SOLAR PHYSICS by Monica Bobra

Is the Sun Changing?

Feeble sunspot cycles and other stars' behavior have prompted speculation on whether something's up with our Sun.

About 290 million years ago, a volcano erupted in what is now eastern Germany. The blast lifted trees straight out of the ground and coated them with liquid rock. Beneath this debris, an entire forest fossilized. Last year, scientists studied tree rings from these ancient trees — but not to learn about Earth. They wanted to learn about the Sun.

To the naked eye, the Sun looks like a uniform whitish sphere. But the solar surface is often mottled with dark spots, like the peel of a ripe banana. These sunspots emerge, live for a few hours or days (or longer), and then decay. Occasionally, 150 or more spots dot the solar surface. During those times, we observe many eruptions of high-energy radiation and, sometimes, superheated material, which can blast through space and hit the planets. At other times, hardly any spots show up at all, and the Sun stays fairly quiet. The Sun smoothly cycles between these two states, ramping the number of sunspots up and down every 11 years.

By studying fossilized tree rings, Ludwig Luthardt and Ronny Rössler (Chemnitz Museum of Natural History, Germany) made a striking discovery: The Sun has been going on like this for at least 300 million years. It's not that long on astronomical time scales — our Sun is, after all, 4.6 billion years old — but it means that some predictable mechanism operates inside the Sun, churning out cycle after cycle for millions of years.

But recent observations of the Sun and other Sun-like stars suggest that the solar cycle might eventually taper off and disappear. This controversial and speculative theory requires more observations, and calculations, before we can confirm it. But we can't rule it out, either. Is the Sun on the brink of a permanent change?

The Cyclic Field

The Sun's cycle of activity originates in its magnetic field. Unlike the dipole bar magnet you may have played with in physics class, the solar field looks like a giant hairball. It pokes out of the surface all over the place, creating sunspots. Each sunspot is a region of concentrated magnetic field. This field acts like a dam, preventing hot gases from flowing into its position. The location of these little magnetic dams, and the number of them, give us clues about the solar interior.

Solar physicists don't fully understand how the Sun generates its hairball magnetic field. They know that this field originates deep inside the Sun, due to the complex combination of various plasma motions in different regions. From there, the field moves outward, roiling around convective bubbles and forming braids, ropes, loops, and kinks. Finally, this twisted field pokes out through the solar surface, where we see it as a sunspot. For reasons that remain a mystery, sunspots appear closer and closer to the solar equator as the Sun moves through its 11-year cycle.

It is obvious, however, that the solar magnetic field governs this cycle. To study this process, scientists develop mathematical models of the solar magnetic field that reproduce the Sun's behavior. But we can also study the Sun by looking at other stars.

