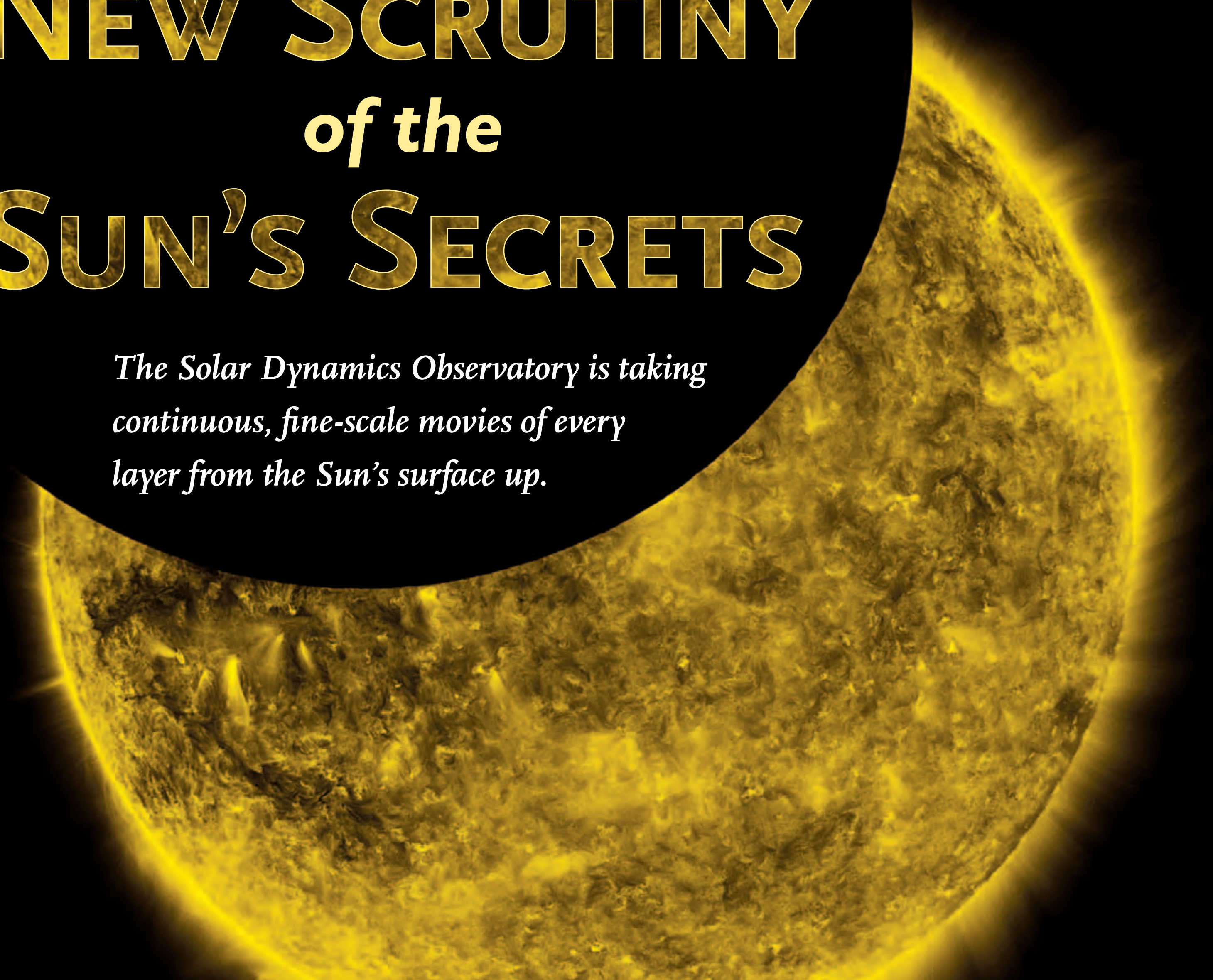
New Scrutiny of the Sun's Secrets

The Solar Dynamics Observatory is taking continuous, fine-scale movies of every layer from the Sun's surface up.

