telescope, we've been collecting solar data almost constantly. Though we don't have thousands of years of data as we do with tree rings, we do have the advantage of directly observing not only sunspots, but also the smaller-scale features that accompany them.

For example, we see that sunspots are made up of two distinct concentric parts — a dark umbra, which contains the strongest magnetic field, surrounded by a penumbra, made up of short-lived filaments. We observe how long spots live (most decay a few days after forming) and how many exist at any given time (the number of spots increases and decreases over a regular 11-year cycle). And from these data, we can predict whether the Sun could produce a superflare.

The largest sunspot group reported since the beginning of the 19th century, when sunspot observations became somewhat standardized, occurred in April 1947. It covered an area on the Sun about twice as large as Jupiter and was visible with the naked eye. Though it did not produce any flares that affected Earth, Guillaume

Aulanier (Paris Observatory) and colleagues recently used a numerical model to calculate the largest possible flare this sunspot could power under realistic solar conditions. The team discovered that even this largest-ever sunspot couldn't produce a flare more than a few times larger than the one in 2003.

Other groups have come up with similar results. Carolus Schrijver (Lockheed Martin Solar and Astrophysics Laboratory) and colleagues recently calculated that 10% of the Sun would have to be covered in spots to power a flare 10 times larger than the largest one observed. And we've never seen the Sun look like that. By statistically analyzing the size of solar flares — the vast majority of which are miniscule — Schrijver's team estimates that there's at most a 10% chance we'll see a superflare within the next 30 years.

Hugh Hudson (University of California, Berkeley) has made a similar calculation by analyzing *supergranules*, giant convective bubbles in the photosphere. Sunspot umbrae are not usually larger than the area of a supergranule, he observed. Thus, the average-size sunspot can contain only so much magnetic field. And the field can release its energy only so fast. After calculating these numbers, Hudson also concludes that the average sunspot can't produce flares much larger than the one in 2003.

All of these calculations, however, don't definitively exclude a solar superflare from ever happening. They simply point to the fact that the Sun, as it behaves right now, is unlikely to produce a superflare. But these data are only from recent historical records, and our middle-aged Sun has been around for 4.5 billion years. During that time, it has displayed some erratic, unpredictable behavior — such as the Maunder Minimum, between 1645 and 1715, when the Sun went nearly spotless — and such behavior might crop up again in the future.

Furthermore, solar superflares *are* theoretically possible. Calculations by Kazunari Shibata (Kyoto University) and colleagues show that in just one solar cycle, the Sun could theoretically build up enough magnetic field to power a solar flare 10 times larger than the 2003 flare. It would take 40 years to build up the magnetism needed to power a flare 100 times larger.

The Road Ahead

So, will the Sun ever superflare?

In truth, we aren't sure. We don't yet understand how closely the Sun's behavior mimics that of other stars like it. Although we detected gigantic stellar flares before the Kepler mission, until its advent we were unable to catalog hundreds of them at a time. The wealth of information in Kepler's data has raised more questions than it answered.

We see solar-like stars with a variety of rotation periods, temperatures, and diameters. We see flares 10 times larger than ones observed on the Sun, and we see flares 10,000 times that large, too. We infer that some solar-like stars have massive spots or are covered in spots, and some don't have any spots at all. Do all these stars have the same mechanism for generating magnetic fields? And how many superflares versus garden-variety flares do solar-like stars produce?

Thankfully, there are more data to comb through for answers. Promising information exists in recently digitized historical records from the Song Dynasty, as well as carbon-14 measurements from Chinese corals. The Solar Dynamics Observatory will continue taking almost-constant images of the Sun, ensuring we never miss another sunspot as it rolls across the solar disk. And observations by larger telescopes, better designed to study stellar flares, may allow us to answer some of these questions by observing fainter signals in more spectral lines. The last few years have been rife with discoveries, and the next few will likely be the same. ✦

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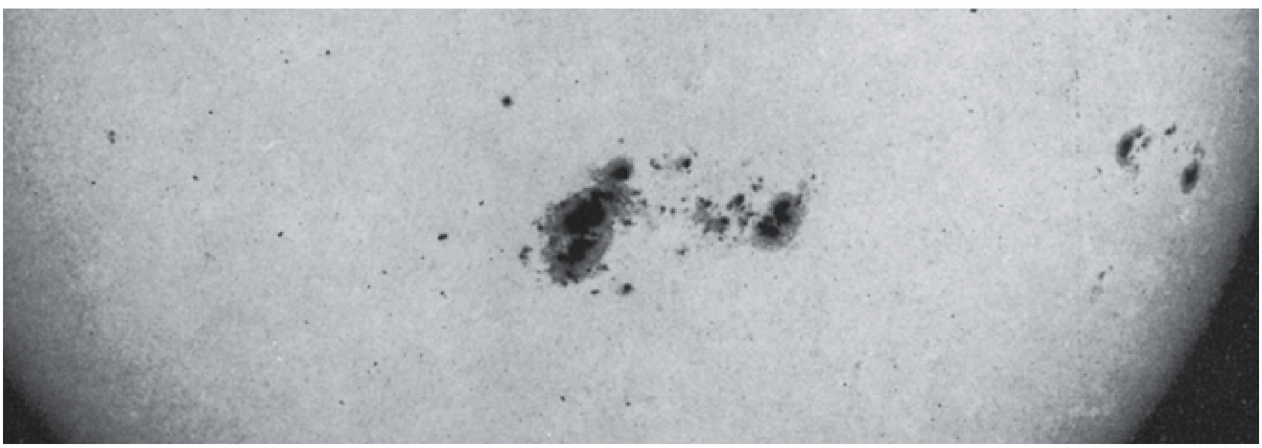
SOLAR BEAUTY MARK In 1947 a gigantic sunspot group marred the solar surface for several months. At its largest, the group spanned an area roughly twice that of Jupiter. This photo shows the Sun as it appeared on April 6th of that year, right around the time the feature was at its maximum size.



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