To Touch the Sun

NASA's Parker Solar Probe is on a record-breaking journey to study our nearest star.

The launch of the Delta IV Heavy sounded of fire and thunder. The rocket's vibrations rumbled over the team of scientists and engineers standing miles away in the early hours of August 12, 2018, as they watched the rocket carrying NASA's Parker Solar Probe lumber into the sky.

Team member Kelly Korreck (Center for Astrophysics, Harvard & Smithsonian) was tense. As the head of science operations for one of the mission's instrument suites, she knew what to listen for from pre-launch vibrational testing — when one particular instrument mock-up had begun to rock violently.

"In testing, we heard the Solar Probe Cup rattle, just 'djr-djr-djr' at one point in time when it hit a certain frequency," Korreck says. "As I was listening to the frequency of the rocket taking off, I was listening like, 'Oh here she is, oh my goodness, she's rattling right now, she's rattling!'"

Relief came soon enough. Within 45 minutes, the spacecraft sent a signal indicating it had reached its expected trajectory; over the following weeks, its instruments switched on one by one. "That thing is actually going to go into the atmosphere of a star," Korreck recalls thinking. "It's an amazing feeling."

By the time this issue reaches newsstands, Parker will already have swung around the Sun six times, with another 18 passes planned, gradually approaching the Sun. During its final three orbits — starting December 24, 2024 —the spacecraft will pass within 6.2 million kilometers (3.8 million miles, or about 9 solar radii) of the seething gases in the photosphere. At its closest, Parker will be traveling at 190 km/s (430,000 mph), fast enough to travel from New York to Tokyo in under a minute — and faster than any other mission before it.

Designed, built, and operated by the Johns Hopkins Applied Physics Lab, the spacecraft carries four independently developed instruments to this unexplored territory. Mostly shielded behind 11.4 centimeters (4.5 inches) of carbon composite, the detectors measure electric and magnetic fields, plasma properties, and particle energies, as well as image the corona and solar wind. "The spacecraft itself is just crammed tight," says Russell Howard (Naval Research Laboratory), principal investigator of the WISPR camera.

After decades of studying the Sun from afar, Parker's various detectors are finally giving scientists a close-up look at our star — a chance to "touch" the Sun and pierce its mysteries.

Parker will swim in the hot corona as it's being heated and taste the nascent solar wind as its particles are being accelerated.

▶ **LAUNCH** The United Launch Alliance Delta IV Heavy rocket lifts into the air, carrying the Parker Solar Probe sunward.

PARKER ARTIST'S CONCEPT: NASA / JOHNS HOPKINS APL / STEVE GRIBBEN; LAUNCH: BILL INGALLS / NASA

Inside the Sun's Atmosphere

The notion that a spacecraft can touch a star is poetic — but it's scientifically defined, too.

The churning ball of plasma that is our Sun has no solid surface, but witnesses of total solar eclipses have long seen an edge of sorts. When the Moon blocks the glare of the burning Sun, it reveals the softer glow of the solar corona. The transition from searing ball to glowing halo represents the Sun's visible surface, or *photosphere*. Nevertheless, the Sun's dominance extends well beyond the photosphere and into the diffuse outer atmosphere.

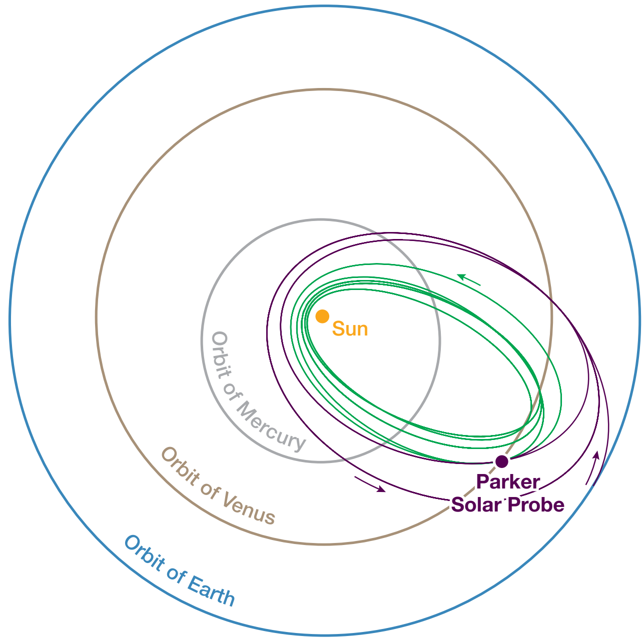
It was observations of the corona during the 1869 total solar eclipse that recorded light emitted by 13-times ionized iron atoms (though it took 73 years to identify them as such). Atoms missing that many electrons can only exist in a plasma heated to millions of degrees, and in 1958 Eugene Parker wrote down the full implications. Such a hot plasma wouldn't stay bound to the Sun, he realized — the charged particles would escape, flowing outward in a supersonic solar wind.