MONICA BOBRA



OFF-PLANET ECLIPSE From its position in geosynchronous orbit 22,000 miles above Earth's surface, SDO sometimes sees the Moon cross the Sun. Low lunar hills are visible on the limb against gossamer loops of plasma in the solar atmosphere.

NASA / SDO / AIA SCIENCE TEAM

AUGUST 1, 2010, was a remarkably active day on the Sun. Several flares erupted, sending gusts of charged particles across the solar system. Some of these particles slid down Earth's magnetic field lines, plunged into the atmosphere, and created vivid curtains of auroral light. Further eruptions have been taking place, and it seems that a new solar-activity cycle is finally under way — providing scientists with a long-awaited opportunity to study renewed solar activity with a new suite of space-borne instruments.

On February 11, 2010, NASA launched its most ambitious endeavor to study the Sun: the nearly $1 billion, three-instrument Solar Dynamics Observatory. SDO was designed to image the activity in every layer of the Sun simultaneously, continuously, and at high resolution and high speed (*S&T:* January 2010, page 22). SDO began observing last April. Here are some early returns from its three instruments.

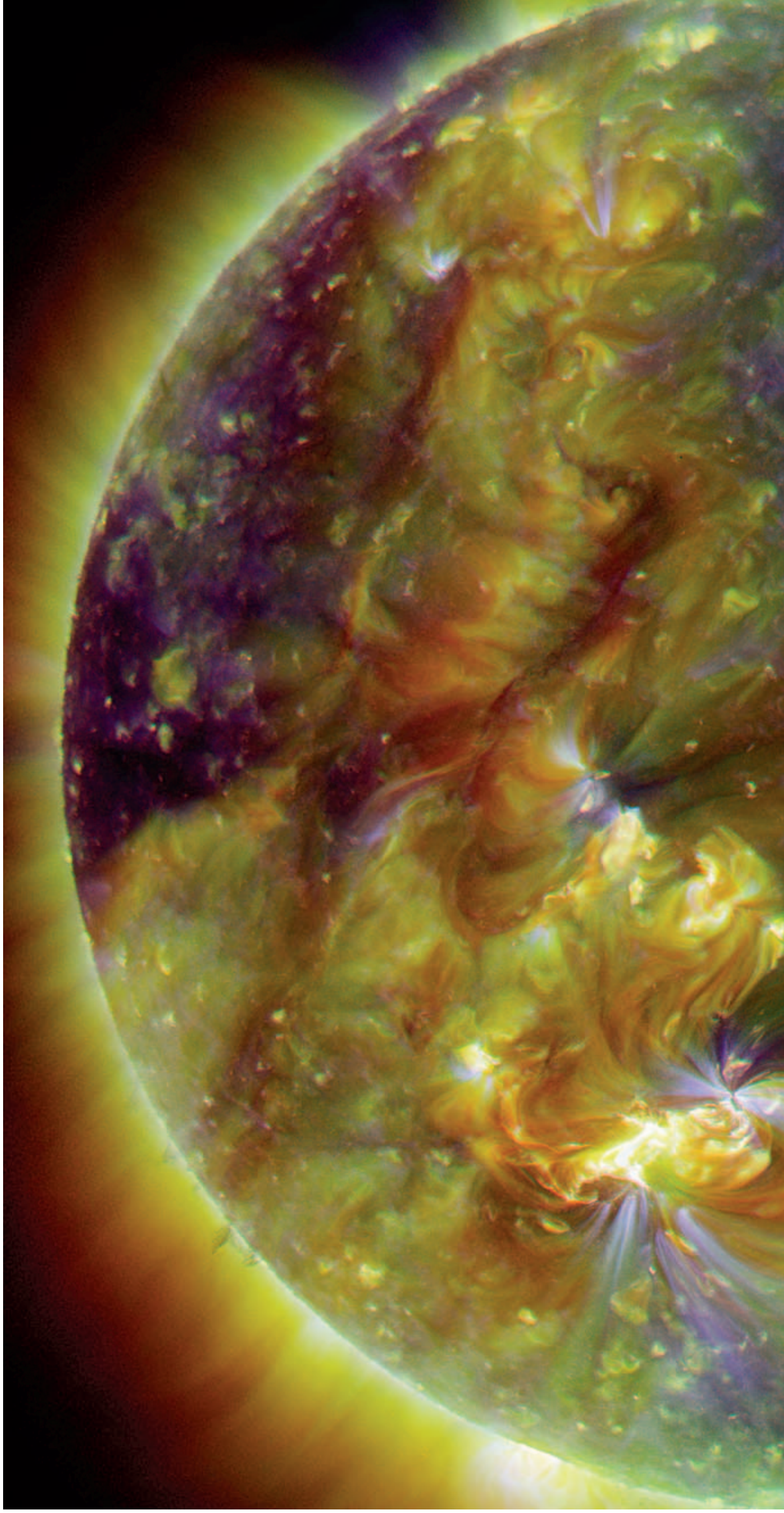
Helioseismic and Magnetic Imager (HMI)

