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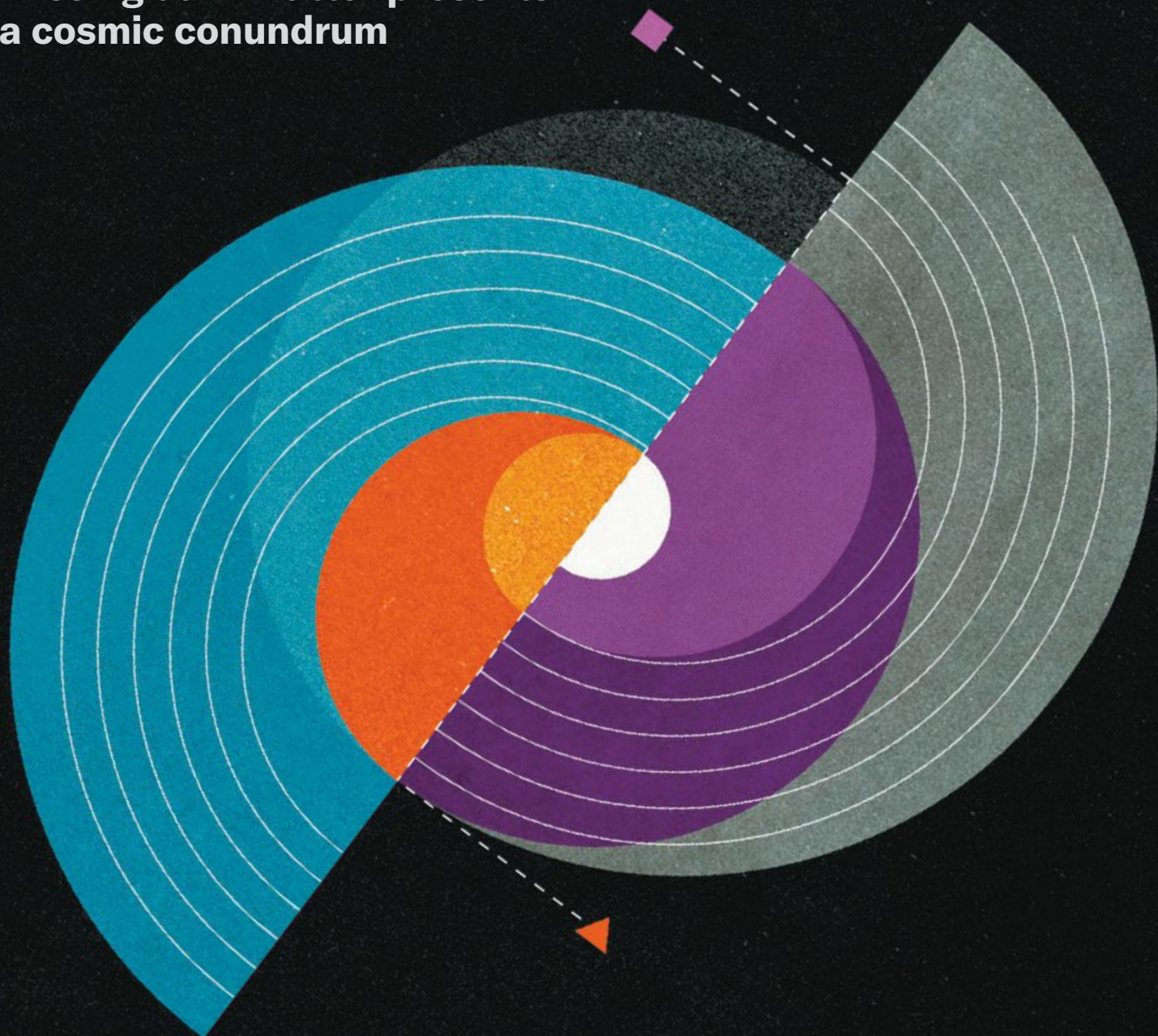
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The Business of Space Weather

A company aims to offer better forecasts based on a new solar model

BY SARAH SCOLES

ON MAY 10, 2024, a John Deere dealer sent out a strange press release. “Please be advised that there is significant solar flare and space weather activity,” it read.

