



A JOURNEY to TOUCH the SUN —

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The Parker Solar Probe is braving extreme conditions to explore the mysterious solar corona, a region that harbors some of the most difficult-to-understand phenomena in astrophysics.

The *Parker Solar Probe* (PSP) is exploring the Sun's atmosphere, one of the last unvisited and extreme regions in our solar system.¹ Launched on 12 August 2018, the PSP has flown closer to the Sun's surface than any other spacecraft. By 24 October 2022, the PSP had completed 13 of the 24 solar orbits scheduled for its seven-year mission. On 16 October 2021, the spacecraft flew by Venus for the fifth time. One month later, it achieved the closest approach yet—13.28 solar radii from the center of the Sun. It will use Venus for two more gravity assists to reach its ultimate perihelion on 24 December 2024: That closest point of 9.86 solar radii is about 4.5% of the Sun–Earth distance.

One of the phenomena the PSP is investigating is the solar corona, the most challenging region of the heliosphere because of its extreme conditions. From the corona, the solar wind flows to fill the whole heliosphere, which extends about 100 astronomical units (AU) from the Sun. The solar surface—the photosphere—is a million times as bright as the corona, yet the corona is more than 300 times as hot. The primary science objective of the mission is to determine the structure and dynamics of the Sun's coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and find what processes accelerate energetic particles.

Challenges of the mission

By 1958 the science case for a solar probe was already mature. It proved, however, very challenging to implement such a mission. The solar

probe has been the top priority of several Decadal Surveys for Solar and Space Physics (Helio-physics) conducted by the National Academies of Sciences, Engineering, and Medicine. Yet five studies (1982, 1989, 1994, 1999, and 2005) did not culminate in the mission's execution. They were all predicated on using nuclear power to propel the spacecraft. Then a Jupiter gravity assist would slingshot it out of the ecliptic into a trajectory in which it would fly above one of the solar poles before plunging to the perihelion at about four solar radii. It would then be sent into the subsonic solar wind. Several scientific, technological, and cost factors, however, thwarted that concept: the short time during which data were collected at perihelion (16 hours pole to pole), the limited number of solar passes (two at most), the high probability that the sonic boundary is below four solar radii, and the lack of nuclear power available for public civilian spacecraft.

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In 2007 NASA endorsed a new mission profile that uses seven Venus gravity assists so that the spacecraft can dive progressively closer to the Sun. Although the new orbit allows the spacecraft to fly only as close as 9.86 solar radii from the Sun's center, it permits a significantly lengthier mission, of seven years, to measure the solar wind's state through the major parts of the solar cycle—namely, from the minimum to the maximum.

Deep roots in coronal mysteries

During the 1869 total solar eclipse, William Harkness and Charles Augustus Young independently observed a new spectral line of the Sun's visible light at a wavelength of 5305 Å, the so-called green line. It did not, however, belong to any of the known elements. Anton Karl Grünwald named the hypothetical new chemical element "coronium." In the late 1930s, Walter Grotrian calculated the existence of an atomic transition that coincided with the green line, and Bengt Edlén confirmed it through laboratory spectroscopy experiments.² The spectral line belonged not to a new chemical element, as proposed five decades previously, but to the highly ionized Fe^{13+} , an iron atom stripped of 13 of its 26 electrons.

Scientists were then faced with a much more complex phenomenon. That Fe^{13+} can exist only in multimillion-degree hot plasmas is why the solar corona is so much hotter than the photosphere. That discovery has become known as the coronal-heating problem. More than eight decades later, it is still puzzling and controversial. To interpret the coronal heating, several theories have proposed various mechanisms, including magnetic field reconnection, Alfvén waves, and turbulence, but none can thoroughly explain the phenomenon.

Another solar mystery was identified in the early 1950s when Ludwig Biermann observed that comet tails flow away from the Sun at about 400 km/s. On a 1956 visit to the University of Chicago, he presented the results to John Simpson. Biermann suggested that some antisunward "corpuscular radiation" flow must affect the comet tails. Simpson refuted the idea by citing another great authority in solar-terrestrial physics, Sydney Chapman, who held that the solar atmosphere, much like Earth's atmosphere, was static. One of Simpson's colleagues, Eugene Parker—the namesake of NASA's *PSP*—showed that the Sun's atmosphere is highly dynamic and some flow could come out of what he called the solar wind. Against the advice of Simpson, Parker decided to publish the research.