Like swarms of needles poking up through a swath of fabric, magnetic field lines poke through the visible solar surface. In his first look at the Sun through a telescope, Galileo unknowingly viewed these field lines; they cause the Sun to be pockmarked with spots. Sunspots, regions of extremely strong, dense magnetic field, appear dark because they're about a thousand degrees Celsius cooler than the surrounding plasma (ionized gas). Such a strong magnetic field inhibits convection and turnover of surface material, allowing it time to cool.

Although people have observed sunspots for millennia (Chinese astronomers noted them around 20 B.C.), they remain bewilderingly complex and unpredictable. Take, for example, the spot at the top of the next page. Over nine days this solitary spot underwent an astrophysical mitosis, splitting into two identical offspring. Why?

The magnetic field loops emerging from below the solar surface are far from random. Sunspots often cluster in groups, which implies some sort of common process occurring below. Thanks to HMI, scientists will be able to infer better what happens down inside. By combining HMI data with theory, they will model the flow of plasma to a depth of some 20,000 km (12,000 miles) underneath every single sunspot for the next five years. That's 5% of the way down to the Sun's center.

In addition, using a 16-megapixel camera, HMI takes images of the ubiquitous magnetic field at the solar surface. At the bottom of the next page is a high-resolution map of the solar magnetic field, constructed from HMI data. Studying the ebbs and flows of the Sun's surface



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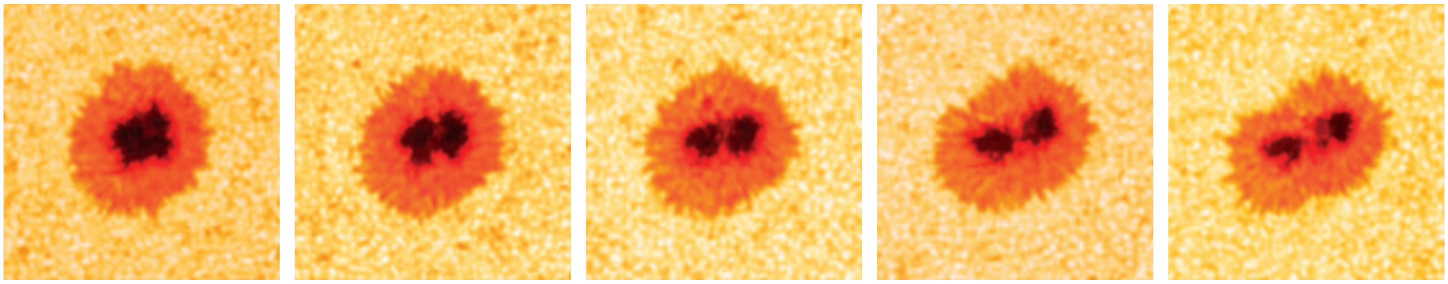
FAST ACTION The resolution of SDO's AIA camera, which took this extreme-ultraviolet image, isn't new. SDO's predecessor, the Transition Region and Coronal Explorer (TRACE), began taking images at 1-arcsecond resolution some 12 years ago. But AIA takes full-disk images at about 500 times the rate ("cadence").



NASA / SDO / HMI SCIENCE TEAM

Get the free tag-linking app for your phone at **http://gettag.mobi**.