At the time, Parker's idea was so contrary to prevailing ideas that it almost didn't get published. *Astrophysical Journal* editor Subrahmanyan Chandrasekhar didn't like the idea, but he couldn't find anything wrong with Parker's math, so he overruled the scientific reviewers and published the paper. It turned out to be good timing: Just four years later, the Mariner 2 probe confirmed the existence of Parker's theorized solar wind. We now know that the Sun loses the mass of Utah's Great Salt Lake every second.

However, while the existence of the multi-million-degree corona and the speedy solar wind are now well established, their sources have been hotly debated for more than six decades. To understand their origins, astronomers realized, we have to get a lot closer to our star — close enough that the Sun is clearly controlling the physics of what we measure.

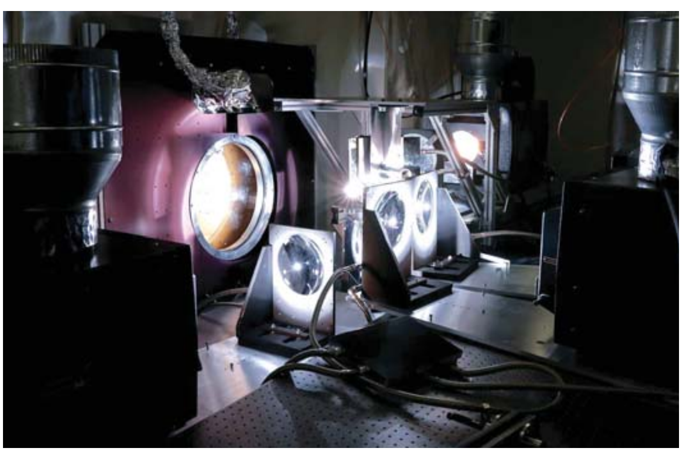
Think of a big prominence rising off the Sun and looping around in the corona, suggests Solar Probe Cup instrument scientist Anthony Case (Center for Astrophysics, Harvard & Smithsonian). As the Sun rotates, the prominence rotates with it — it has to, because the plasma in the prominence follows the magnetic fields that are rooted in the Sun. In a sense, the prominence still "belongs" to the Sun. But at Earth, the magnetized plasma of the solar wind is no longer part of the Sun; it's flowing directly away from it. At some point in between, Case says, there's a transition, one scientists call the *Alfvén radius*.

The Alfvén radius isn't any more solid than the Sun is. Magnetic fields, the density of the solar wind, and other conditions near the Sun are constantly changing. So the boundary between the Sun and its outflowing atmosphere is



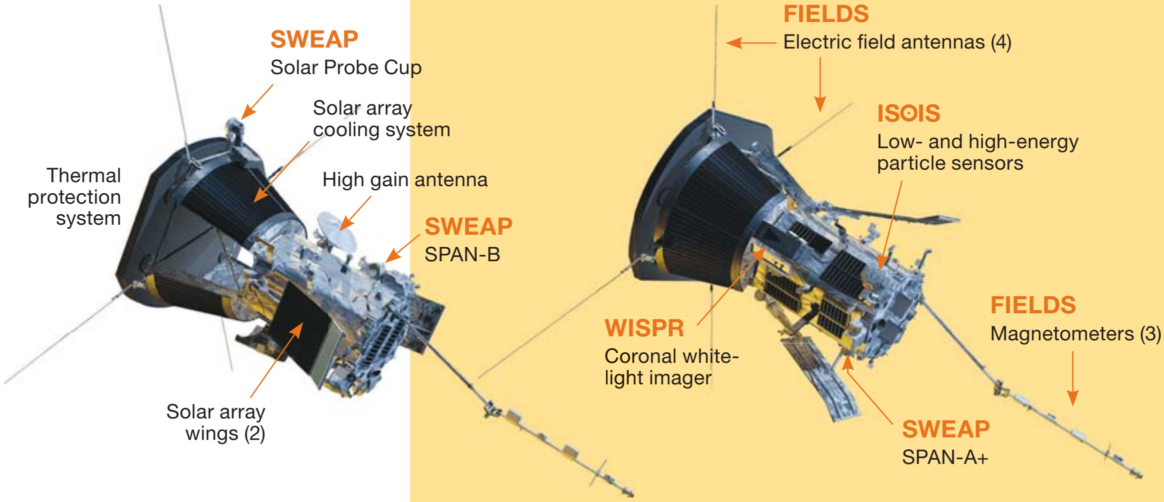
▲ **APPROACH** Parker approaches the Sun over 24 orbits, pictured here. The first perihelion took the spacecraft within 36 times the Sun's radius from the visible surface. The last three perihelia will take Parker within 9 solar radii. Parker's past trajectory and current position are shown in purple; green shows its future path.