Several journals rejected the single-authored paper.³ One of Parker's critics suggested that he go to the library and do some reading before writing papers on the subject. But Subrahmanyan Chandrasekhar, the editor of the *Astrophysical Journal*, decided to publish the article. A few years later, the *Mariner 2* mission confirmed the existence of the supersonic solar wind. It was magnetized, hot, fast, and complex.⁴ Since Parker's prediction, astronomers have been trying to figure out how the solar wind accelerated from a near-static state at the base of the corona to several hundreds of kilometers per second over a very short distance.

A final, critical mystery that astronomers hope the *PSP* will solve is the Sun's energization of particles. In 1859 Richard Carrington observed the first solar white-light flare,⁵ followed by the most intense geomagnetic storm in recorded history. Telegraph communication failures occurred all over the world. Although some scientists suggested a connection between the

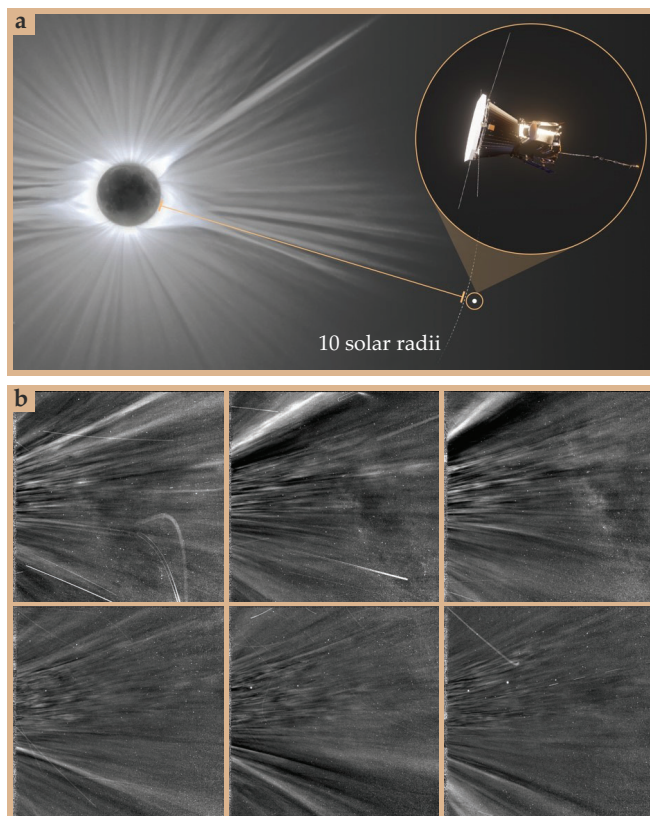


FIGURE 1. THE PARKER SOLAR PROBE, (a) as depicted in this illustration, flies through coronal structures like those visible during total eclipses. **(b)** Images from the spacecraft's WISPR instrument show the spacecraft gliding above and below the structures of the solar corona. That upward and downward motion of coronal features, however, is only apparent. (Courtesy of NASA/Johns Hopkins APL/Naval Research Laboratory.)

solar event and the geomagnetic storm, the link between the ground-induced currents and the explosive solar activity was unknown then. The true nature of the solar activity and the solar cycle had to wait until George Hale observed strong magnetic fields in sunspots.⁶ Chapman and Vincenzo Ferraro later explained the relation between solar activity and geomagnetic storms. The Sun-Earth connection, mainly driven by solar magnetism, became more evident after the 1957 launch of *Sputnik 1* and the advent of the space age. Whatever happens in the solar corona can affect Earth's environment, planetary systems, space equipment, and exploration.

Why so close?

