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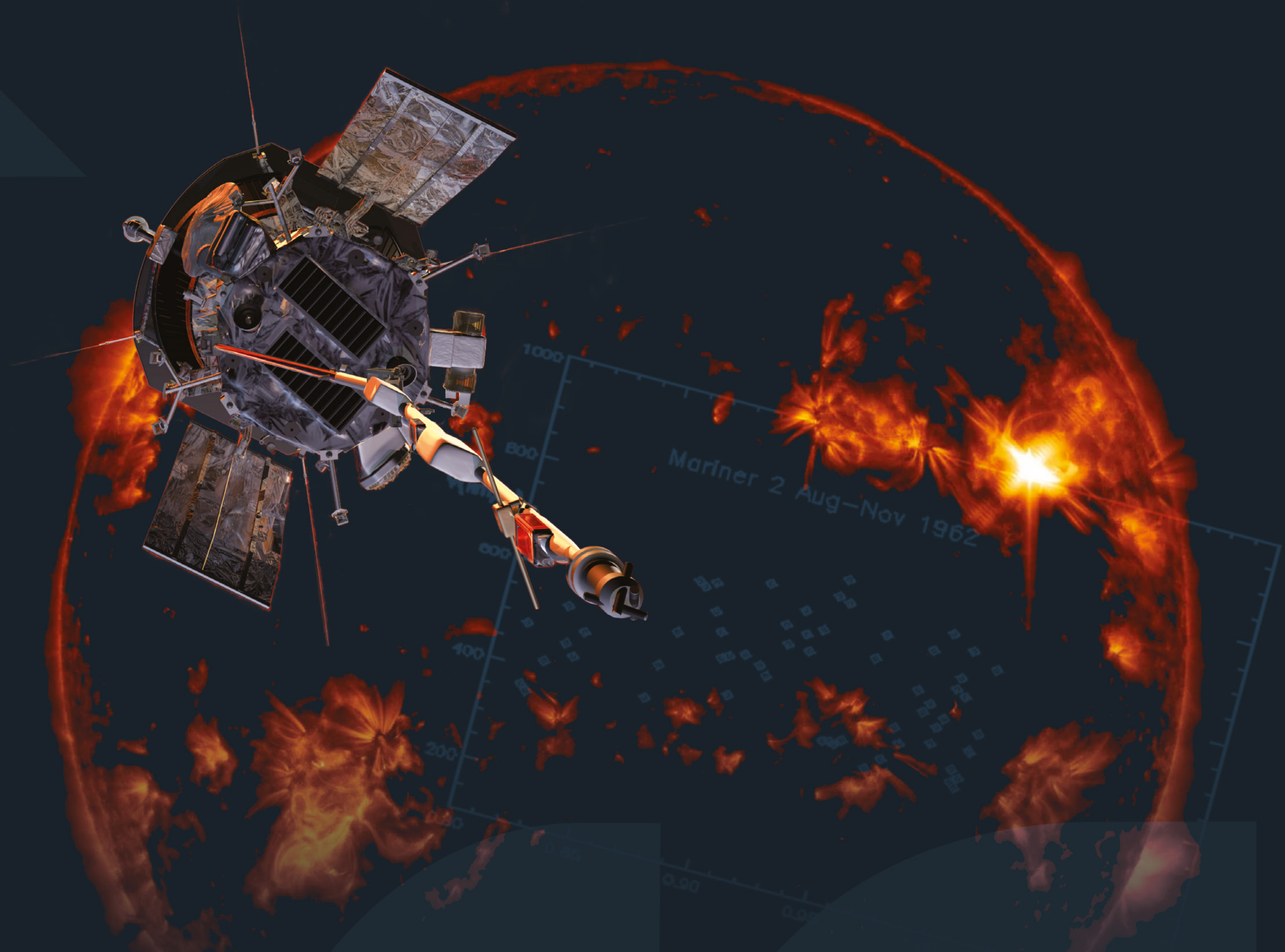

Unveiling the Mysteries of Solar Magnetic Activity

from the Earliest Observations to Parker Solar Probe

By Marco Velli

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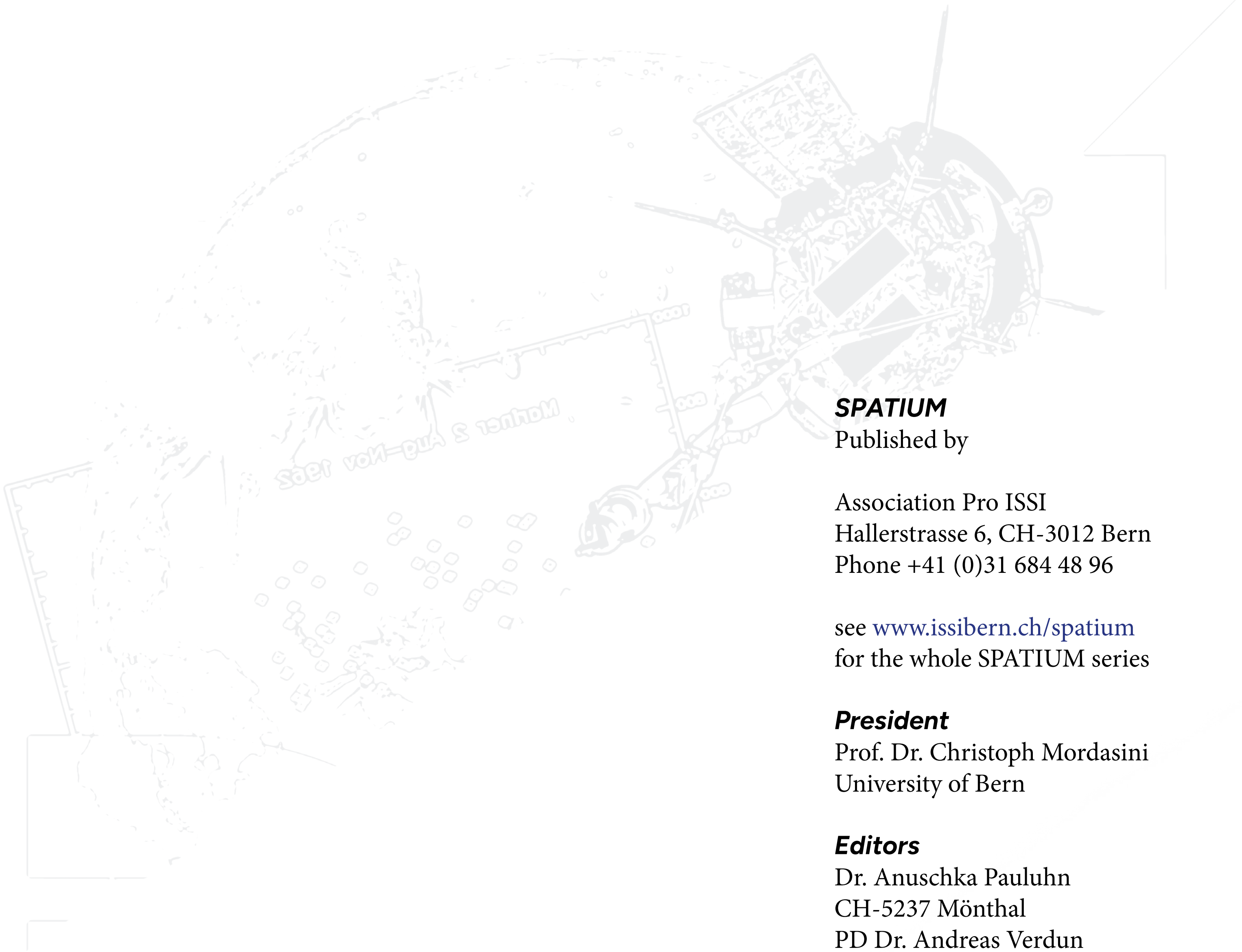