Above: **A sunspot's umbra, or dark inner area, is held in the grip of a strong magnetic field. Nevertheless this one, for reasons not well understood, split in two.** ***Left:*** **To watch movies of the Sun in action, you can load the free Microsoft Tag app onto your phone from the URL at left. Then take a picture with your phone of the code square. A page with movies from SDO will open on your screen.**

magnetism is a key to understanding many of the frenetic things happening on and above the Sun, as told on the facing page.

Atmospheric Imaging Assembly (AIA)

The magnetic field is tightly anchored in the Sun's surface. When a flare erupts, the surface itself generally remains unperturbed. The atmosphere above, however, rapidly changes shape. The solar magnetic field is like a willow tree — the branches flail in stormy winds, but the roots stay firm in the ground.

In the AIA image of the solar atmosphere on the previous page, the colors represent different layers spanning more than 2 million degrees Celsius. Blue is the coolest, and red is the hottest. There's a lot going on: bright patches, dark holes, tiny spots ... a circular magnetic wellspring marks an active region, the source of solar flares. Dark, rope-like filaments run across the upper atmosphere. (Where filaments appear against the background of space rather than the solar surface, they glow as prominences.) After this frame was taken, several flares went off in the tangled mess of magnetic activity, sending the filaments flying off the Sun in the direction of Earth. AIA filmed the whole thing.

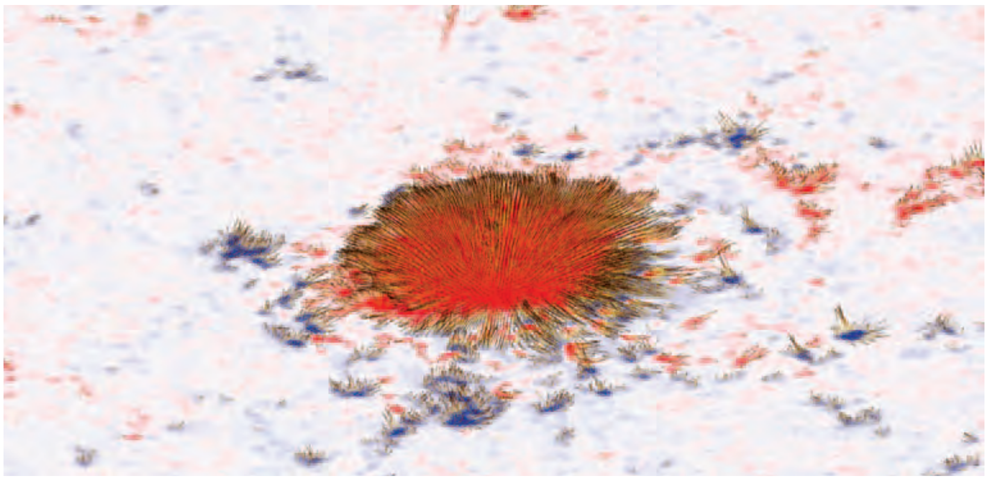
Already, AIA is challenging the notion that flares are isolated patches of activity. Instead, data show that a flare is inextricably linked to the rest of the features across the Sun's 865,000-mile-wide disk.

The AIA movies will likely give scientists clues as to how filaments form in the first place. Some think that shear motions on the churning surface are what create them. Others suspect that filaments bubble up as-is from the solar interior.

When a filament lifts off the Sun, it cools and disperses into interplanetary space. And because the four AIA telescopes take simultaneous exposures in four wavelengths, they can study how this twisted rope of magnetic material changes in temperature, structure, and mass during the beginning of its journey across the solar system.

Extreme-ultraviolet Variability Experiment (EVE)

When a solar eruption hits Earth, it dumps a lot more than just particles into the upper atmosphere. It also delivers lots of high-energy, ionizing radiation, affecting the shape of Earth's ionosphere. Determining how Earth's atmosphere reacts to such energy is an outstanding prob-



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MAGNETIC MAP This is a frame from an SDO movie that maps the swarming magnetic activity in the Sun's light-emitting layer, or photosphere. The photosphere is strangely cooler than the tenuous corona; a mere 6,000°C, compared to the corona's millions of degrees. Magnetic structures leading up from the surface are likely a major part of the coronal heating mechanism.