The Space Science Board of the National Academies of Sciences was appointed in spring 1958 at the request of the executive committee of the US National Committee for the International Geophysical Year to survey the scientific aspects of human and robotic exploration of space. The board chairman, Lloyd Berkner, appointed 12 committees to prepare reports on specific fields of space research, review proposals for experiments, and recommend a scientific program. The work of two committees—optical and radio astronomy, and physics of fields and particles in space—contributed to the nation's space science program and influenced NASA's process for selecting

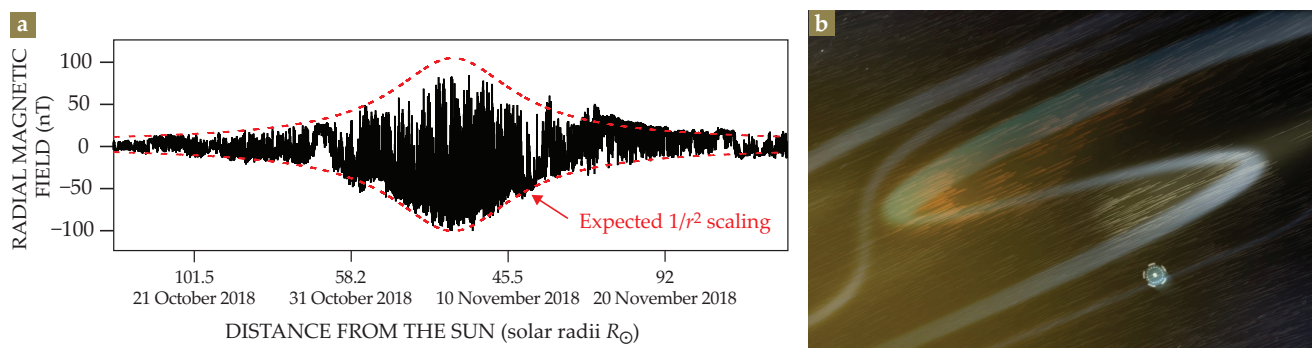


FIGURE 2. THE RADIAL COMPONENT (a) of the solar wind's magnetic field was measured by the *Parker Solar Probe*'s *FIELDS* suite during the first perihelion encounter. The measurement is peppered by high-amplitude fluctuations in which the field rotates almost 180° back to the Sun and out again. **(b)** The fluctuations appear as S-shaped switchbacks along the magnetic field lines and are grouped in periods of time separated by quiet spans of the magnetic field and other plasma parameters. (Adapted from ref. 13, S. D. Bale et al.)

space scientists. For the latter committee, Berkner designated Simpson as chair and James Van Allen as cochair. (To learn more about the Space Science Board, check out the NASA History Series Exploring the Unknown.)

The 1958 Simpson committee report recognized the need to fly a solar probe within the orbit of Mercury to sample solar-wind conditions and understand fundamental coronal phenomena. Beginning in the early 1960s, measurements of the solar wind around 1 AU revealed that it is impossible to trace the physical processes that create and accelerate the solar-wind plasma. During its journey to Earth and beyond, the solar wind is heavily affected by waves, instabilities, turbulence, and other physical phenomena. The only way to understand how hot plasma originates and flows is to sample it at its source, the solar corona.

The region where the solar wind's plasma acquires most of its heat and acceleration is below the Alfvén critical surface—where the solar-wind speed equals the Alfvén speed. The Alfvén critical surface defines the surface beyond which the plasma ceases to corotate with the Sun; that is, the magnetic field loses its rigidity to the plasma. Knowing the physical conditions below that boundary is essential to determine the solar wind's angular-momentum loss, the global heliospheric structure, and other large-scale properties. The physics of the solar wind also changes because the sunward and antisunward propagation of plasma waves affect the local dynamics, including the plasma's turbulent evolution, heating, and acceleration. In addition, velocity gradients develop between the fast and slow streams and set the initial conditions for forming corotating interaction regions, which are a major source of recurring geomagnetic storms.⁷