▼ **INGENUITY & IMAX** *Left*: The team combined the light from four IMAX-like projectors to simulate the light and heat that would be coming from the Sun. Special lenses of fused silica concentrated and directed the light into a vacuum chamber (the glowing hole seen at left), illuminating the Solar Probe Cup on one side. Particles from an ion gun (wrapped in foil and pointed down at the chamber) simulated the solar wind. *Right*: Instrument scientist Anthony Case prepares the Solar Probe Cup before its integration onto the spacecraft.



PARKER ORBITS: GREGG DINDERMAN / *S&T*; SOURCE: NASA / JOHNS HOPKINS APL; IMAX SETUP: LEVI HUTMACHER / MICHIGAN ENGINEERING, COMMUNICATIONS & MARKETING; SOLAR PROBE CUP: ANDREW WANG / ANDREWTAKESPHOTOS.COM dynamic and bumpy, too. "It's not just plus or minus a mile," Korreck explains. "It's plus or minus a solar radius."

A primary goal for the Parker Solar Probe is to slip inside this boundary, something no spacecraft has ever done. Within the Alfvén radius, Parker will swim in the hot corona as it's being heated and taste the nascent solar wind as its particles are being accelerated.



▲ **ALL ABOARD** These views show the instruments aboard the Parker Solar Probe. The view at right shows the side of the spacecraft that faces the direction of motion.

Taking the Heat

Before Parker can do any of that, though, it must first survive its close approaches to the stellar furnace. The good news is that the environment doesn't feel as hot as one might think. While the temperature of the corona is more than a million degrees, that number describes the motions of the plasma's particles, and they're too sparse to transfer heat to Parker. The heat the probe does feel comes from the sunlight itself. The difference is like sticking your hand in a hot oven rather than in a glass of hot water.

Still, radiational heat at closest approach is 500 times what we receive at Earth. Unshielded, Parker would reach temperatures approaching 1,400°C (2,500°F) — hotter than any lava on Earth. Most of the instruments therefore take their measurements from behind the shelter of a heat shield, a masterpiece of thermal engineering that took more than a decade to create. Two thin layers of a graphite-like carbon material sandwich a thick slice of carbon foam that's so lightweight it's 97% empty. An ultra-white aluminum oxide coating on the shield's sunward-facing side reflects most of the light and

▼ **STANDING TALL** The Parker Solar Probe looks small inside one half of the 19.1-meter-tall (62.7-foot-tall) fairing. Although the probe was small compared to what a Delta IV Heavy usually carries, the rocket provided the necessary lift to bring Parker close to the Sun.

▼ **PARKER'S SUNSCREEN** The heat shield consists of two main components: a light carbon foam that's mostly space and a bright white coating of aluminum oxide. A thin tungsten layer separates the two so that they don't interact.

PARKER INSTRUMENTS: NASA / JOHNS HOPKINS APL (2); HEAT SHIELD: NASA / JOHNS HOPKINS APL / ED WHITMAN; PARKER IN ROCKET FAIRING: NASA / JOHNS HOPKINS APL / ED WHITMAN heat; a fine layer of tungsten keeps the aluminum oxide from interacting with the carbon foam and turning gray.