Why Is the Sun So Complicated?

This wild solar landscape was imaged in the extreme ultraviolet (17.1 nm) by TRACE, the Transition Region and Coronal Explorer.

NASA / TRACE

THE SUN IS JUST A BALL OF GAS, mostly hydrogen. How can something so simple produce such complex, bizarre, unpredictable structures and behavior?

The key is that the Sun's gas is hot enough to be *ionized*: some of its atoms have had an electron knocked off. These free electrons can move around. Any substance with freely movable electrons conducts electricity; metal is an example. So for this purpose, you can think of the Sun as like a churning ball of liquid copper.

The slightest electric current in a conductor creates a magnetic field. Magnetic field lines try to stay fixed in a conductor, like strings in clay. It takes energy to drag the lines sideways through the material, like dragging strings sideways through clay. Instead, if the field lines move they'll tend to drag the conducting material — the gas of the Sun — along with them.

But the Sun's ionized gas doesn't want to cooperate. It has its own agenda: churning and boiling, driven by heat flowing up from below. So the gas sometimes overpowers the magnetic field lines and carries *them* with *it*.

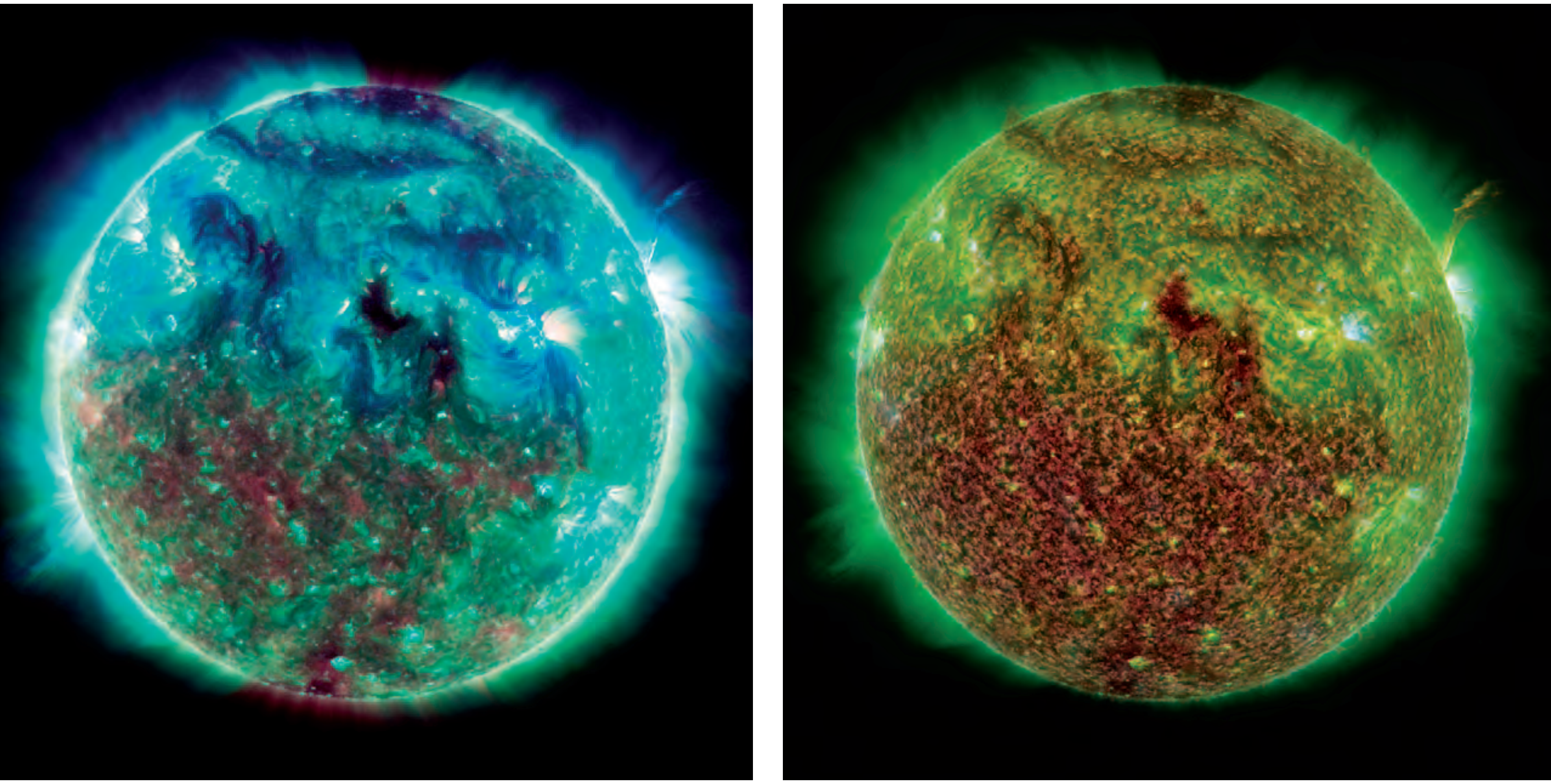
And as you learned in school, a moving magnetic field generates electric current. This current in turn creates *new* magnetic field, which generates new current, and so on.