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President
Prof. Dr. Christoph Mordasini
University of Bern

Editors
Dr. Anuschka Pauluhn
CH-5237 Mönthal
PD Dr. Andreas Verdun
CH-3086 Zimmerwald

Layout and Design
Fabio Crameri, ISSI Bern

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Länggass Druck AG Bern
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Solar flare—as seen in the bright flash in the upper right portion of the image—captured by NASA's Solar Dynamics Observatory on March 31, 2022. Graphically superposed are an illustration of the Parker Solar Probe and a graph of Mariner 2 measurements. Credit: NASA/SDO

Editorial

The Sun is the source of energy which has allowed life to develop on Earth. The Suns influence pervades the Solar System not only through its general bolometric radiation that illuminates planets and satellites, but also via its magnetic activity. Although the Sun is as "close" to us as a star can be, especially the latter aspect still holds a multitude of mysteries. With the current solar cycle 25 (counted from 1755) approaching its maximum, and thus the powerful eruptions on the Sun such as energetic flares and coronal mass ejections (CME) increasing in number, the interest in solar activity rises again.

The start date of the solar cycle count was set by the Swiss astronomer Rudolf Wolf (1816–1893) as the start of a continued series of regular observations of sunspots, for example carried out by the Danish astronomer Christian Pedersen Horrebow (1718–1776) and the German astronomer Samuel Heinrich Schwabe (1789–1875). In September 1859, british astronomer Richard Carrington (1826–1875) observed a large sunspot and its eruption into what would later become identified as a combination of a solar flare and a coronal mass ejection. The corresponding geomagnetic storm hit the Earth a few days later, strongly affecting the telegraph systems and generating aurorae around the world. Carrington suspected a solar-terrestrial connection, and this assumed most powerful geomagnetic storm observed to date has subsequently been called the Carrington event.

The magnetic field of the Sun plays a pivotal role in these processes. The sunspot cycle is a manifestation of a magnetic dynamo hidden in the solar interior, completing a full period every 22 years. The Suns magnetic activity also causes the Earth, Moon, and the other planets to be immersed in a hot, rarefied, energetic flow of particles and electromagnetic fields originating from the Sun, the solar wind. This magnetic activity also shapes the heliosphere, a bubble in the interstellar medium created by the solar wind, which extends about 100 times the Earth-Sun distance. Within the heliosphere, solar magnetic fields and the nonlinear dynamical phenomena associated with their expansion from the Sun dominate the space environment.

The solar wind, discovered at the beginning of the space age right after its prediction in 1958 by Eugene Parker, owes its existence to the extremely hot solar corona, with temperatures up to 300 times hotter than the underlying photosphere. Although small steps towards better understanding of the coronal-heating riddle are in sight, the full solution has not yet been found. Spacecraft measurements have shown that the solar wind flows in distinct streams, with fast wind streams coming from the open magnetic fields around the solar poles at solar minimum, with slower, much more variable streams originating above the closed magnetic loops in the corona. At solar activity maximum, such fast and slow streams are also observed but their association with coronal structures is much harder to identify.

In 2018, NASA launched the Parker Solar Probe spacecraft, named in honor of Eugene Parker, to explore the origins of the corona and heliosphere. On 30 March 2023, Prof. Marco Velli, the Johannes Geiss Fellow 2022, presented his work on coronal heating and the solar wind in a Pro ISSI lecture. Starting from the beauty of solar eclipses to the fascinating properties of the hot ionized gas making up the solar corona and wind, he went on to discuss questions of coronal heating and solar wind acceleration all the way up to the most recent discoveries by the Parker Solar Probe.

This issue of Spatium adheres closely to Professor Velli's original manuscript from 21 February 2024, and his lecture, complying with time and other boundary conditions.

Anuschka Pauluhn
Mönthal, February 2024

Unveiling the Mysteries of Solar Magnetic Activity

From the Earliest Observations to Parker Solar Probe

As Douglas Adams[1] has it, "Far out in the uncharted backwaters of the unfashionable end of the western spiral arm of the Galaxy lies a disregarded yellow sun …". Beyond the comical effect of course quite the reverse is true, the Sun having been revered as a god since time immemorial with "rare" events such as total solar eclipses inducing terror in prehistoric and primitive populations. Solar eclipses retain their fascination even today. **Figure 1** is a photograph of the total solar eclipse of August 2017, processed so as to enhance details and contrast in the periphery of the image and very similar to the view of the corona of the naked eye through binoculars or a telescope.[2]

What is immediately striking is the overall shape and structure of the light coming from the solar corona. Large so-called helmet streamers appear on the west and south east limbs of the Sun (the Sun rotates towards the observer on the left -east- of the image and into the picture plane on the right -west-), while narrow plumes emerge from what appear to be the slightly inclined north and south poles of the Sun. In-

1 D. Adams, The Hitchhiker's Guide to the Galaxy, Arthur Barker Limited, London

2 Except for the brief period of totality during the eclipse, the Sun should never be observed directly without a suitable filter transmitting less than 0.1 permille of the solar radiation in order to prevent eye damage.

Figure 1. *Processed white-light image of the solar corona taken during the 21 August 2017 total solar eclipse (Courtesy of M. Druckmüller, P. Aniol, S. R. Habbal).*

termediate-size closed arches, with clear impressions of overlapping along the line of sight, are seen within the helmet streamers, with the larger streamer to the right-west also displaying two reddish blobs of what we call prominences.

This paper provides a historical – necessarily brief – overview of the development of our understanding of the dynamics of the solar corona and the window it opened into fundamental physical processes occurring throughout our Universe. These processes, that occur over widely different scales in energy, dimension and time, may be studied in our local space environment, what we call the heliosphere. Scientific debates and strong disagreements are drivers of scientific discovery and never more so than in the history of the nature of our star and the influence on the environment of the Earth. This article highlights some of them, starting in the post-renaissance counter reformation period, with Galileo and Scheiner. It also focuses on the modern development of plasma physics and its advances, concurrent with the beginning of space exploration and the immediate realization that space exploration should reach for its natural internal boundary, the corona, and the implementation, nearly sixty years later, of the Parker Solar Probe (PSP) mission.

The heliosphere is the volume carved out in space by the magnetized high-temperature corona and its supersonic extension into interplanetary space, the solar wind. Even though the power involved is only two to five thousandths of a percent of the energy of solar radiation that powers life on Earth, solar magnetic fields can store energy and focus their release into extremely intense bursts on all scales, from large solar flares to the much smaller brightenings, "micro-flares" seen by space telescopes. The heliosphere extends out from the Sun to around about 100 AU[3], within which the flux of cosmic rays is regulated by scattering in the solar magnetic field. Solar magnetic activity affects the environment of the Earth, producing both magnificent auroral displays as well as streams of energetic particles dangerous to astronauts. It also causes changes in the Earth's magnetic field – responsible for protecting life from the hazardous effects of the wind – that induce large electric fields in the atmosphere that can cause current disruptions in power plants and blackouts.