The company, a maker of tractors and ball caps, isn’t the first entity you’d turn to for advice about the sun. But the star’s storms were messing with the GPS systems on John Deere’s precision agricultural equipment, which uses geographic guidance to help farmers precisely plant, spray and harvest crops. “We apologize for the inconvenience,” the press release continued, even though no one should have to apologize on behalf of space.

We tend to think of the sun in terms of its regular daily activities (rising, setting). But “[solar activity](#)” causes eruptions from the sun’s surface that release energy and charged particles into space. Those eruptions have a profound effect on terrestrial life. [Solar storms](#) produce [space weather](#) that can irradiate astronauts and people in planes, disrupt satellites’ electronics and drag their orbits down, and even affect the electrical grid and cell-phone coverage.

These problems are part of why scientists try to [predict how active the sun will be at given times](#), so they can tell farmers when their tractor might drift down the wrong alfalfa row or let electric companies know when they might experience outages. There’s just one problem: we don’t really understand how the sun works in the present, let alone how it will act in the future. Still, heliophysicists, as sun scientists are called, have different, if imperfect, ways of modeling the nearest star so they can make better forecasts.

And a relatively new idea about how solar cycles work could help. It’s called the “terminator” model, and it posits that the sun is dominated by doughnut-shaped magnetic bands that migrate across its surface. According to the theory, which is a departure from traditional models of solar activ-

ity, the appearance, disappearance and travel of these bands on the sun rule our star’s unruly behavior. The theory has worked so well with the most recent solar cycle that one of the scientists who helped to originate the idea has founded a company to sell predictions based on its model.

THE SUN DANCES to its own (currently less than deciphered) rhythms, moving through an [11-year-long cycle](#). It begins relatively quietly, with few sunspots and little stormy activity. As years pass, though, the sunspot number and solar activity ramp up, reaching a maximum about midway through. At that point the sun’s polar magnetic field switches direction, and then its activity wanes back to a minimum before starting the entire process over again. Two of these cycles put together make up a larger one called the Hale cycle, in which the magnetic field finds itself back the way it started.

But precisely how active the sun will be at any given time in any given cycle is up for debate. Near the beginning of each solar cycle, experts get together for a panel sponsored by NASA and the National Oceanic and Atmospheric Administration. There they come to a best-guess consensus about how strong the sun’s activity will be and when that level of activity will occur. “Everybody wants to know what the solar cycle looks like so they can plan for the future,” says Lisa Upton, a scientist at the Southwest Research Institute in Texas and co-chair of the most recent panel.

That last one took place in 2019. Since then, based on what’s actually happened on the sun, Mark Miesch of NOAA’s Space Weather Prediction Center has made [monthly updates](#) to the panel’s forecast—whose timing was off and whose sunspot-activity prediction had proved too low. These updates look “at what we know about the cycle so far and how we expect it to proceed,” Upton says.