Here comes the important part. Wherever in nature a runaway positive-feedback arrangement like this gets going, you're likely to see it spawn remarkable, chaotic, endless complexity. Unpredictable *emergent phenomena* appear from it — forms of higher-level organization and structure that you could never have predicted from first principles.

And why does *that* occur? Because — key point, now! — we live in a universe with an interesting property: *energy flowing through a system tends to organize that system* into greater complexity, producing emergent phenomena (at the expense of greater disorder, or entropy, elsewhere).

After all, that's the only kind of universe we could arise to find ourselves living in. Life is an example of this process. On Earth, the energy flow consists of sunlight arriving, driving processes and complexification on the ground, and eventually radiating away to space as waste heat. In the Sun's own case, the energy flow consists of heat coming up from the interior and radiating to space.

The interaction between magnetic fields and fluid conductors is called *magnetohydrodynamics*, or MHD. It is a notoriously difficult field, precisely because MHD systems break so easily into positive feedback, chaos, and emergent phenomena. — *Alan MacRobert*



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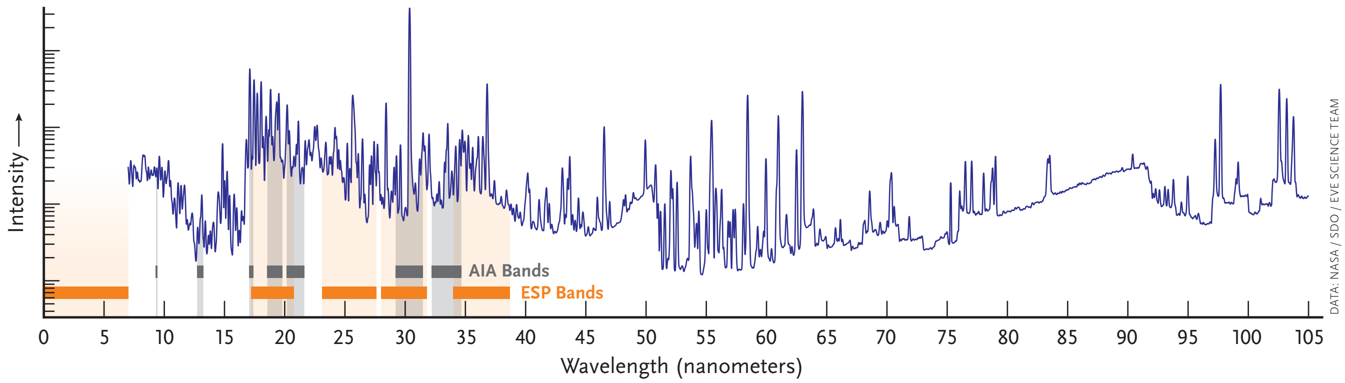
LAYER BY LAYER These images, taken at the same time, show the Sun in different combinations of wavelengths, highlighting layers from the chromosphere just above the white-light surface (30.4 nanometers, shown red) to the upper corona (9.4 nm, blue). The temperature skyrockets in the "transition region" above the chromosphere. As a result, a lot of solar activity happens in this layer.