From the birth of the scientific method to the space age

Attributed by Galileo to the effect of mountains on the moon, it was Kepler who correctly realized that the solar corona's brightness must be due to the scattering of solar light by material surrounding the Sun, but he could not know the material in question was ionized gas made up mostly of protons and electrons. Galileo in 1610's Sidereus Nuncius had made the first astronomical discoveries using a telescope but only addressed observations of the Sun in his three 1612 letters (published in 1613) to a fellow member of the Accademia dei Lincei, Marcus Wesler, "Istoria e dimostrazioni intorno alle macchie solari e loro acci-

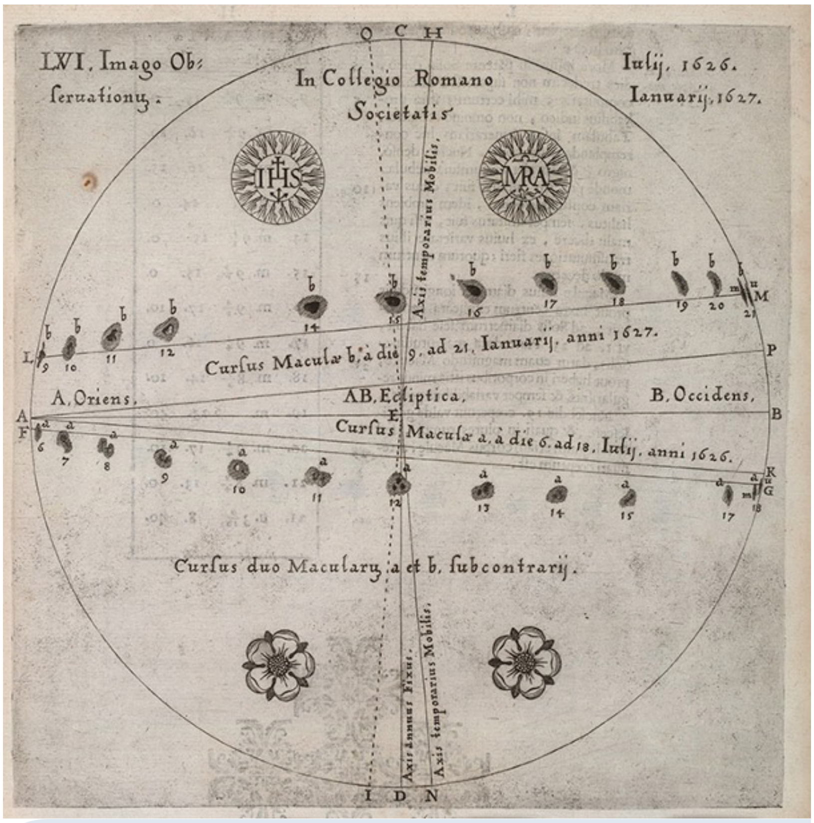

Figure 2. A drawing of the Sun showing sunspot observations from Scheiner's De Rosa Ursinae. Days of observation together with the variable inclination of the apparent rotation axis (as seen from Earth in January and July, i.e., opposite sides) are marked.

3 1 AU or 1 ua (astronomical unit) corresponds to the distance from Earth to Sun, roughly 1.5×10^{11} m.

denti" where he claimed the discovery of sunspots for himself. The letters were a response to Wesler, who had published and sent Galileo three letters concerning sunspots written under the pseudonym "Apelles latens post tabulam" (Apelles hiding behind the canvas – referring to the legend of the Greek painter who would hide behind his paintings to listen to criticism of his art) by the Jesuit priest Christopher Scheiner. Scheiner concealed his name fearing accusations of heresy, and in his work described how sunspots could be used to measure the rotation of the Sun as well as the inclination of the Sun's axis with respect to the ecliptic plane (as seen in **Figure 2**, where daily sunspot observations at different times establish solar rotation as well as the inclination of the Sun's rotation axis with respect to the ecliptic plane). Though Galileo characteristically claimed the discovery of sunspots as his, there is little doubt that he had not been the first to discover them, Johannes Fabricius' "de Maculis in Sole observatis et apparente earum cum Sole conversione, Narratio" of 1611 having preceded Scheiner as well as Galileo.

Galileo and Scheiner disagreed vehemently on the origin of sunspots, Galileo correctly attributing them to a solar surface phenomenon while Scheiner argued in favor of celestial bodies passing between the observer and the Sun, much like the the dark spots observed on the Sun during transits of Mercury and Venus. Galileo's letters also contained his initial arguments in favor of a theory of science, or natural philosophy, adopting the scientific method, later espoused in detail in his monumental "Dialogo sopra i due massimi sistemi del mondo, Tolemaico e Copernicano", where the lack of rational thinking of his opposing contemporaries, including Scheiner, was extensively ridiculed – perhaps a contributing cause to Galileo's condemnation by the church.

Nonetheless, when Scheiner's "Rosa Ursina sive Sol ex Admirando Facularum et Macularum Suarum Phaenomeno Varius" was finally published, it contained a wealth of additional observations of what we now call the solar magnetic cycle, including the change in time of sunspot numbers on the Sun and the slow drift over time in the location of sunspot appearance on the Sun from latitudes around 35° and downwards towards the equator.

A further three centuries had to go by before an association between sunspots and the Sun's magnetic fields would be made, and the sunspot cycle could therefore define the Sun as a magnetic star with an activity cycle. George Ellery Hale, a fundamental figure in the history of astronomy and the man behind the construction of the 100-inch telescope on Mount Wilson used by Hubble to discover the expansion of the Universe, invented, among other things, the spectroheliograph. Pointing the instrument to the Sun, in 1907 he observed the strong Zeeman effect in sunspots and later wrote in the Astrophysical Journal – a journal he had established with James Keeler in 1895 – that "…a sunspot is a vortex, in which electrified particles, produced by ionization in the solar atmosphere, are whirled at high velocity. This might give rise to magnetic fields in sunspots, regarded as electric vortices. A search for the Zeeman effect led to its immediate detection, and abundant proofs were found of the existence of a magnetic field in every sunspot observed."

Indeed, intense magnetic fields, with magnitudes that are of the order of a thousand or more times greater than the Earth's, do permeate sunspots and greatly influence the appearance of the solar corona and the structure visible in the rays emanating from the corona, as dramatically illustrated in **Figure 3**.

The material in the photosphere is only partially ionized, and though sunspots do often rotate, the vertical motion of ionized particles as invoked by Hale is mostly invisible. However, the magnetic field in sunspots must be generated by a current much like the currents that flow in the wires in a solenoid, and in this sense Hale was correct. In fact, the ionization in the upper solar atmosphere is sufficient for the atmosphere to become what is called a magnetized plasma. The stratification in density and temperature in the corona makes the plasma ever more conducting with height, with lighter atoms in the corona like hydrogen and helium completely ionized, while heavier species, such as oxygen and even iron, are multiply ionized.

A window into the behavior of magnetized plasmas

A magnetized plasma is a globally neutral collection of charged particles, where the interactions between particles and the self-consistent electromagnetic fields, i.e., the fields determined not only from the outside but also due to the motions of the charged