To make the necessary measurements, the *PSP* has four suites of instruments. The *FIELDS* suite measures electric and magnetic fields, waves, Poynting flux, densities, temperature, and radio emissions.⁸ The Solar Wind Electrons Alphas and Protons (SWEAP) instrument measures velocities, densities, and temperatures of electrons, protons, and alpha particles of the thermal solar wind.⁹ The Integrated Science Investigation of the Sun (IS²) suite¹⁰ measures energetic electrons, protons, and heavy ions in the energy range between 10 keV and 100 MeV. The Wide-Field Imager for Solar Probe (WISPR) takes pictures of the solar wind, coronal mass ejections, shocks, and other structures as they approach and pass the spacecraft.¹¹

Figure 1 shows a set of WISPR images around the perihelion

of the ninth solar encounter—when the spacecraft flew through the solar corona. WISPR captures coronal structures moving upward in the upper field of view and downward in the lower part, although the motion is only apparent. The images also show various small structures that could not be seen from 1 AU. Those features reflect the highly dynamic nature of the young solar wind. The plasma data from both *FIELDS* and SWEAP confirmed that the *PSP* did cross the Alfvén critical surface, a significant milestone for the mission.¹²

Magnetic field switchbacks

Since the first solar encounter, the *PSP* has provided a dramatic close-up picture of the solar wind with features not seen in previous data. Although the magnetic field magnitude follows the r^{-2} behavior expected from flux conservation, the field is highly structured closer to the Sun and shows pronounced, ubiquitous high-amplitude fluctuations. Figure 2a delineates the measured radial component of the magnetic field vector, which comprises rapid, large-amplitude polarity reversals that are associated with jets of plasma. The magnetic field reversals, or switchbacks (SBs), are rotations of the field vector.¹³ Rather than changes in magnetic-field polarity, the field lines fold over to form an S shape (see figure 2b), as shown by measurements of suprathermal electrons, the differential streaming of alpha particles, measurements of proton beams, and the directionality of Alfvén waves. The SBs are Alfvénic in nature, and the solar-wind velocity, therefore, is highly correlated with the magnetic field. Although SBs were observed sporadically in the solar wind before by the *Ulysses*, *Helios 1*, and *Helios 2* missions, their importance took center stage only after the recent observations by the *PSP*.

The SB occurrence rate, morphology, and amplitude and the fact that SBs are ubiquitously observed in slow, mostly Alfvénic solar wind made them one of the most intriguing aspects of the first few *PSP* perihelia passages. The magnetic reversals are grouped in spans of time separated by quiet periods during which the magnetic field and plasma parameters—velocity, density, temperature, and others—are devoid of large fluctuations. The reversals also carry excess energy, and their presence diminishes significantly farther out, as observed by the European Space Agency and NASA's *Solar Orbiter* and other space missions. Somewhere in the solar wind, therefore, the SBs must dissipate and release that energy to the plasma, likely in the form of heat and speed.

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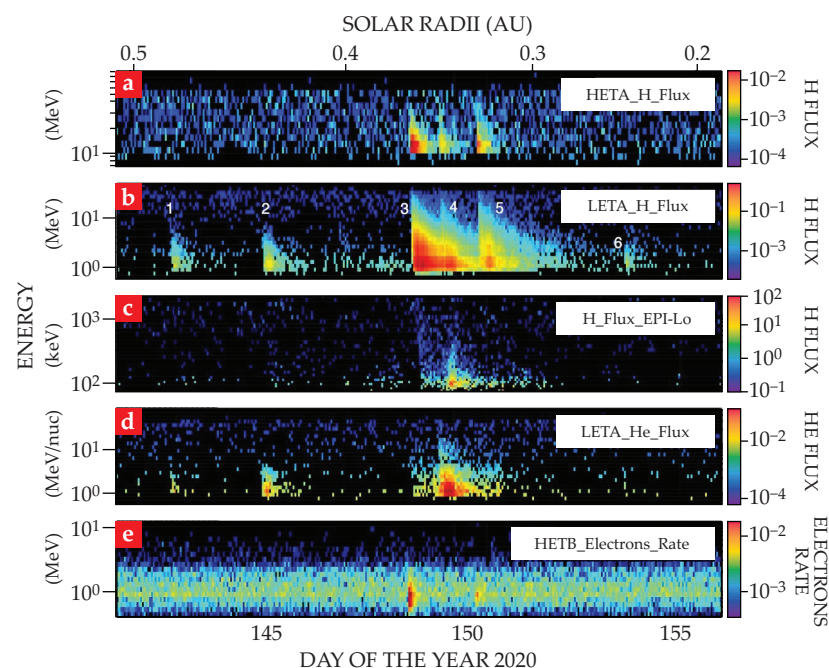