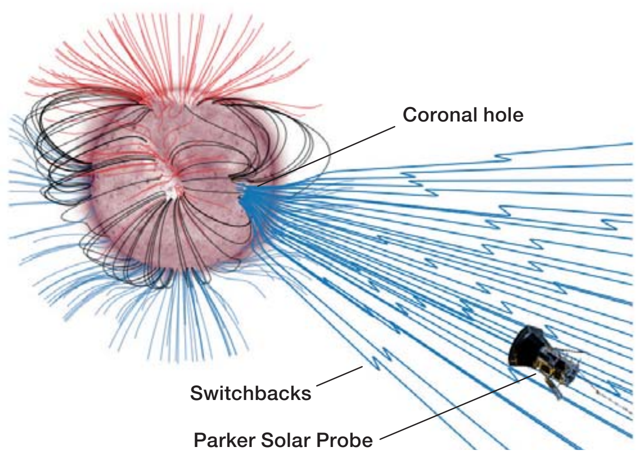
The shield keeps most instruments at roughly room temperature, except for two that extend beyond it. The Solar Probe Cup (SPC), one of the Solar Wind Electrons, Alphas, and Protons (SWEAP) instruments, hangs outside the heat shield to point its particle-collecting receptacle directly toward the Sun. And four whip antennas that help measure the electric field, part of the FIELDS electromagnetic instrument suite, also extend beyond the heat shield.

Developing instruments that could function so close to the Sun took trial and error, sometimes behind a welding curtain. During material tests, the lab smelled like a pan left on the stove too long. The "mistakes" still hang on the wall: deformed plates of stainless steel and unalloyed titanium. At testing temperatures of some 1,600°C, "all steels melt, all aluminum is long gone," says structural engineer Henry Bergner (Center for Astrophysics, Harvard & Smithsonian). The only options remaining are refractory metals, like those used in nuclear reactors or rocket nozzles.

In the end, the team decided on molybdenum alloyed with titanium and zirconium for the bulk of the cup. The team also used lab-made sapphire to insulate the electronics, after figuring out how to grow the crystals in a way that keeps them from cracking at extreme temperatures.

Testing the instrument required some ingenuity. To simulate the light and the heat that the SPC would experience near the Sun, the team concentrated the light of four IMAX-like projectors into a vacuum chamber using special lenses of fused silica. Sometimes the building's air conditioning couldn't keep up.

For the FIELDS instruments, the whip antennas that extend beyond the shield easily withstand the heat. But these



▲ **CORONAL WINDOW** This schematic shows a possible magnetic configuration for the Sun during Parker's first perihelion. The color of the Sun represents extreme ultraviolet emission; white areas on the surface represent regions where magnetic field lines escape into interplanetary space, known as coronal holes. Parker encountered such a region during its first pass around the Sun — along with thousands of magnetic switchbacks.

PARKER'S VENUS FLYBY: NASA / JOHNS HOPKINS APL / STEVE GRIBBEN; MAGNETIC FIELD SCHEMATIC: UNIVERSITY OF CALIFORNIA, BERKELEY; SPACECRAFT IMAGE: NASA / JOHNS HOPKINS APL

To the Sun, Via Venus

▲ **VENUS FLYBY** Seven gravity assists from Venus boost the Parker Solar Probe on its journey toward the Sun.

Approaching the Sun takes more energy than leaving the solar system altogether, as any spacecraft leaving Earth inherits its orbital speed of 30 km/s (66,500 mph). Slowing that momentum counterintuitively takes more energy, says mission designer Yanping Guo (Johns Hopkins University Applied Physics Laboratory). "The launch energy required to reach the Sun is more than 50 times that required to reach Mars and twice that to reach Pluto!"

When mission planning began, the best option for losing so much speed — a swing around Jupiter — was out of the question. A Jupiter flyby usually requires nuclear power, and NASA's limited supply of plutonium-238 was already spoken for by other missions.

For Parker to even begin development, it would need another way to the Sun. Guo realized that seven swings by Venus rather than one by Jupiter could do the trick. It only works because the braking maneuvers around Venus are tightly coupled, so that one flyby sets the spacecraft up for the next one.

The flybys serve as more than a trajectory assist. Inhospitable Venus has been relatively neglected by spacecraft in the last three decades (*S&T:* Sept. 2018, p. 14). Parker gives planetary scientists an opportunity to explore its alien atmosphere as well as the fields induced by the charged plasma that flows around this magnetically dead world.

Shannon Curry (University of California, Berkeley) says the initial results from the first two Venus encounters are promising. "We're finding things that have never been explored outside Earth, not even at Mars," Curry says. "Microscale physics that explain a lot of how things like bow shocks form, how the magnetotail structure works, how magnetic reconnection works."