Oddball Sun

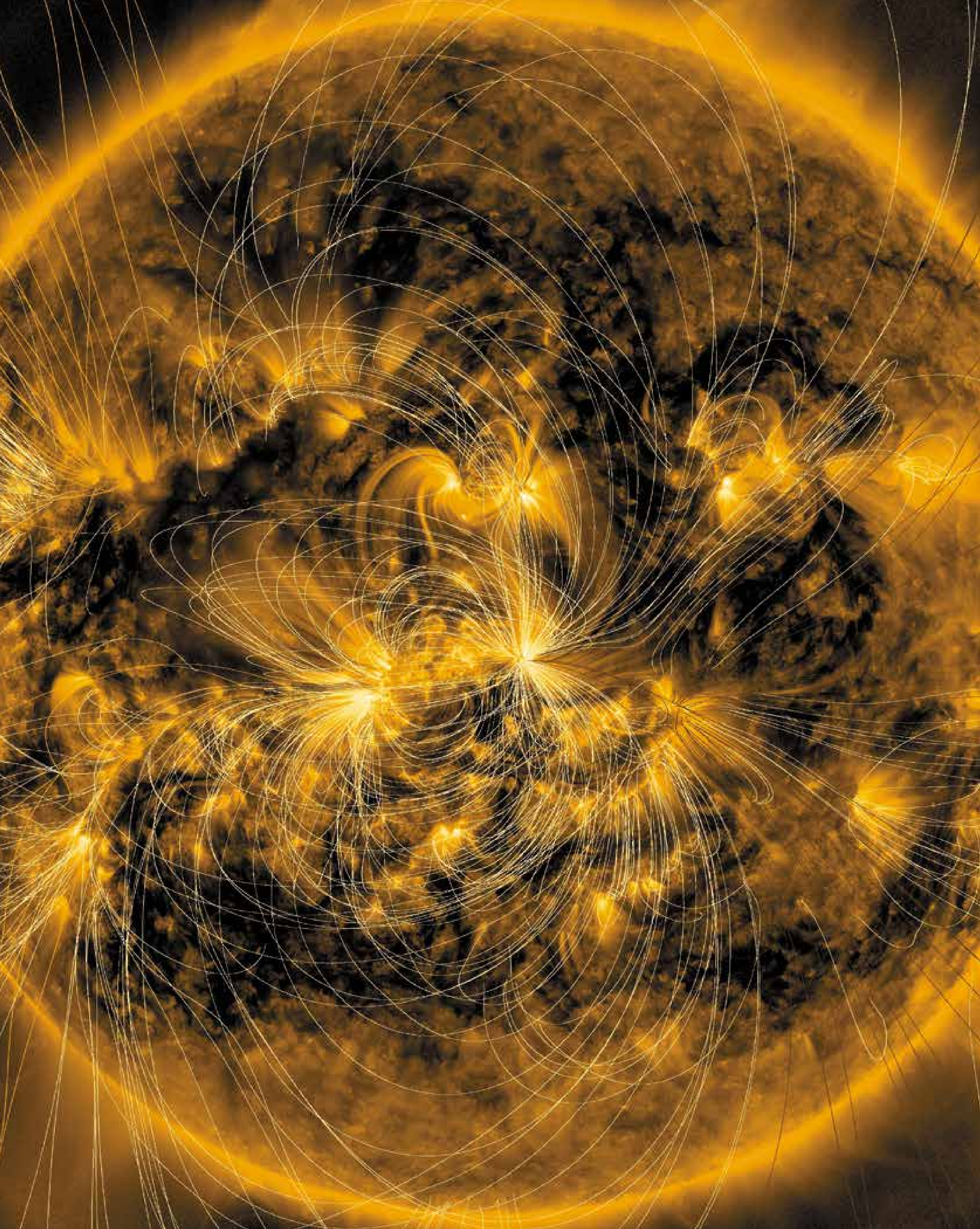
The Mount Wilson Observatory sits atop a hill that overlooks the sprawling city of Los Angeles. Pine trees surround the dome, which, on a clear day, affords vistas of Catalina Island nestled in the shimmering waters of the Pacific. It was from this serene setting in 1966 that astronomer Olin Wilson used the 100-inch reflector to begin the first long-term study of spot cycles on other stars.

Wilson found spot cycles on all sorts of stars. Stars similar to the Sun (*G*-type) sported cycles, and so did ones slightly hotter (*F*-type) and cooler (*K*-type) than the Sun. On all these stars, the stellar magnetic field created spots and powered eruptions. From these data, it's clear that stars generate

◀ **SUNSPOT BANDS** Sunspots appear in two bands that sandwich the Sun's equator. At the beginning of the solar cycle they're high in the hemisphere (roughly 30° latitude), but as the cycle progresses the bands move closer to the equator.

▶ **SOLAR BALL OF STRING** The Sun's magnetic field is a complex, intertwined system that continuously rearranges itself. Shown is a field model overlaid on a picture from January 7, 2014, both from NASA's Solar Dynamics Observatory.

JSOC / HMI / SDO; FACING PAGE: NASA / SDO / LMSAL



their magnetic fields using common processes that somehow create cyclic behavior.