FIGURE 3. ENERGETIC PARTICLES near the Sun were observed by the *Parker Solar Probe*'s ISOIS suite. The spectrograms indicate the proton intensity (panels a, b, and c); the helium intensity (panel d); and the electron-count rate (panel e). High Energy Telescope (HET) A, Low Energy Telescope (LET) A, Energetic Particle Instrument-Low (EPI-Lo), and HETB are sensors of the ISOIS suite. (Adapted from ref. 15.)

The SBs' contribution to the heating and acceleration of the solar wind is not yet fully understood. There are, however, hints in the *PSP* data that after a certain point the SBs become unstable and shred themselves through turbulent mechanisms. If that is indeed the case, would they then be the smoking gun that scientists have sought for decades to explain the coronal heating and solar-wind acceleration? Solar scientists first need to understand and quantify their contribution to the thermodynamics of the solar wind's plasma.

Another controversial aspect of the SBs is their origin. Is there more than one flavor of SBs, such as some that form lower down in the solar atmosphere and are carried upward by the solar wind to *PSP* altitudes and beyond? And can SBs develop locally in the solar wind? Several models that may explain their formation can be put into two categories. The first favors SB formation through magnetic field reconnection at the base of the solar corona, and the second in the solar wind.

In other words, understanding the physical processes of SB formation could help researchers discriminate between the two most prominent solar-wind theories to explain the plasma heating and acceleration: magnetic field reconnection and turbulence. The most recent *PSP* observations seem to indicate a potential connection between the solar-wind SBs and magnetic field structures on the solar surface in the form of supergranules and magnetic field funnels at the base of the corona. SB observations hold promise as a way to better constrain our understanding of the solar wind.

Energetic particles

The energetic-particle environment closer to the Sun below 0.3 AU was not accessible until the *PSP* era. Previous studies,

mostly from a distance of 1 AU, show that energetic particles originate from solar flares, shocks driven by coronal mass ejections, corotating interaction regions and stream interaction regions (both are interfaces between slow and fast solar-wind streams), coronal jets, and rarer smaller events. The energetic particles show a great diversity in composition—including electrons, protons, alpha particles, and heavier ions—and other properties. Among the fascinating phenomena discovered by the *PSP* ISOIS suite closer to the Sun are small solar energetic particle (SEP) events, which are radiation storms that result from small explosions at the solar corona's base.¹⁴

Figure 3 shows six of those SEP events over several days.¹⁵ They're diverse in composition and origin but share some common characteristics with larger events. The triplet of events numbered 3, 4, and 5 in figure 3b is particularly interesting. They occurred within 24 hours of each other and seemed to originate from the same active region on the Sun. The composition of event 4, however, is quite different from the others. Events 3 and 5 show clear flux enhancements in the protons and electrons, whereas event 4 does not. Event 4 also has a helium-3 enhancement compared

with the other two events. The cause of the compositional differences remains unclear. Event 4 may have originated from a different active region from that of events 3 and 5, which later produced event 6. The composition of event 6, however, is similar to that of event 1.

Solar activity is picking up as the current solar cycle progresses toward its maximum, so the *PSP* will have the opportunity to observe events of different intensities and distances from the Sun. The *PSP*'s new observations will help resolve fundamental questions about the origin, acceleration, and transport of SEPs in the heliosphere.

The dust-free zone

The zodiacal dust cloud consists of particles that orbit the Sun and fill the inner interplanetary space of the solar system. The thick circumsolar cloud of material is created mainly by asteroid collisions and cometary activity in the inner solar system. An excess of small-sized particles is observed in the inner heliosphere because of the grinding of dust grains. Small dust particles will lose angular momentum and gradually spiral toward the Sun because of the solar-radiation pressure, or more precisely, the Poynting–Robertson effect. The phenomenon mainly affects dust particles smaller than 1 mm in size, which are produced by catastrophic collisions, partial sublimation of larger particles, erosion through sputtering by solar-wind particles, and rotational bursting of grains.