Previous missions had quantified how much atmosphere typically manages to escape, Curry adds, and Parker's data are now revealing how and why. Scientists can then extrapolate back in time to understand how Venus was able to maintain its thick shroud without a magnetic field to protect it — a question relevant to other worlds such as Titan and even exoplanets.

long, hollow tubes of reactor-grade niobium, which help measure the electric field, still have to connect to a room-temperature spacecraft. Fortunately, the tubes' walls are so thin that they fix their own problem: They barely conduct heat. "Once you put that tube behind any little bit of shadow, it just chokes the heat flow down," explains Stuart Bale (University of California, Berkeley), FIELDS principal investigator.

The other instruments of SWEAP and FIELDS hide in the shadow behind the spacecraft. Their protection from the heat is so effective, they actually need heaters to keep them warm at closest approach.

The solar panels are also behind the heat shield but are, for obvious reasons, partially exposed to the Sun's light. They keep cool with about a gallon of deionized water, which flows through small channels embedded in the panels and then into four radiators. Like our vascular system, the water absorbs heat, then radiates it back into space — keeping the panels efficiently generating energy.

"The spacecraft is like a warm-blooded animal, it regulates its own temperature," says SWEAP principal investigator Justin Kasper (University of Michigan).

Indeed, Parker is one of the most autonomous spacecraft ever launched. Communicating with Earth takes power that's required for instrumentation, so during its searingly close passes by the Sun, the spacecraft flies on its own. "It's quite a bit of the mission that we're not communicating with this thing at all," Bergner says.

A variety of sensors and controls aids Parker in its decision-making. In response to rising heat, the spacecraft can fold back its solar panels, and star trackers and light sensors help the spacecraft keep all its instruments in the heat shield's shadow. "She's an adult," Korreck says. "She's taking care of herself now."

▲ **GOING TO THE SOURCE** An artist's concept shows Parker flying into the solar wind. By sampling the charged particles closer to where they are first accelerated, the mission hopes to understand their origin.

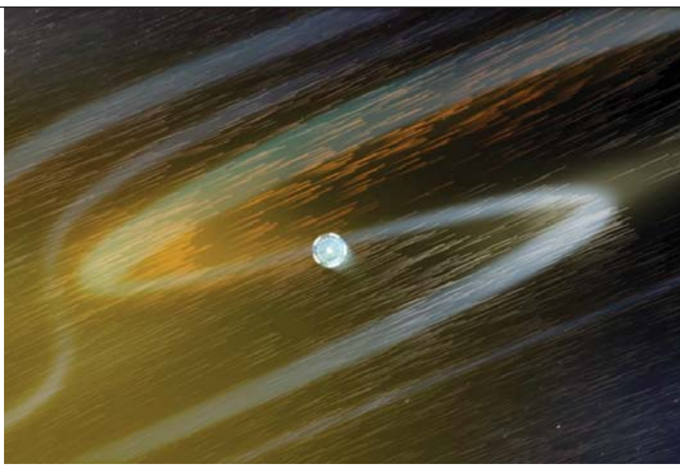
First Encounters

Data from Parker's first three perihelia have already shown scientists the unique environment that exists around our star.

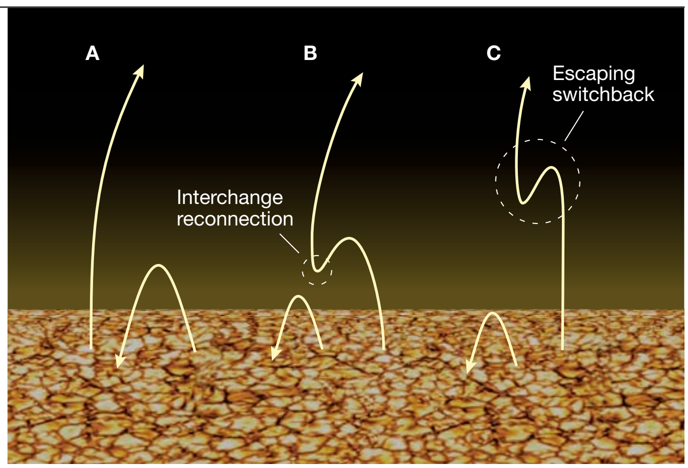
To study the solar wind, Parker's SWEAP and FIELDS instrument suites combine forces. SWEAP uses three instruments, including the Solar Probe Cup, to measure particles' density, speed, direction, and temperature. Meanwhile, FIELDS uses its three magnetometers and five voltage sensors to feel out the magnetic and electric fields entrained in the particles sweeping past.