But the way this cyclic magnetic field manifests itself from star to star is far from clear. Subsequent researchers discovered that stars in the Mount Wilson data fall into two rough classes: young, swiftly rotating stars with strong magnetic activity and cycles that last for 300 to 500 rotations, and older, more sluggish stars with less magnetic activity and cycles that last less than 100 stellar rotations.

One of the big problems with this picture is that it's based on a small amount of data. But this picture also caught astronomers' attention because it casts the Sun as the odd man out, sitting squarely in between both classes and producing a new cycle every 160 rotations. Some researchers decided to figure out why.

Kepler Weighs In

Soon after Kepler launched from Cape Canaveral, Florida, on a clear night in March 2009, the mission made headlines around the world for its discovery of planets orbiting stars in the Milky Way. But Kepler discovered more than that. It also found hundreds of stars with starspot cycles.

A few months ago, Travis Metcalfe (Space Science Institute) and Jennifer van Saders (Carnegie Observatories) studied Kepler observations of *F*-, *G*-, and *K*-type stars to understand how the Sun might evolve over time. In the process, they unearthed other stars that didn't fall into the two groups from the Mount Wilson data.

Perhaps, Metcalfe and van Saders reasoned, the Mount Wilson data don't describe two static classes of cycles, but rather two bookends of a star's evolutionary track. In this scenario, a star starts its life in the swift group, hits a critical turning point (which depends on a star's rotation rate and the depth of its convective bubbles), and experiences a weakening of its magnetic field, which transitions it to the other, sluggish group. Eventually, the field stops cycling altogether. In fact, maybe our Sun sits between these two classes because its magnetic field has already started to decay.

If so, this transition may take another 800 million to 2.4 billion years, according to Metcalfe and van Saders. During this period, the solar cycle will slow down. As it does, our familiar Sun — with dark, concentrated spots that appear and disappear over time — will change its look completely: Thanks to its steady field, it will wear a permanent coat of magnetic flecks like speckles on an egg. Eventually, the Sun, no longer an anomaly, will sit comfortably with its elderly companions.

It's an elegant theory, but not without controversy. Some worry we're seeing a relationship that, with more observations, we'll realize isn't there. Others think Kepler's sample may be biased, because Kepler can only observe cycles on stars with huge spots. Cycles on stars with tiny spots would go unnoticed by Kepler's detectors. Furthermore, the original Kepler mission's data only span four years — which means the space telescope couldn't detect cycles as long as the Sun's.

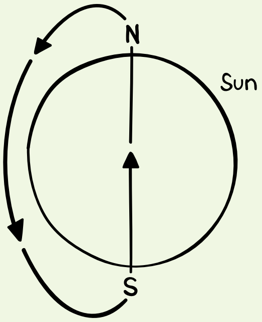
Luckily, solar observations go back much longer than that.

HOW THE SOLAR CYCLE WORKS

By Monica Bobra

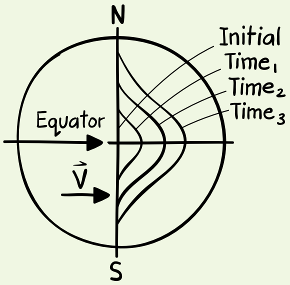
1

Start with a dipolar magnetic field. (This is a simplification.)



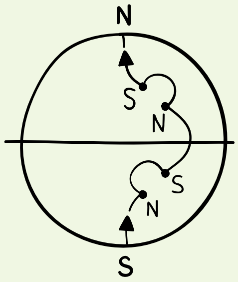
2

The Sun rotates faster at the equator than the poles. This *differential rotation* stretches out the field along the equator. (v is for velocity)



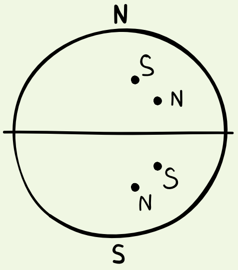
3

Convective bubbles within the Sun transport blobs of plasma to the solar surface, which kink up the stretched magnetic field. This creates mini dipoles at the surface, which we see as sunspot pairs. (Note: The spot pairs are at an angle, and the higher footpoint has an opposite polarity as the solar hemisphere it's in. Important!)