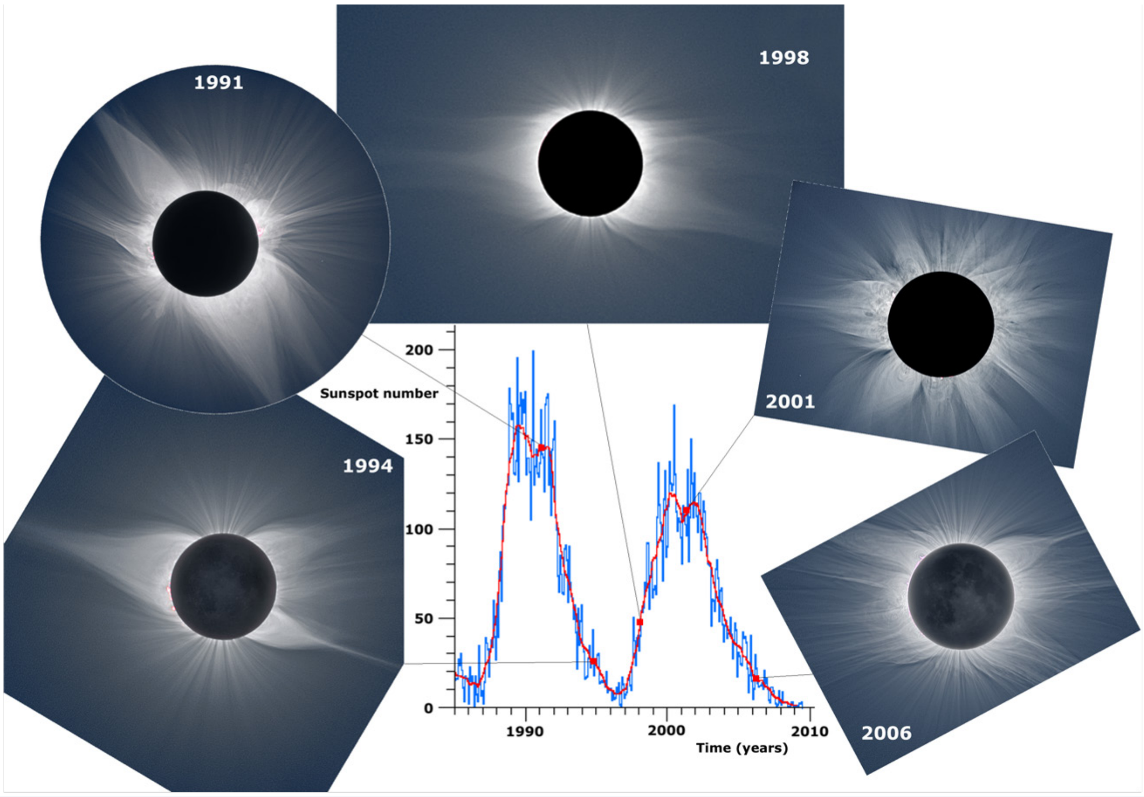

Figure 3. *The appearance of the solar corona in total solar eclipses over the full solar cycle. The central plot shows the monthly average sunspot number over time and arrows show the eclipse times, two occurring at solar maximum and two at solar minimum. At solar maximum thicker plumes and rays emanate from everywhere around the Sun, while at solar minimum polar regions with narrower thin plumes are clearly visible. Images courtesy S.R. Habbal and M. Druckműller.*

particles themselves, dominate over the direct $1/r^2$ Coulomb force, attractive or repulsive depending on the charge of the particles, between nearest neighbors.

The collective behavior of hot plasmas is incredibly counter-intuitive, as the presence of magnetic fields endows the gas with properties more reminiscent of fluid behavior than that of a collection of individual particles. In this regard, two fundamental aspects summarize plasma behavior. First, contrary to a neutral gas, the collisions between particles, mediated by the Coulomb force, become less effective as the temperature or speed of the particles increases. In other words, hotter, faster particles see the other particles as smaller, and collide less than slower ones, so they are more easily accelerated. Second, in the presence of a magnetic field, charged particles are only free to move along the field, while they are constrained to gyrate around the field, slowly drifting in directions orthogonal to it (the drifts depend on charge, so that typically currents develop that create a self-consistent magnetic field opposing the changes in field the particles experience as they move). The combined motions tend to preserve the magnetic moment associated with the dipole generated by the rotating particles, so that as particles move into regions of stronger magnetic field, they gyrate faster, but slow down their parallel motion (because the force caused by a magnetic field does not change the total energy of a particle). This means that some particles in a dipole field, which has stronger intensities at the poles, may be confined and reflected back and forth along field lines. But if there happens to be an electric field aligned along the magnetic field, particles, especially the faster ones, will be accelerated, leading to the formation of particle beams.

To summarize magnetized plasma behavior, magnetic fields tend to constrain the motion of particles, but the particle motions generate currents that tend to keep the magnetic field that the particle senses as it moves of similar magnitude and direction. From a fluid point of view, it appears that particles and the

Current Sheets

In magnetohydrodynamics, the magnetic field can move around but the total flux across any surface (the number of field lines) moving with the fluid is conserved (a theorem proved by Alfvén). When separate systems of fields, for example the fields of two sunspots, approach, the natural tendency of the fluxes to merge is counteracted by currents. As the interface of two flux volumes occurs at a surface, currents tend to collapse into current sheets.

The mutual attraction of parallel currents can then lead such sheets to tear, or reconnect, a process that violates the Alfvén theorem because it happens on microscopic scales where collisions and wave-particle interactions introduce dissipation.

The largest occurring current sheet in the solar system is the so-called heliospheric current sheet (HCS) or interplanetary current sheet (ICS), which is about 10,000 km thick near the orbit of the Earth, and extends out beyond the orbit of Pluto. This surface separates regions of the heliosphere where the interplanetary magnetic field points toward and away from the Sun.

The current sheet is warped by the Sun's rotation and the inclination of the rotation axis with respect to the north-south magnetic field axis. Parker first showed that the combination of rotation and expanding solar wind twists the magnetic field into an Archimedean spiral.

magnetic fields are forced to move together as a conjoined flow. Perhaps a way to summarize how a magnetized plasma behaves is to say that in a plasma, particles and fields are inextricably intertwined. To get an instinctive feeling of the complexity involved, repeat „inextricably intertwined" now ten times quickly and let it sink in.

The first indications that the solar corona was a plasma came from the interpretation of a previously unknown emission line that was observed during the 1869 total solar eclipse by Charles A. Young, initially attributed to an unknown element, coronium. The line was subsequently identified as due to emission from thirteen times ionized iron by Walter Grotrian and Bengt Edlén in the 1930s and 1940s. This places the temperature of the solar corona well above 1 million degrees, a temperature sufficient to completely ionize hydrogen. The changing shape of the solar corona throughout the sunspot cycle now begins to make sense: the reason for that changing appearance must come from the structure and dynamics of magnetized plasmas! However, a new question immediately arises: the Sun's visible surface, or photosphere, is at the relatively moderate temperature of 6500 K, and the temperature rises inwards towards the source of solar energy, nuclear fusion, that occurs in the core of the Sun, at the center of which the temperature reaches twenty million degrees. Thermodynamics states that heat naturally flows from hot to cold, and not vice-versa. What then causes the temperature to rise again above the solar photosphere and into the corona?

In 1942, Hannes Alfvén – the only plasma physicist to receive the Nobel prize – noted that in a magnetized plasma "a kind of combined electromagnetic -hydrodynamic wave is produced which, so far as I know, has as yet attracted no attention". Alfvén calculated the properties of such waves, that propagate along the magnetic field much like waves on a string and can be of frequencies very much below that of the electromagnetic waves we are used to (such as radio waves) and still propagate freely in a plasma. In fact, Alfvén suggested that they could be important in the dynamics of sunspots. In 1949 in the Physical Review, Enrico Fermi proposed that such oscillations could provide a mechanism – now named after him – for the acceleration of cosmic rays, and demonstrated how the distribution of the cosmic rays in energy, observed at Earth to be a power-law, would naturally be accounted for.