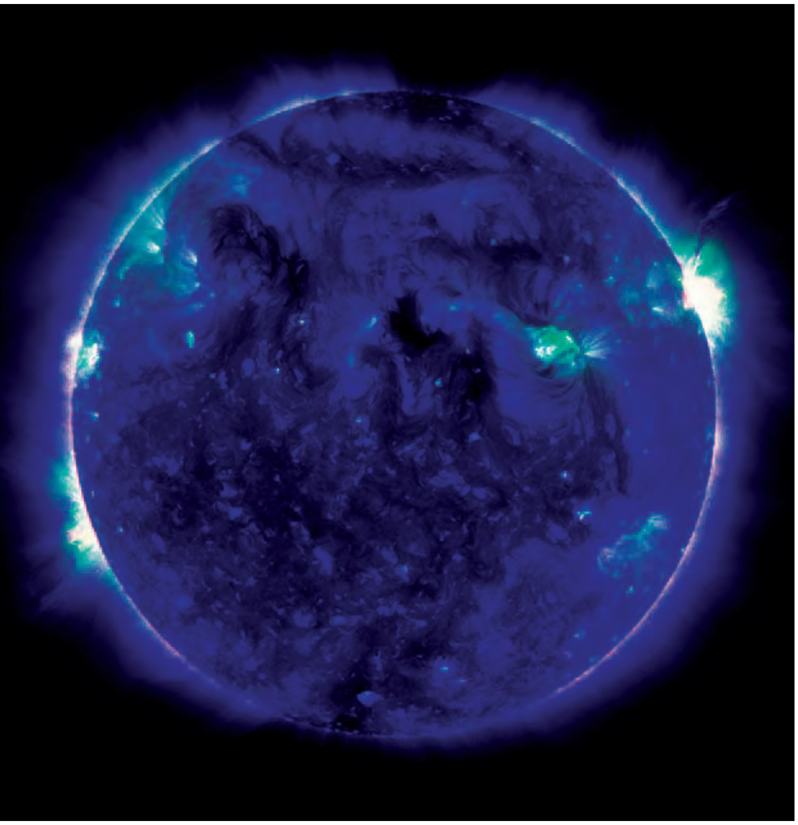
lem in space physics with many practical consequences.

EVE is helping solve this problem by monitoring the Sun's total extreme-ultraviolet output. It sees the Sun as one pixel but resolves a thousand wavelengths from 0.1 to 105 nanometers (1 to 1050 angstrom units), as seen in the spectrum below. Using EVE and AIA data, scientists found a peculiar behavior of solar flares: they shine brightest in ultraviolet when they erupt, but they almost always emit another burst of ultraviolet light some hours later, like an aftershock following an earthquake. That sort of result is integral to learning how flares affect Earth's atmosphere.

EVE scientists have also deduced that a tiny, long-duration flare dumps as much energy into Earth's ionosphere as a huge brief one. The latter ones get the press, but the former are just as important.



BROAD SPECTRUM Instead of taking images, the EVE instrument watches the Sun's ultraviolet spectrum from 0.1 to 105 nanometers. This spectrum is typical. The gray bands indicate the wavelengths that AIA can see. The orange bands show the wavelengths covered by the Extreme Ultraviolet Spectrophotometer, one of EVE's five channels.