Closer to the Sun, there could be a dust-free zone (DFZ). In 1929, in fact, Henry Norris Russell predicted that there should be such a region around all stars. Small dust grains in the vicinity of the Sun are heated to the point of sublimation. The resulting gaseous product is then washed away by the solar

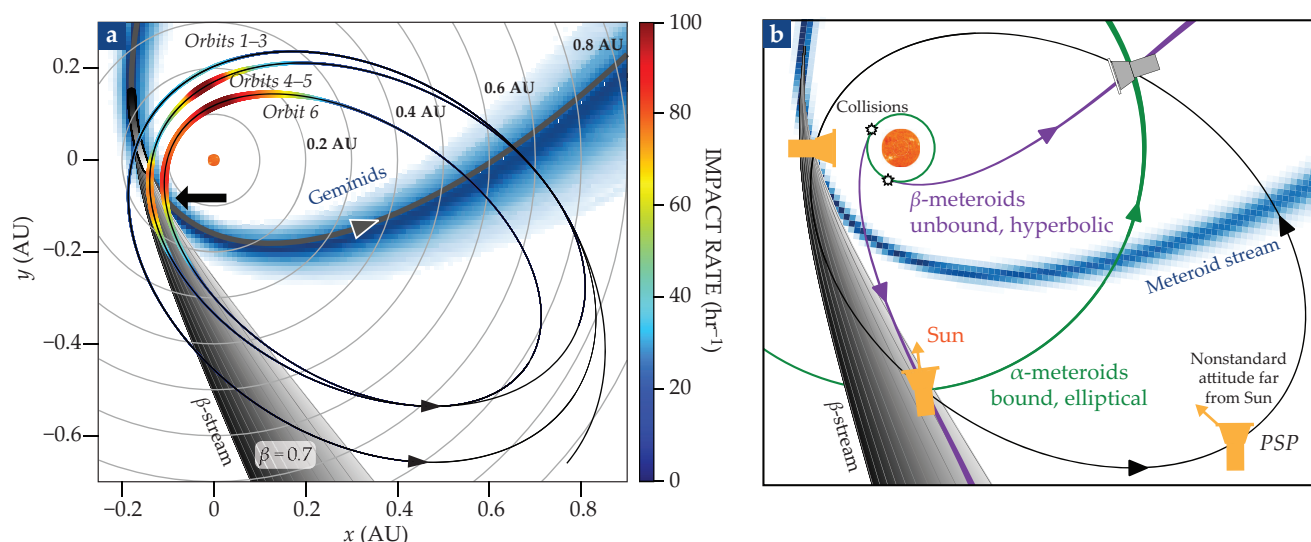


FIGURE 4. DUST IN THE INNER HELIOSPHERE and (a) dust-impact rates were measured by the *Parker Solar Probe*'s *FIELDS* electric antennas and are overlaid here on the *PSP* trajectory for orbits 1–6. (b) Several dust populations (not drawn to scale) were identified using the *PSP* measurements: gravity-bound α -meteoroids, unbound β -meteoroids, and a potential dust stream, known as a β -stream. The gray fanlike feature is a new dust stream produced by interactions between the Geminids meteor trail and the zodiacal dust cloud. (Adapted from ref. 17.)

radiation pressure and the solar wind, thus creating a depletion zone whose inner boundary marks the perimeter of the DFZ. Subsequent studies pointed to the same conclusion of a DFZ around the Sun and defined the boundary at about 4–5 solar radii. Observations, however, have failed for decades to provide any consistent evidence for the DFZ's existence.