The years after the Second World War were fundamental in advancing the understanding of plasma dynamics. Once thermonuclear reactions were demonstrated in the development of hydrogen bombs, top-secret research into the development of fusion energy sources using magnetic fields to trap extremely hot plasmas began in the USA (Project Sherwood), Europe, and the Soviet Union. However, the confinement of dynamically fusing plasmas in devices using magnetic fields turned out to be such a complex problem that hope for a rapid solution soon faded. In 1956, Soviet physicist Igor Kurchatov gave a talk in the UK where he revealed the entire Soviet fusion program and detailed the problems they were having, namely the stability of the plasma discharges. Of particular interest were the global stability of current-carrying plasma columns (that tend to kink and expand) and the evolution of concentrated currents in regions of weak magnetic fields, where the currents collapse on themselves and lead to plasma heating and acceleration in an energy releasing process that annihilates magnetic fields, known as magnetic reconnection. These processes are fundamental not only in laboratory plasmas, but also in the natural plasmas of the solar corona, in the Earth's magnetosphere and magnetotail, in accretion disks and other astrophysical environments. Magnetic reconnection as a source for coronal heating was originally proposed by Thomas Gold in the early sixties, but the idea was further developed much later by Eugene Parker, who suggested that reconnecting current sheets in the corona were a necessary consequence of the driving of magnetic fields by photospheric motions, as well as buoyant emerging magnetic flux. Such current sheets would power nanoflares, intermittent bursts of energy at scales billions of times smaller than large solar flares (see **Figure 4**).

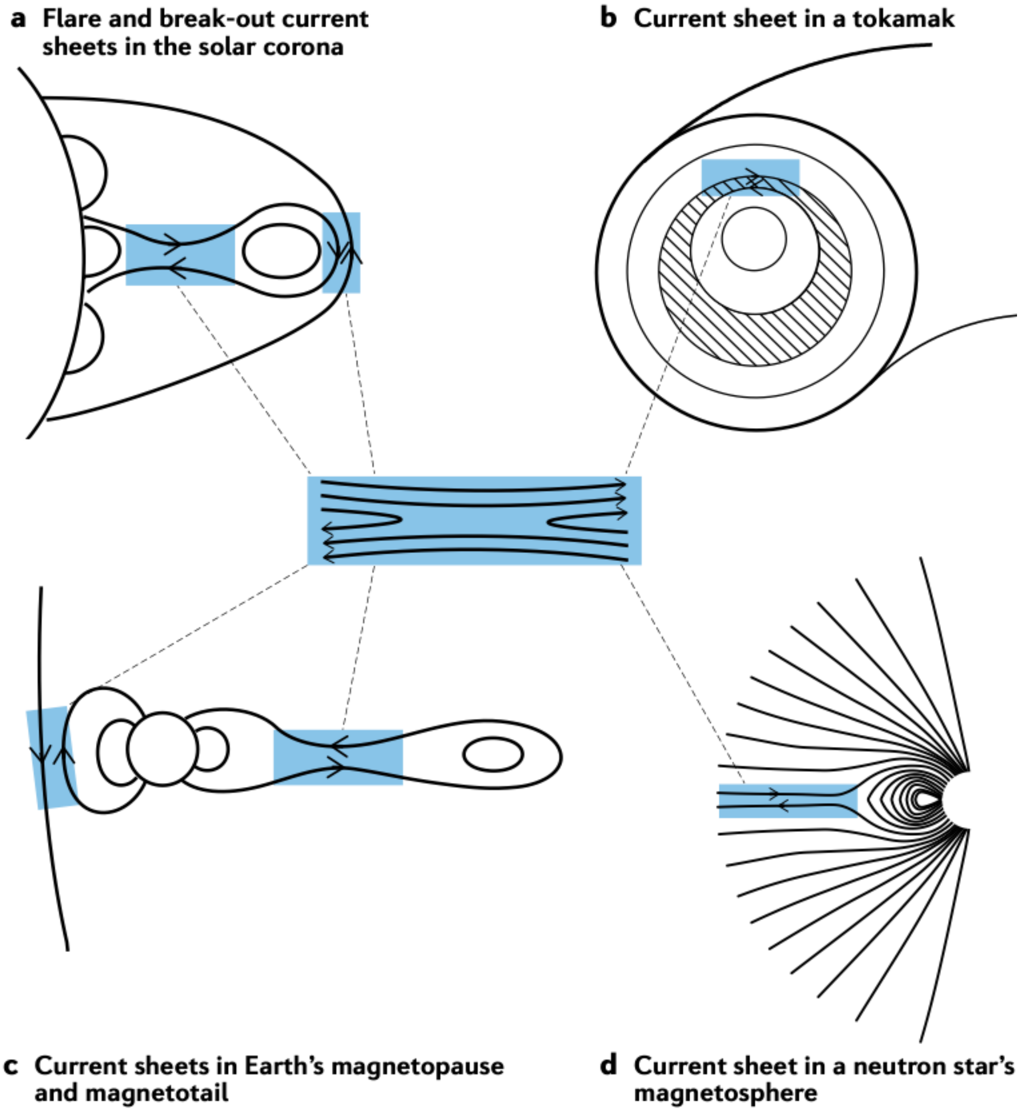

Figure 4. *Current sheet configurations relevant to laboratory and natural plasmas. Image courtesy of H. Ji.*

The interplanetary environment

In the same years, a German astronomer, Ludwig Biermann, studied the behavior of comet tails and realized that the presence of the secondary tail emanating from the comet in anti-sunward direction (the blue tail seen in **Figure 5**) should imply the existence of an outflow of "Solar Corpuscular Radiation" escaping from the Sun with speeds in the range of (400 to 500) km/s.

That at least intermittently the Sun must emit particles had been hypothesized in 1859, as spectacular auroral displays were observed throughout the world just a day and a half after Carrington and Hodgson had observed a brightening on the Sun, the first recorded observation of a white-light solar flare. This was followed by the suggestion from the "Maxwellian" Fitzgerald (1892) in "Is it possible then that matter starting from the Sun with the explosive velocities we know possible there, and subject to an acceleration of several times solar gravitation, could reach the Earth in a couple of days?" However in the same year 1892, William Thompson, on the occasion noting his change of name to Lord Kelvin, had given his imprimatur as leader of the Royal Society that "we may also be forced to conclude that the supposed connexion between magnetic storms and sun-spots is unreal, and that the seeming agreement between the periods has been a mere coincidence." Lord Kelvin however had limited his proof to the (correct) fact that the storms could not be directly due to inductive effects associated with variations in the Sun's magnetic field, and Hale's subsequent measurements of the Sun's field had confirmed this. At the same time (1898), Birkeland in Norway had hypothesized that it must be beams of particles from solar sunspots striking Earth and causing the aurora to glow, a fundamental breakthrough. Chapman and Ferraro similarly suggested in 1931 that bursts of particles from the Sun might provide an explanation for geomagnetic storms and auroral displays, but Biermann insisted on a more continuous outflow, contrasting the static models of the outer solar atmosphere developed by Chapman, who concluded in 1957 that a static conductive corona starting at 10^6 K at the Sun should maintain a high density out to far distances (in fact, after an initial decrease, the density should increase outwards).

Figure 5. *Image of comet C/1995 O1 (Hale-Bopp), taken on 4 April 1997. Courtesy E. Kolmhofer, H. Raab; Johannes-Kepler-Observatory, Linz, Austria.*

In 1957, Ludwig Biermann visited John Simpson's group at the University of Chicago. While in Chicago he had extensive discussions with Eugene Parker, who was working on the problem of cosmic ray modulation in the solar system. Biermann explained his comet tail idea and Parker began to work on the Biermann–Chapman puzzle: how to reconcile Chapman's hot, highly conducting corona with Biermann's idea of a continuously outward streaming fast solar corpuscular radiation. Parker noted two fundamental difficulties with the idea that Chapman's corona could remain static. The first arose from the fact that far from the Sun the slow decline of the temperature leads to the thermal energy per ion exceeding the gravitational binding energy of the Sun. The second difficulty was that a tenuous static corona would not permit the passage of Biermann's universal solar corpuscular radiation. Even if there were no transverse magnetic fields in space, the two-stream plasma instability would quickly arrest the flow of one plasma through the other. It was evident that, somehow, the strongly bound and seemingly static corona near the Sun must become the corpuscular radiation at large distances. Arguing, also on the basis of the unreasonably high pressures that static solutions yielded at large distances, that "probably it is not possible for the solar corona, or, indeed, perhaps the atmosphere of any star, to be in complete hydrostatic equilibrium out to large distances", he proceeded to show how a viable stationary solution yielding negligible pressures at infinity consisted in a flow accelerating continuously from very low speeds at the Sun and becoming supersonic at large distance. In addition, a magnetic field continuously distributed on the solar surface would be stretched out by this wind, eventually wrapping itself into a spiral shape in the interplanetary space (Parker, 1958). Soon before the submission of his paper to Astrophysical Journal, the Soviet Union surprised the world with the successful launch of the first man-made satellite, Sputnik.