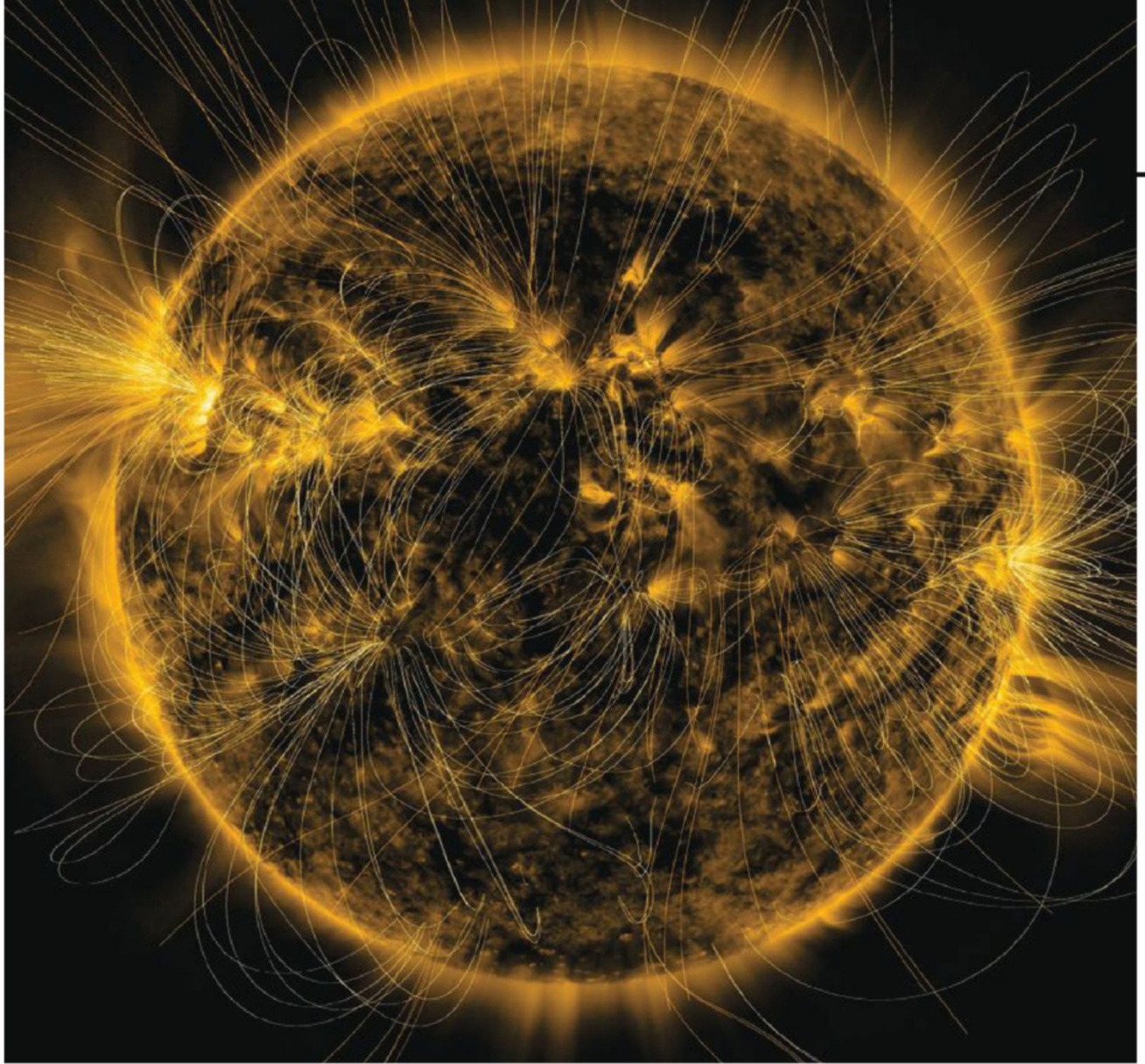
The 2019 forecast—made by some of the world’s

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When solar storms flare up, they can scramble the GPS signals that farmers rely on to guide their high-tech tractors.



Scientists are turning magnetic modeling into a business, selling forecasts to help airlines and satellite firms dodge harmful space weather.

foremost solar experts—has needed modification because the sun is complicated. For one, says Mausumi Dikpati, a senior scientist at the National Center for Atmospheric Research (NCAR) High Altitude Observatory in Boulder, our star's magnetic fields get generated and organized below its surface. "It is very difficult to see what is happening in the inside, in the interior of the sun," Dikpati says.

On top of that, Upton adds, the sun requires scientists to analyze massively different scales—from the spatially small to the extremely huge, from thousands to millions of degrees Fahrenheit, from pressures that would crush a person to pressures millions of times higher than that. It isn't easy to capture those ranges all at once.

That said, scientists use models to simulate aspects of our star, even if they can't capture all of its physics at once. Some researchers use statistical models in which they look at the star's historical behavior and pick out patterns. Others focus on simulating how the sun's plasma and magnetic fields in-

teract or on how its surface magnetic field changes over time. Still others use the sun's oscillations (essentially hot liquid earthquakes) to get a second-hand glance at its interior. Artificial intelligence and machine learning are helping to bring data together with the physical theories, Dikpati says.

Although the progress isn't perfect, it is happening. For instance, researchers are homing in on "seasons" of activity that are interspersed with quiet over periods of six to 18 months. Knowing when a burst might happen within the larger cycle could allow for storm warnings on medium timescales—kind of like a heliophysics *Farmers' Almanac* for both satellite and tractor operators.