Together, these measurements provide the data necessary to watch the sea of charged particles flowing by — and they have been crucial to identifying thousands of so-called *rogue waves* crashing over the spacecraft (*S&T:* Apr. 2020, p. 10).

These sudden bursts of speedy particles come with 180° flips in the magnetic field. "There's some dynamics down below Parker that's creating these impulsive things that are



▲ **SWITCHBACK** This still from an animation shows what a single switchback might look like, depicting both the S-shape curve to the magnetic field line and the accompanying burst of solar wind particles that Parker observes as it flies through the structure. While a known phenomenon, switchbacks surprised astronomers in their abundance during Parker's initial flybys.



▲ **SWITCHING SOURCE** One potential explanation of switchbacks is the reorganization of magnetic fields nearer the visible surface of the Sun by a process called *interchange reconnection*. Here, two opposing magnetic field lines meet (A), connecting at the point where they would cross (B), and then sending a burst of particles accelerating outward accompanied by an S-shape twist in the magnetic field (C).

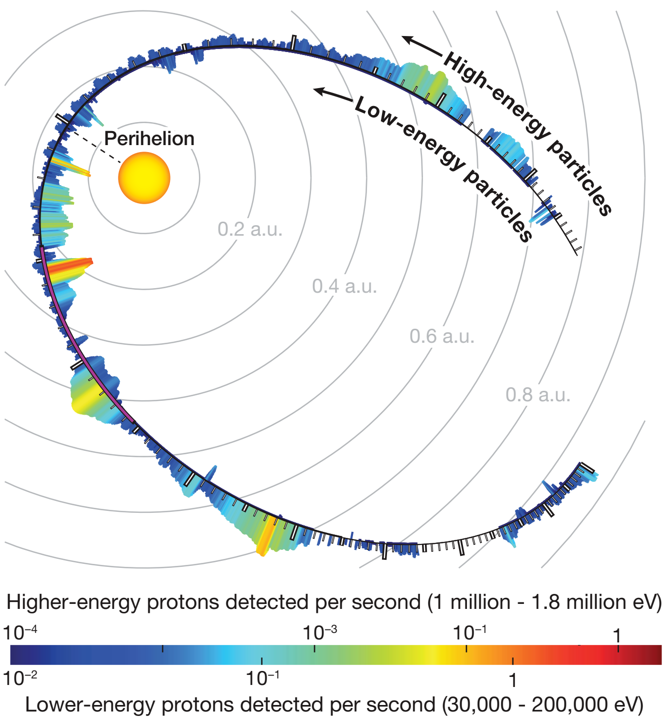
PARKER FLYING THROUGH SOLAR WIND: NASA; SWITCHBACKS ILLUSTRATION: NASA GODDARD / CIL / ADRIANA MANRIQUE GUTIERREZ; INTERCHANGE RECONNECTION: GREGG DINDERMAN / *S&T*; SOURCE: JUSTIN KASPER / LEVI HUTMACHER / UNIVERSITY OF MICHIGAN ENGINEERING being carried out by the wind," Bale explains. In other words, deep down in the corona, still beyond Parker's reach, *something* happens.

By the time it reaches Parker, the event appears as a huge S-shape twist in the magnetic field extending outward from the Sun that's about 50 times longer than it is across. The particles within this magnetic switchback are flowing about twice as fast as the particles outside.

Scientists had seen signatures of these switchbacks in data collected by the Helios and Ulysses missions. But Parker revealed that the events were both more transient and more prevalent than previously thought — basically, whatever's producing these events nearer the solar surface, it's happening everywhere, all the time. "The sheer number of them and the size of them is surprising," says Case.

Some have suggested that the rogue waves come from magnetic reconnection at or near the solar surface. When the magnetic field reorganizes — an open field line jumping from here to there — the process lets loose a burst of particles that then, much later, zooms past Parker.

"But my own feeling is that they are not direct evidence of reconnection," Bale says, "because it looks to us like the plasma inside the switchbacks and the plasma outside the switchbacks are basically the same." Reconnection, on the other hand, would be heating particles in addition to accelerating them.



▲ **SPED-UP PARTICLES** ISOIS's energetic particle instruments monitored particle energies and densities throughout the first pass around the Sun, with few gaps between October 2018 and January 2019. Most of the energetic particles are protons, at both low (30,000–200,000 eV) and high (1 million–1.8 million eV) energies. Both the color and length of the bars indicate how many particles per second the instruments were detecting in their respective energy ranges.