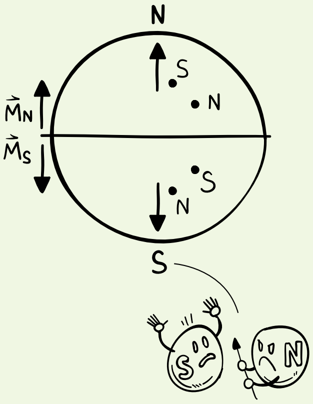
4

Most sunspot pairs cancel each other out quickly: Burbling plasma motions move them around, and their magnetic field lines snap into new configurations. These cancellations leave behind bits of magnetism. Think of them as sunspot debris.

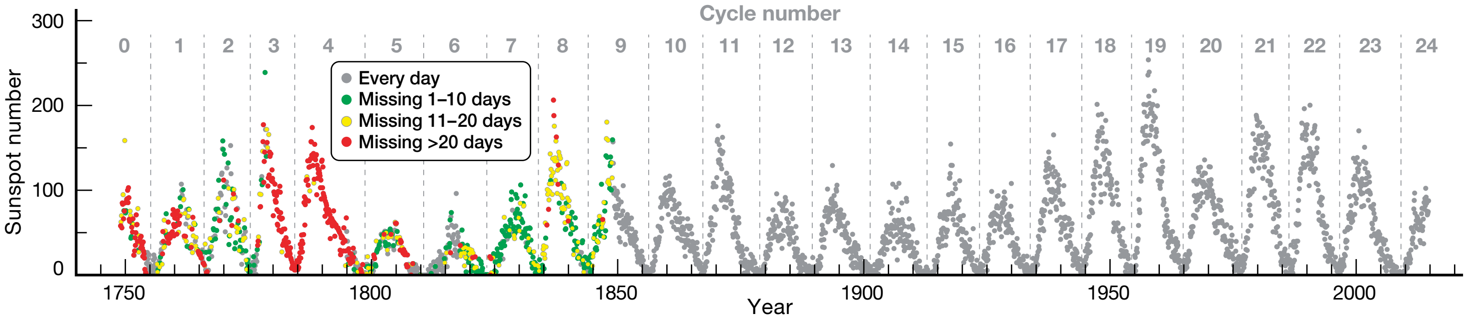


5

Now another motion becomes important: the *meridional flow*. It slowly transports stuff toward the poles. It's also stronger farther from the equator. It drags the bits of opposite-polarity magnetism to the poles, where over time (about 11 years) they chip away at the Sun's polar field.



GREGG DINDERMAN / *S&T*, SOURCE: MONICA BOBRA



▲ **HOW SUNSPOT NUMBERS CHANGE WITH TIME** Scientists use monthly averages of the International Sunspot Number (shown), itself a statistical combination of many observations, to track the solar cycle. (The number of missing days from 1750 to 1818 might be an overestimate.) Dotted lines mark the approximate start of each cycle. As clear from the chart, the solar cycle's strength and duration vary on multiple time scales.

Superficial Sun

The interior of the Sun pulsates as rhythmically as a human heart. Magnetic fluids swish around the solar interior at thousands of different frequencies. Pressure changes inside the Sun create these reverberations, just like pressure changes in the air create sound.

Reporting in early 2017, Rachel Howe (University of Birmingham, UK) and colleagues listened to these heartbeats to study the structure of the solar interior. In particular, they wanted to know why this last sunspot cycle was the weakest one in a hundred years (*S&T:* Nov. 2013, p. 10). Their stethoscope of choice was a series of ground-based telescopes called the Birmingham Solar-Oscillations Network.