Working Continously

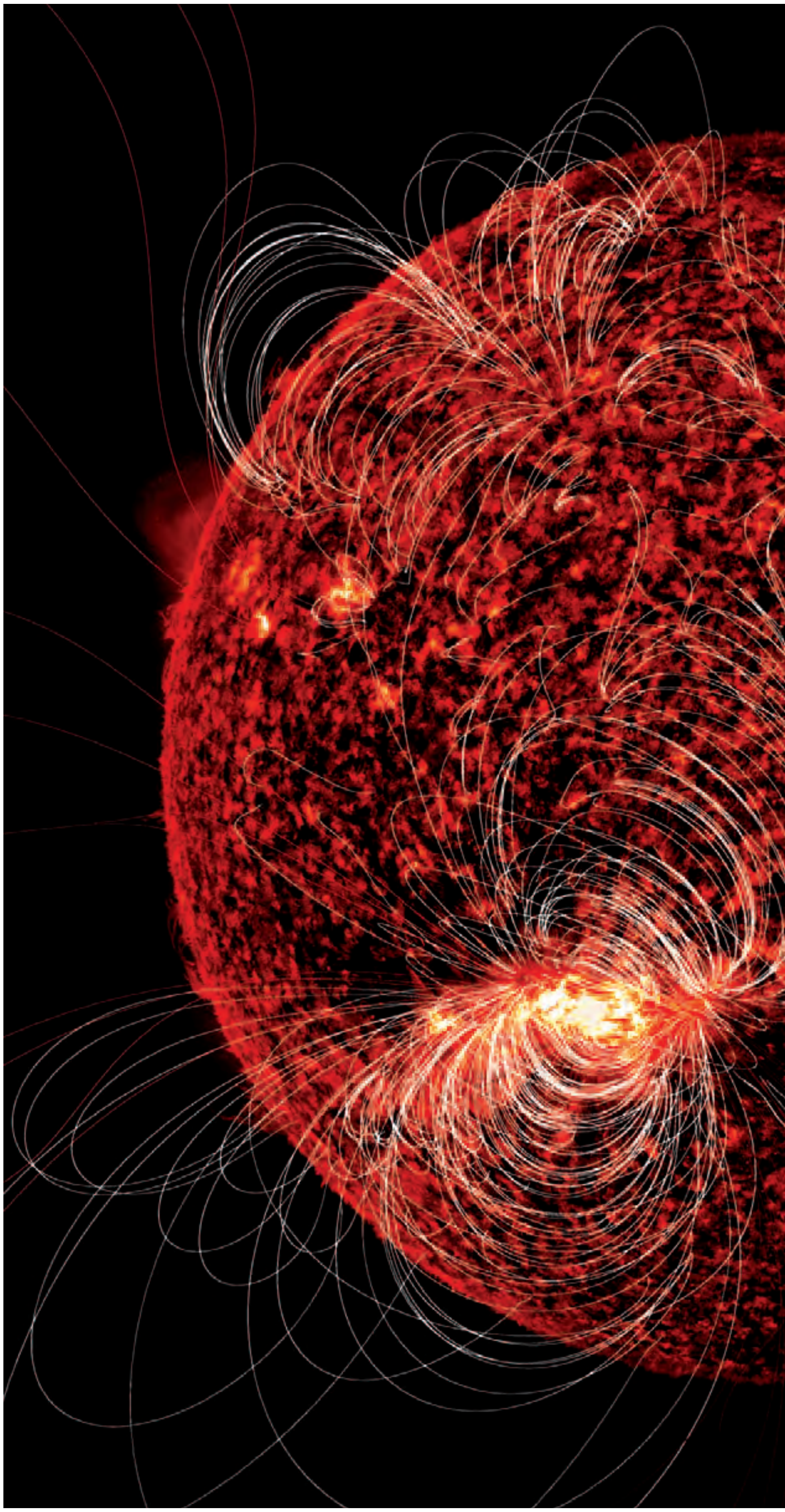
Because it's critical to study not only transient, big events but also the ever-present small ones, SDO doesn't have time to blink. Taking images nearly continuously (95% of the time for the next 5 years), SDO sends back nearly two terabytes of data a day, the highest rate of any spacecraft NASA has flown. By comparison, the Hubble Space Telescope sends down about a thousandth as much.

With so much data, solar scientists hope they can finally study the entire Sun for what it is — not just the star that gives life to Earth, but an immense untapped opportunity to view important universal phenomena up close. ✦

Former S&T *editorial intern* ***Monica Bobra*** *is now a member of the SDO HMI science team. She studies the solar magnetic field at Stanford University.*

For movies, more images, and more about SDO and its work, see SkyandTelescope .com/sdo.

NASA / SDO



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EVERYTHING IS CONNECTED **Combining HMI magnetic-field data at the surface with theoretical models, scientists can predict the shape of the outer field lines and hence the solar corona. In this image, the field lines from a theoretical model (white) are added to an AIA image of the chromosphere. Active regions far apart are revealed as linked.**