Instead, Bale suggests, the switchbacks could be heralds of *Alfvén waves* deep in the corona. Alfvén waves are a simple feature of just about any magnetized plasma. As charged particles move around, so do the magnetic fields tied to them, wiggling like so many plucked guitar strings. "We're just seeing Alfvén waves that have grown to be so big that they're flipping over on themselves," Bale speculates. But it's not the only idea out there, he adds: "Reasonable people would disagree with me."

Whatever switchbacks are, they're giving us information about what heats the solar corona, whether that mechanism involves magnetic reconnection, plain ol' Alfvén waves, or something else entirely. Thinking over the possible scenarios is half the fun. "The whole point of getting closer is that we'll see the [switchbacks] in more of their original state," Case says.

Harbingers of Storms

Not all of what comes from the Sun is solar wind. Some tiny fraction of charged particles in the corona somehow accelerate to near-light speed, following different paths than their brethren. While the solar wind typically streams at 400 km/s (almost 1 million mph), *solar energetic particles* can carry anywhere from 10 to 100,000 times that energy.

When the Sun is active, these particles can serve as the Paul Reveres of solar storms. But even during quiet times, as now, these particles — though few in number — are constantly flying out from the Sun.

Rather than blowing outward in bulk, the way most of the solar wind does, these charged particles are more like individuals, spiraling around the magnetic field lines that coil outward from the Sun. Because of their different paths, "they're actually sampling quite different regions than the [solar wind] plasma that you're measuring at the same time," explains David McComas (Princeton), principal investigator of the Integrated Science Investigation of the Sun (ISOIS) instruments. So connecting the particles to the processes that created them can be tricky.

ISOIS has two instruments that together detect energetic particles across a wide range of energies, from thousands to millions of electron volts. To maximize the number of particles it can capture, ISOIS sits right at the edge of the heat shield. "It's completely out of the view of the Sun, but just by a degree or two," McComas says.

From this vantage point, ISOIS has access to details impossible to tease apart near Earth. So McComas can finally start answering one of the many questions he has had since the beginning of his career: "Why is it that some particular proton ends up being the million-electron-volt particle and almost none of the rest of them do?"

The answer, he says, has to do with the very first processes, the ones that accelerate particles a little bit, so that they can then efficiently reach much higher energies later on. For the first time, ISOIS can detect these tiny accelerating events, and it's showing that they may be much more common than previously thought.

GREGG DINDERMAN / *S&T*; SOURCE: MCCOMAS ET AL. / *NATURE* 2019 DECEMBER 12

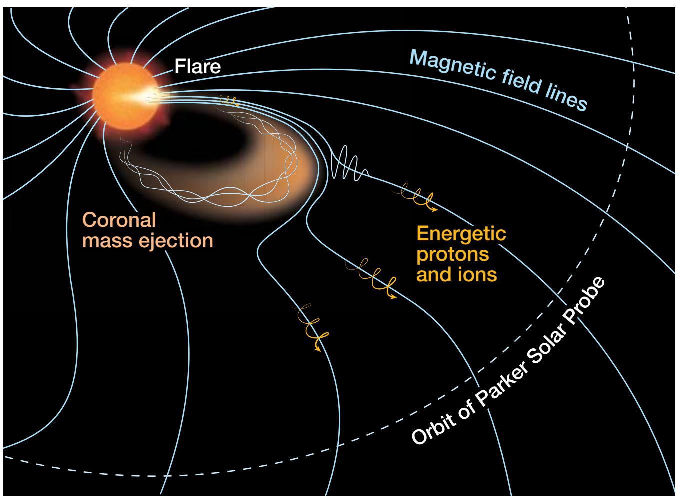
Researchers are only starting to untangle the data, and there are much more to come. "One of the most exciting things so far — and we haven't even gotten that close yet — is that we're seeing smaller and smaller and smaller events as we get in closer," McComas says.

Where the Dust Never Settles

There's one other thing that Parker encounters that doesn't actually come from the Sun: dust. The spacecraft is flying through the densest region of the solar system's *zodiacal cloud*. Comets and asteroids coming too close to the Sun break up and their fragments collide, grinding down until nothing but micron-scale electrically charged particles remain. Due to their interactions with sunlight, these particles slowly spiral in toward the Sun, though when the particles become small enough sunlight may instead push them away.