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SOVIET FIRES EARTH SATELLITE INTO SPACE; IT IS CIRCLING THE GLOBE AT 18,000 M. P. H.; SPHERE TRACKED IN 4 CROSSINGS OVER U. S.

HOFFA IS ELECTED TEAMSTERS' HEAD; WARNS OF BATTLE

COURSE RECORDED

Navy Picks Up Radio Signals—4 Report Sighting Device

560 MILES HIGH

Visible With Simple Binoculars, Moscow Statement Says

Device Is 8 Times Heavier Than One Planned by U.S.

FAUBUS COMPARES HIS STAND TO LEE'S

Flu Widens in City; 10% Rate Predicted; 200,000 Pupils Out

ARGENTINA TAKES EMERGENCY STEPS

SATELLITE SIGNAL BROADCAST HERE

Figure 6. *The front page of the New York Times from Saturday 5 October 1957.*

The space age and discovery of the solar wind

The New York Times of Saturday, 5 October 1957, (**Figure 6**) narrates the Sputnik successful launch with a resoundingly patriotically protective article claiming that the only reason for accessing space is scientific. In fact, the article outlined the goals of what has become the field of Heliophysics: to unveil the mysteries surrounding the effects of the Sun and corpuscular radiation (cosmic rays) of solar and non-solar origin on the Earth and other planets: "Military experts have said that the satellites would have no practicable military application in the foreseeable future. The satellites could not be used to drop atomic or hydrogen bombs or anything else on the earth, scientists have said. Real significance would be in providing scientists with important new information concerning the nature of the sun, cosmic radiation, solar radio interference and static-producing phenomena radiating from the north and south magnetic poles. All this information would be of inestimable value for those who are working on the problem of sending missiles and eventually men into the vast reaches of the solar system."

In January of 1958, Parker submitted the solar wind paper, and at the end of the month, the first successful USA launch of a satellite, Explorer 1, was completed, providing evidence of the existence of the Earth's radiation belts, regions of the Earth's magnetic field filled with energetic ions and electrons, now named after James Van Allen. In the spring of 1958, the United States created NASA, the National Aeronautics and Space Administration, directing it to maintain U.S. leadership in space science and technology. At the same time, the National Academy of Sciences created a Space Science Board to interest scientists in space research and to advise NASA and the other federal agencies the Academy expected to be engaged in space research. It was the same John Simpson, at the University of Chicago, who was charged with the task of chairing the Committee on Particles and Fields. Simpson's committee submitted to the Space Science Board an Interim Report that summarized its recommendations, within which, together with studies of the Earth's magnetosphere (including multiple satellites and the detonation of atomic bombs!) we have the first mention of "a solar probe to pass inside the orbit of Mercury to study the particles and fields in the vicinity of the Sun".

Luna 1 (launched 2 January 1959) or Mechta, the dream, as the great Soviet spacecraft designer Sergei Korolev called it, was supposed to crash-land on the moon, but missed. It then became the first artificial object to go into orbit around the Sun. During its voyage, the particle sensor onboard detected particle fluxes and researchers arrived at the conclusion that the "proton fluxes observed were, apparently, part of the solar corpuscular radiation, thus, recorded for the first time in interplanetary space outside Earth's magnetic field" (Gringauz et al., 1960).

On the NASA side, the official discovery of the solar wind was claimed by Mariner 2, flying between Earth and Venus. Launched in August 1962, it recorded a continuous stream of plasma with high peaks of activity and calm periods for 104 days. The flow was always directed away from the Sun, and its speed varied from 400 km/s to 700 km/s, but in some periods, it could exceed 1250 km/s (Neugebauer and Snyder, 1962). It was also shown that another component of the ion flux besides protons were alpha particles, which were a few percent of the protons.

While the solar wind discovery made the discussion of whether Parker's solution was the only answer to the issue of how a star's outer atmosphere comes into equilibrium with its interstellar space environment somewhat redundant, the question of how the so-

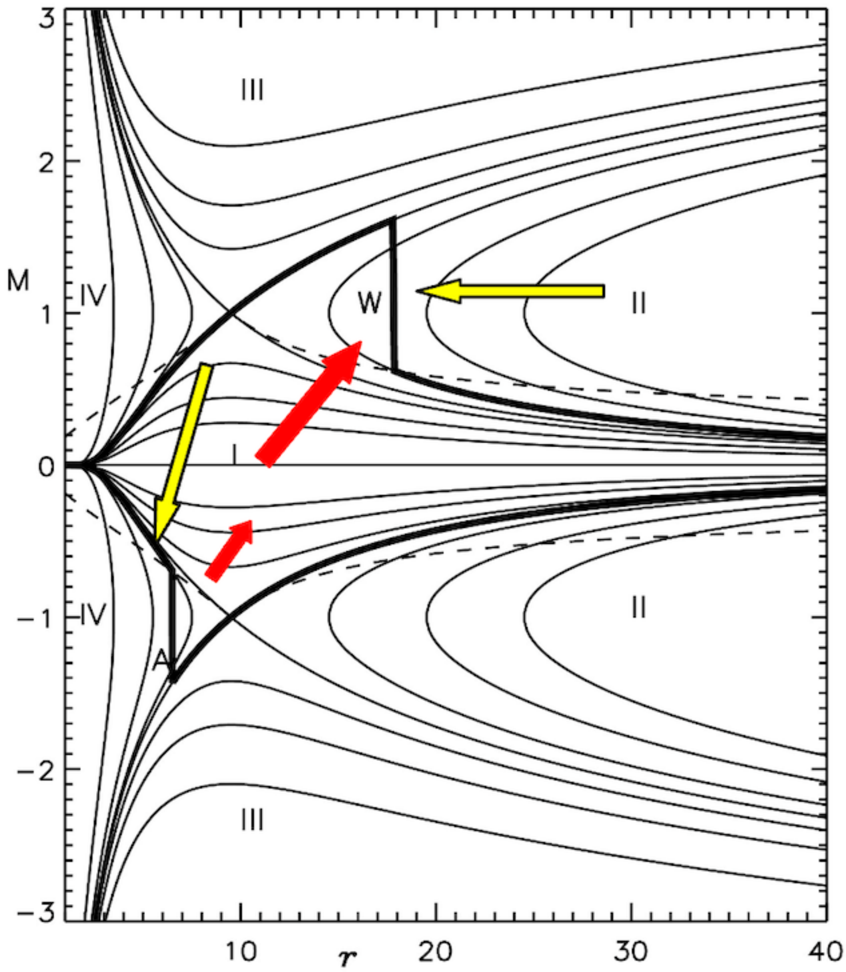

Figure 7. *The Hysteresis Cycle predicted by Velli (1994). Plot shows the solar wind Mach number M as a function of distance from the Sun r for different steady-state solutions of an isothermal flow. For small interstellar pressure, a shocked solar wind exists (top dark line); as the interstellar pressure increases (first yellow arrow) the shock moves inward until collapse into supersonic accretion with a shock occurs (second yellow arrow); once the interstellar pressure reverts to its initial value, the flow goes through a subsonic accretion breeze and then to supersonic outflow with a shock (red arrows).*

lar atmosphere should know which flow to choose, when many such flows might satisfy the same boundary conditions (including subsonic flows or breezes) remained. For example, Leon Mestel (quoted in Roberts and Soward, 1972) first remarked that "were the temperature at the base of the solar corona 10^5 K rather than the generally accepted (1 to 2) 10^6 K, the total pressure far from the Sun would suffice to suppress the solar wind entirely". Such a statement makes the argument for a supersonic wind much less cogent on the basis of pressure arguments only.