Before the launch of the *PSP*, scientists expected to find hints of the DFZ late in the mission. To many people's surprise, sufficient evidence for its existence came during the spacecraft's first orbit. Observations from 1 AU before the *PSP* show that the brightness of the F-corona continues to increase linearly on a log-log scale all the way to the Sun, and the data do not indicate evidence for a DFZ. Data from the *PSP* taken closer to the Sun, however, show significant brightness decreases at small elongations from the Sun.¹⁶ That can only result from a depletion of the dust-particle density closer to the Sun. More recent orbits with lower perihelia have confirmed the significance of the brightness depletion.

Dust in the inner heliosphere

In addition to solving the nine-decade historical DFZ puzzle, the *PSP* is revealing previously unknown phenomena related to dust dynamics in the innermost region of the heliosphere. Observations from previous space missions indicate the existence of several populations of zodiacal dust. The most prominent are α -meteoroids—gravity-bound particles on elliptical orbits around the Sun—and β -meteoroids, which are unbound grains on hyperbolic orbits that are likely the product of collisions of the α -meteoroids. Figure 4 shows indications of other dust populations too.

The dust environment in the innermost region of the heliosphere, however, has been unknown. Before the *PSP*, no spacecraft had flown into that region of space. To evaluate the risk to the mission, significant effort went into modeling that dust environment, which is particularly close to the Sun. The modeling results were only predictions, though, as there were no

observations from that region of the heliosphere to compare with. Although the *PSP* lacks a dedicated dust sensor, the whole spacecraft can be used as a giant detector for measurable dust impacts. As fast dust particles hit areas of the spacecraft, they create a plasma cloud whose electric potential can be measured by the *FIELDS* electric antennas. Those impact rates carry critical information on the collisional environment of the inner solar system.

Figure 4 illustrates the dust-impact rates measured by the *PSP*. Dust-impact rates during the spacecraft's first three orbits show a single peak occurring slightly before the perihelion followed by a gradual drop-off after the perihelion (figure 4a). Subsequent orbits show two peaks: one before and another after the perihelion. Modeling indicates that preperihelion peaks are consistent with the α - and β -meteoroids populations. The *PSP* dust-impact data also show that the collisions producing β -meteoroids occur in a region that's 10–20 solar radii from the Sun. The postperihelion peaks could not be reproduced by the models unless a third population, known as a β -stream, is considered (see figure 4b). If the *PSP* is observing a β -stream, it would be the first direct observation of asteroidal and cometary debris trails collisionally eroding as they transit the zodiacal cloud.¹⁷

As the mission progresses, it could reveal additional meteoroid streams that would be difficult to detect via other means. The potential β -stream is likely related to the Geminids meteor stream, associated with the mysterious 3200 Phaethon asteroid. It brightens close to sunlike comets that have a dust tail 2.5×10^8 m long. What remains puzzling is how a rocky asteroid can leave behind a trail of debris that sparks the Geminids meteor shower.

Venus's circumsolar dust ring

The *PSP* collected science data during an extended campaign from 12–23 January 2020 before the fourth perihelion encounter. The spacecraft traveled from 0.5 AU to 0.25 AU and rolled