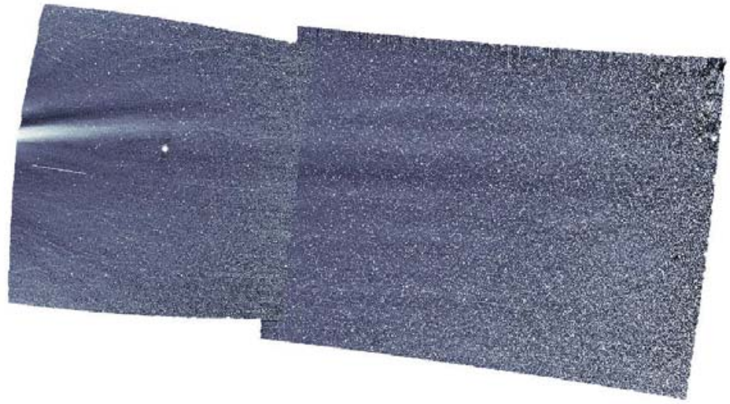
The Wide-field Imager for Solar Probe (WISPR) is Parker's only imager, a roughly shoebox-size telescope that peeks over the edge of the spacecraft to capture sunlight scattering off electrons and dust. The heat shield acts like a coronagraph, blocking the light from the Sun itself, which is 13 to 15 orders of magnitude brighter than the corona. The images provide context for Parker's other measurements, revealing structures — such as large-scale solar storms or even small-scale twists of the magnetic field — before the spacecraft flies into them and samples them directly.

Already, WISPR's PI Howard and colleagues have seen that the emission from dust-scattered sunlight drops off in a way that suggests a dust-free region extends out to at least 10 solar radii from the Sun's surface (*S&T:* Apr. 2020, p. 10). The drop-off is so smooth, Howard says, that he doesn't think the heat is sublimating dust grains, species by species, directly into gaseous form. Instead, he thinks the particles are eroding, broken up by the pervading solar wind, and gradually being pushed back out.



▲ **"PAUL REVERES"** This schematic shows an explosion on the visible surface of the Sun that ejects material out into the solar system, termed a *coronal mass ejection*. ISOIS scientists discovered that energetic charged particles rushed ahead of one such eruption that Parker witnessed during its first orbits. The particles could provide advance warning to satellites and astronauts of the incoming space weather threat.

SOLAR ENERGETIC PARTICLES: NASA / PRINCETON / JOHNS HOPKINS APL; WISPR IMAGE: NASA / NAVAL RESEARCH LABORATORY / PARKER SOLAR PROBE



▲ **SEEING SOLAR WIND** Parker's views of the streaming solar wind are oblique — its WISPR imager cannot stare straight at the Sun, so it looks off to the side in the direction that Parker is traveling. Nevertheless, the images are critical to seeing ahead of time what space environment Parker will encounter.

Parker's other instruments can detect dust indirectly, too. FIELDS, for example, measures the momentary voltage generated when a dust grain slams into the spacecraft and vaporizes into plasma. ISOIS can likewise detect dust impacts. Jamey Szalay (Princeton) and colleagues have used these data to conclude that the Sun is ejecting dust from the solar system at a rate of at least half a ton per second. Ultimately, such results could help astronomers understand planetary formation in systems around other stars.

Every Orbit Closer

The Parker Solar Probe launched during solar minimum, giving scientists the opportunity to study the extraordinarily quiet Sun and its relatively undisturbed (but still churning) fields and particles.

But even as scientists continue to pore over the data from the initial orbits, the Sun's activity should begin to ramp up, and solar eruptions will dump more and more energy into the corona. The maximum in solar activity will come between 2023 and 2026 — around when Parker is at its closest to the Sun, swinging within 9 solar radii of the visible surface.

Other telescopes will soon be joining in on the fun. The Daniel K. Inouye Solar Telescope in Hawai'i, which is still in the process of coming online, took its first light images in January, and the European Space Agency's Solar Orbiter reached its first perihelion in June (see page 9).

Crucially, well before solar maximum, Parker will pass within the Alfvén radius. "We almost did it with encounter four," Bale says. "In the next couple of orbits for sure, probably." Once inside, the spacecraft will finally "touch" the Sun. Will scientists find answers there? Certainly. But as McComas points out, "The point is to get more questions. Answer the questions you've had for a while, and uncover the next, more difficult round."

■ *Sky & Telescope*'s News Editor **MONICA YOUNG** is glad to see that the Parker Solar Probe has put on sunblock before catching some rays.