The lore surrounding Parker's paper, the fact that it was initially rejected and finally published only thanks to Subrahmanyan Chandrasekhar's – also at the University of Chicago and director of Yerkes Observatory as well as editor of the Astrophysical Journal – direct intervention (though apparently both Simpson and Chandrasekhar disagreed with its conclusions), have amplified its remarkable status. However, in a famous 1952 paper, Hermann Bondi had solved the very same equations describing steady-state flows in spherical geometry but trying to understand spherically symmetric accretion onto a star. Stationary state equations are symmetric under a sign change for the radial flow, so that additional arguments, such as causality, must be used to understand the attainability of the solution. After Bondi's paper, published in Monthly Notices of the Royal Astronomical Society, William H. McCrea in 1956 had discussed how to introduce shocks into such flows. Though by 1963 Parker knew about such work (McCrea's paper is cited in his book on interplanetary gas dynamics), he had no knowledge of Bondi's work when he explored the solar wind equations, as he himself explained to me; the context was completely different, that of understanding the environment of the Earth in space. Nonetheless, there is a connection between Parker's solar wind and Bondi's spherically symmetric accretion solutions, described by **Figure 7**: for a star with a hot corona normally the pressure of the interstellar medium (ISM) is so small that a shock transition exists far from the star (in the solar case, around 100 AU). If the pressure of the interstellar medium grows, the shock moves inward, ultimately reaching the sonic point, at which point a catastrophe occurs, and the star accretes material from the ISM as Bondi predicted. However, once the pressure of the ISM decreases again, the star accretes more slowly, before a critical pressure corresponding to a static atmosphere is reached. Even a small further decrease of ISM pressure then leads again to

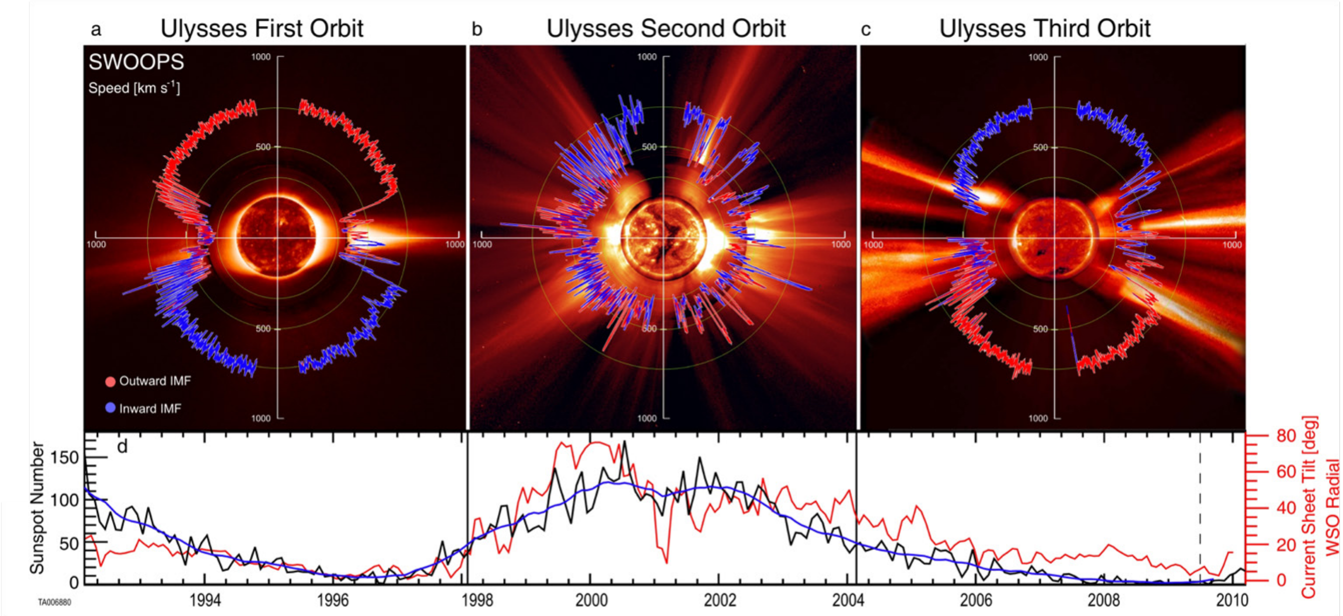

Figure 8. *(a–c) Polar plots of the solar wind speed, colored by IMF polarity for Ulysses' three polar orbits. In each, the earliest times are on the left (nine o'clock position) and progress around counterclockwise. (d) Contemporaneous values for the smoothed sunspot number (black) and heliospheric current sheet tilt (red), lined up to match Figures 1a–1c. In Figures 1a–1c, the solar wind speed is plotted over characteristic solar images for solar minimum for cycle 22 (8/17/96), solar maximum for cycle 23 (12/07/00), and solar minimum for cycle 23 (03/28/06). From the center out, blended images from the Solar and Heliospheric Observatory (SOHO) Extreme ultraviolet Imaging Telescope (Fe XII at 1950 nm), the Mauna Loa K coronameter (700 nm to 950 nm), and the SOHO C2 white-light coronagraph are shown as background. From McComas et al. (2008).*

a supersonic wind with a shock. In other words, the transition from accretion to wind and back is necessarily of an abrupt nature, and very special, and hence rare conditions are necessary to establish steady state quasi-static or subsonic flows between a star and its interstellar environment.

Solar corona and wind before Parker Solar Probe

In the decades following the solar wind discovery and the Simpson report, multiple satellites were launched dedicated to studying the solar wind via direct in-situ measurements and/or the solar corona using remote sensing techniques. These provided immense progress on understanding the outer solar atmosphere, from the chromosphere to corona, as well as local solar wind properties. Skylab X-ray images of the solar corona showed the existence of darker, less dense, electronically cooler regions called coronal holes, corresponding to the polar regions of the corona seen in eclipse at solar minimum, while the in-situ measurements from Mariner and the German Helios I and II missions, that explored the inner heliosphere in between the orbits of Earth and Mercury in the ecliptic plane, showed how recurrent solar wind streams of different speed arose in correspondence to the large scale coronal hole features of the solar corona. They also showed how the supersonic solar wind plasma streams, at Mach 10 or above, were universally permeated by turbulent fluctuations with well-defined power-law spectra. Helios demonstrated that properties such as solar wind speed, ion temperatures, and turbulence amplitude increase with distance from the heliospheric current sheet or as a function of heliomagnetic latitude[4]. The continuous monitoring at 1 AU by Wind and composition measurements from ACE have allowed a detailed categorization of the in-situ solar wind in the ecliptic as a function of solar cycle, yet it has still been difficult to trace the origin of solar wind streams beyond the generic association of fast wind with coronal holes and slow wind with the streamer belt.