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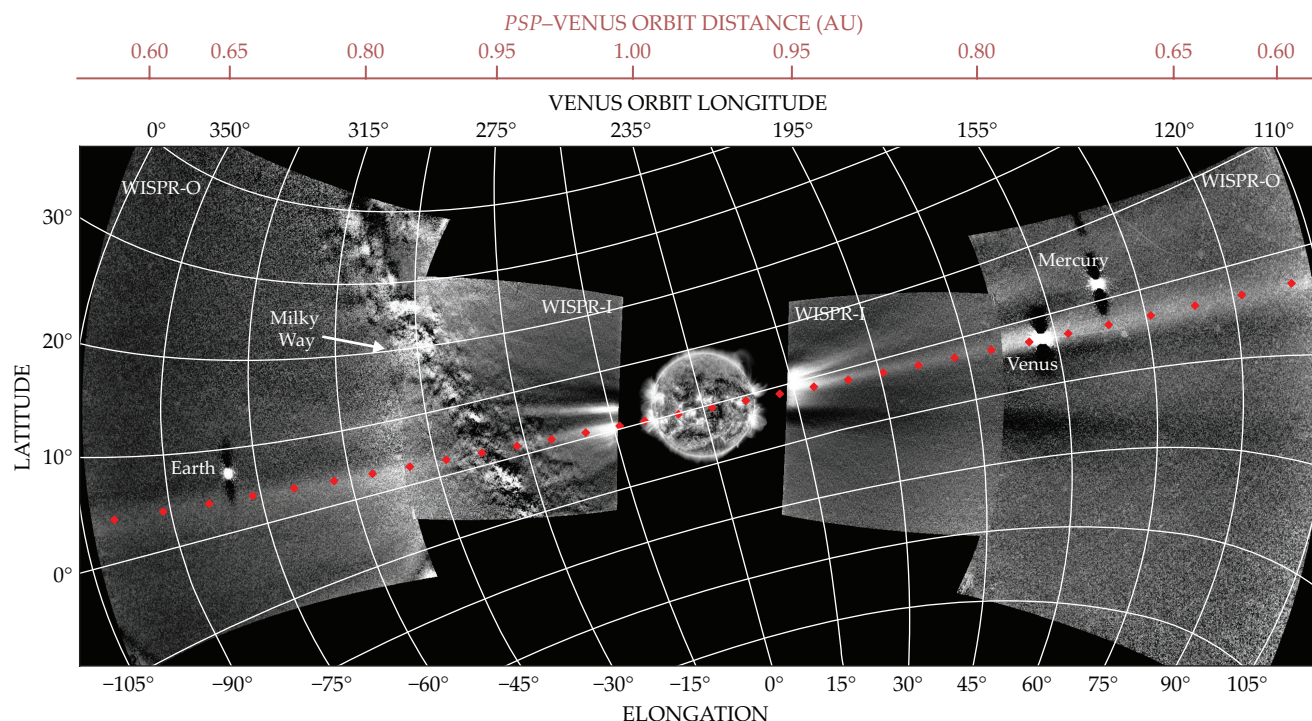


FIGURE 5. A CIRCUMSOLAR DUST RING, identified by the faint emission along the orbit of Venus (red dotted line), was first observed by the *Parker Solar Probe*. The spacecraft's WISPR sensor collected the images during the extended campaign that preceded the fourth perihelion encounter. The Sun—not to scale and masked by the spacecraft's heat shield—is the disk at the center. The images on the right- and left-hand sides are in the direction of the spacecraft's motion and the opposite motion, respectively. (Adapted from ref. 18.)

180° back and forth to communicate with Earth and manage its own momentum. Those maneuvers are not performed during solar-perihelion encounters, when the WISPR imager is always looking in the spacecraft's direction of motion, known as the ram direction. During the extended campaign, the WISPR imager was recording images in the ram and antiram directions. Figure 5 shows a composition of WISPR images projected onto the surface of a sphere.

The data required a new processing technique different from the one used during the first two perihelion encounters, when WISPR was imaging along the spacecraft's path of motion. The new data show a faint emission that extends through the instrument's entire field of view with an excess brightness of about 1% above the background zodiacal light. The emission is clearly not an artifact and cannot be of coronal origins, because coronal structures do not extend that far from the Sun.

The emission coincides precisely with Venus's orbit (see figure 5). The *PSP* imaged the full extent of the circumsolar dust ring along the orbit for the first time.¹⁸ Previous and subsequent data analyzed with the new processing technique confirmed the existence of the ring. Now the question is, How can such a dust ring form? There are two competing theories: resonant gravitational trapping of dust by the planet and co-orbital asteroids along the Venusian orbit. Either theory could be correct, or perhaps another interpretation could better explain the dust ring.

The *PSP* is four years into its primary mission. So far, it has uncovered numerous phenomena. Most of those discoveries

were about phenomena occurring during solar minimum. But the Sun's activity level is rising toward solar maximum, predicted to occur in 2025. Solar scientists will undoubtedly discover other aspects of the solar corona and inner heliosphere. They are eager for the spacecraft to fly through many of the most violent solar eruptions, the data from which may reveal how particles are accelerated to extreme levels. The *PSP* is rewriting the textbooks on our understanding of the Sun, the solar wind, and, more generally, stars and their winds.

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