Using 31 years of observations, they found that the structure of the Sun's surface layer, where sunspots form, changed markedly in 1994. Since then, far more tiny, weak sunspots have dotted the solar surface than before. And these spots live in the shallowest layer of the Sun, unanchored to deeper layers as in previous cycles. Perhaps, Howe's team speculated, the Sun's surface magnetic field is thinning and its magnetic activity is weakening, its cycle slowing down.

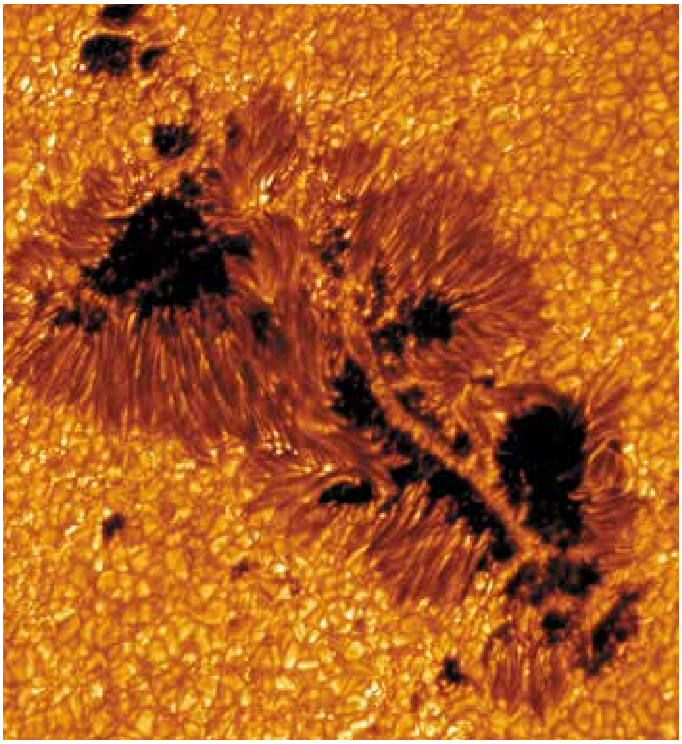
We still don't know whether this change is permanent or temporary. The Sun has deviated from its regular behavior before: The most famous example is a 70-year period in the 17th and 18th centuries called the Maunder Minimum, during which the Sun shed all but a few of its sunspots, only to resume its cycle again. But our star has done the same thing during the Spörer (1450–1540) and Dalton (1790–1830) minima. It might simply be doing it again.

Enduring Mystery

Whether we're in a momentary lull or an everlasting decline, spot cycles can teach us about a lot more than the fate of our Sun. We can also learn about the fate of other planets. For example, scientists pore through data from Kepler and other, ground-based observatories, to search for exoplanets that might be able to support life. But determining a planet's habitability also depends on its host star. If a star plastered with spots releases giant flares, hundreds of times larger than the ones we see on the Sun, a planet in a habitable zone might not be so habitable after all.

In a few months, NASA will launch the Transiting Exoplanet Survey Satellite, which will observe nearly the entire night sky. Kepler, by contrast, only looked at a single patch of the Milky Way during its primary mission, and it can only observe along the ecliptic in its revitalized form (see page 22). With many more nearby stars to observe, we'll undoubtedly learn more about spot cycles. These data will help support, or quench, today's controversial theories. In the process we'll learn a little more about the star closest to home.

■ **MONICA BOBRA** is a solar physicist at Stanford University.



▲ **SUNSPOT CLOSE UP** Twisted, concentrated field lines poking out of the solar surface keep surrounding convective plasma (bright orange) from flowing into their locations, creating local cool spots that we see as sunspots. The widespread, bumpy cells are called *granules*; the feathery edges are the sunspot's *penumbra*, where magnetism leaks out to the rest of the surface.

GRAPH: GREGG DINDERMAN / *S&T*, SOURCE: DAVID H. HATHAWAY / *LIVING REVIEWS IN SOLAR PHYSICS* 2015;
SUNSPOTS: THOMAS BERGER (LMSAL) AND MATS LÖFDAHL (ISP) / SWEDISH 1-METER SOLAR TELESCOPE