A SMALL GROUP OF SCIENTISTS, led by Scott McIntosh, a former deputy director of NCAR, has a different way of thinking about the sun. The researchers' terminator model is gaining traction in part because what it predicted for this cycle has been closer to reality than the expert

GSFC/NASA

prediction that the U.S. government put together.

The model's name is not based on any likelihood of its bringing about the end of the world as we know it. Rather it refers to a type of solar event that McIntosh and his colleagues had identified and christened a terminator.

According to McIntosh, the Hale cycle and the sunspot cycle are both ruled by magnetic bands that wrap around the sun like rings. Near the maximum of the traditional solar cycle, two new bands appear at high latitudes in the sun's northern and southern hemispheres; they have opposite polarities. As the cycle continues, they gradually migrate toward the equator, and new bands again appear at high latitudes—picture the arrangement as kind of like a conveyor belt.

A terminator happens when the older magnetic bands finally collide at the equator. That meet-cute isn't actually cute: it annihilates both old bands because their opposing fields zero them out.

McIntosh's model suggests the annihilation is the definitive end of a solar cycle. The sun's polar magnetic field starts to reverse, and swift sunspots related to the next solar cycle pop up at midlatitudes within days or weeks. "It's like this massive global communication system," McIntosh says of the star's magnetism. And the scenario flips the script on traditional models, making the magnetic field itself the main driver of solar activity and framing the cycle's start and finish around the bands rather than the sunspots.

The amount of time between two terminators—never *exactly* 11 years—is a strong indicator of the strength of the next cycle, according to the model. A shorter gap suggests a more intense sun—which is what the terminator model team predicted for this cycle.

On its own, the model does have limitations. For instance, it doesn't include an underlying physical theory for *why* the sun should work this way; it's more just a statement that, in the scientists' view, our star *does* work this way. "Their thing is purely observational," Dikpati says, although she and her colleagues have published a [paper](#) proposing a mechanism that could explain how terminators set off new sunspot cycles.

In the years since McIntosh and his team first published the idea, they have gone back and "hindcast" previous cycles based on when a terminator has terminated. The model was highly accurate for the tests run on cycles between 1996 and 2006.

Christian Möstl, head of the Austrian Space Weather Office, which maintains the website

[Helio4Cast](#), says that applying the timing of terminator events to make solar-cycle forecasts is highly useful. Although the approach did overestimate the strength of the current cycle, solar cycle 25, a bit, Möstl says his office will use it again to predict the next one. "We don't know yet what it will bring, but the possibility should be taken into account that it might be even stronger than cycle 25," he says.

On the back of his success, McIntosh, with business partner Katherine Monson, has founded a company called Hale SWx. Their goal is to use the terminator model to provide businesses with better solar forecasts. (McIntosh had previously left NCAR to join a company called Lynker, which primarily does solar and space weather work for NOAA.) Hale is working in the industries of precision agriculture, oil and gas, and airlines, among others, Monson says. And it's partnering with Lynker to do work for the Space Weather Prediction Center.

A key clientele will be satellite operators: space weather drags satellites, either leading them to an early death by deorbit or requiring them to use lots of fuel to boost themselves up. A company called Capella Space experienced these effects recently. In August 2024 the firm published a press release, entitled "[Capella's Battle with the Sun](#)," detailing how the atmosphere in low-Earth orbit was two to three times denser than predicted because of solar activity that was higher than in the official forecast. Capella Space's satellite was going to fall back to Earth early; in a [2024 conference paper](#) about the company's experience, an author who was then part of Capella Space's team stated that its members found the terminator forecast to be accurate and began to use it in their modeling. Planet Labs, another company that uses small satellites to observe Earth, also turns to the terminator forecast for modeling.

Regardless of whose forecast people rely on, solar predictions are more important than ever as we Earthlings rely more on electronics and satellites for our own daily cycles. Although the terminator model has caught on, plenty of other ways of thinking about the sun exist—some of them with more physics reasoning underlying them. Given that fact and the sun's complexity, Dikpati has one dictum: "Many models should be allowed," she says, because only diversity in terrestrial thinking can capture celestial complexity—and help John Deere devotees prepare for the solar flares of the future. ●