4 Latitude referenced to the solar magnetic equator.

In its three orbits over the Sun's poles Ulysses explored the three-dimensional structure of the solar wind as it changes over the course of a solar activity cycle (**Figure 8**). Ulysses showed that the fast solar wind, with a speed around 750 km/s, is the basic, quasi-steady outflow from the high-latitude solar corona during the minimum phase of the solar cycle and proved what had previously been surmised from the Helios spacecraft, as well as indirect interplanetary scintillation measurements, namely that fast solar wind streams originate from polar coronal hole regions. Remarkably, such regions are relatively cool, for electrons, the electron temperature maximum remaining close to and perhaps less than about a million kelvin, well below the 2 million degrees of the confined corona. The solar wind plasma advects the solar magnetic field outward, resulting in the clearly visible dipolar structure (blue/red hemispheres) seen in **Figure 8**.

While fast wind originates from the cooler coronal hole regions on the Sun, Ulysses measurements also showed an inverse correlation between flow speed and coronal electron temperature; this poses a fundamental challenge to one of the basic tenets of the original Parker theory of the solar wind, which assumes the wind to be driven by high coronal electron temperatures and heat conduction. A further challenge to the original theory came from the Ultraviolet Coronal Spectrometer (UVCS) measurements of the joint ESA/NASA Solar and Heliospheric Observatory (SOHO), which suggested that the open field corona expands principally because of the very high, anisotropic temperatures of the coronal ions, with the minor species reaching temperatures of 10 MK at a few solar radii.

Unlike the fast wind, which originates in coronal holes, the slow solar wind is confined to regions emanating from the magnetic activity belt. SOHO observations suggest that the slow wind flows in a bursty, intermittent fashion from the top of helmet streamers, which were first seen to expand continuously, in X-rays, by the Japanese satellite Yohkoh (Sunbeam). The organization into fast and slow components characterizes the solar wind around solar minimum. As the solar activity cycle progresses, however, Ulysses showed that the simple bimodal structure gives way to a much more variable, but typically slower, solar wind at activity maximum, apparently originating not only from the much more sparse coronal hole regions and the quiet Sun, but also from coronal active regions, with a much more complex polarity structure of the magnetic field entrained into the heliosphere.

A third type of flow arises from large eruptions of coronal magnetic structures, known as coronal mass ejections (CME). Their initiation requires an entirely distinct mechanism from the slow and fast wind. One of the important developments in solar and heliospheric physics during the last twenty-five years is the recognition that shock waves driven by fast CMEs can relatively often accelerate particles to energies exceeding 1 GeV and that such shock-driven "gradual" energetic particle events are distinct from "impulsive" events associated with solar flares. However, the identity of the seed particles and the physical conditions necessary for the acceleration of particles in gradual events are not known.

The solar wind was shown from the initial explorations to be everywhere permeated by fluctuations bearing characteristics of turbulence, i.e., with energy distributions in frequency displaying power-law spectra. But especially in fast streams, anomalous, unexpected characteristics were found as well: fluctuations in density are suppressed, though the magnetic field component oscillations are of the order of the mean field, and the total intensity of the magnetic field oscillates at a much lower level than the components. At the same time, the correlation of velocity and magnetic field fluctuations corresponds to incompressible waves propagating away from the Sun, the waves discovered and named after Alfvén. This type of turbulence was called Alfvénic turbulence. Turbulence measured by Helios in the inner heliosphere and further out by other satellites seems to provide sufficient energy for heating the wind. The source of the turbulence and its potential role in coronal heating and solar wind acceleration remained difficult to assess, without measurements close enough to the Sun in the acceleration region of the wind, and in particular below the region where the wind becomes faster than the Alfvén speed[5], defining the boundary of the magnetically controlled corona. **Figure 9** illustrates how the Alfvén critical height acts to separate the corona proper, where waves propagate up and down (left and right panels, heights below 12.5 solar radii) from the super-Alfvénic wind, where all waves propagate

5 The Alfvén speed is the velocity of propagation of Alfvén waves, it is proportional to the magnetic field strength and inversely proportional to the square root of the mass density.

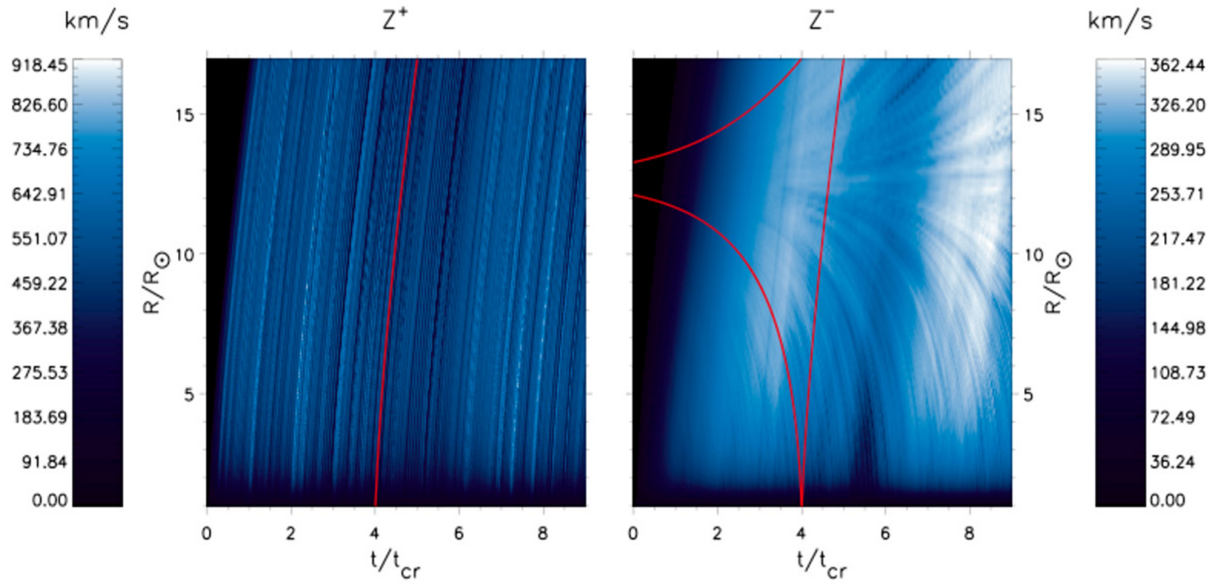

Figure 9. *Contour plots of the energy expressed in terms of Elsässer variables (Z) defining outward (Z+) and inward (Z-) propagating Alfvén waves as a function of time and distance. (Elsässer variables are often used in MHD to express the wave amplitude as a sum (Z+) /difference (Z-) of velocity and magnetic field fluctuations in Alfvén speed units.) tcr is a typical forcing time at the base of the corona. The red line in the left panel outlines the outward propagation. In the right panel, one sees red lined displaying the same outward propagation, due to wave reflection, as well as curves going out and in emanating from the Alfvén critical height (12.5 solar radii). This is seen to be a source of inward waves (Z-) that can not be measured by a probe remaining outside the Alfvén height, because all waves propagate outward there. Adapted from Verdini et al. (2009).*

outward (left and right panels, heights above 12.5 solar radii). This provides a clear visual that motivates exploration of the inner, sub-Alfvénic region of the wind: one can not directly observe the coronal engine driving the wind, without accessing this region of space, as it is causally disconnected from in-situ observations in the super-Alfvénic region.

Although there are many models for various aspects of magnetic activity, coronal heating, and solar wind acceleration, the lack of magnetic field and detailed plasma measurements in the inner heliosphere inside the orbit of Mercury meant that over the years the original suggestion of a mission to probe the solar corona remained a high priority. Several science and technology definition teams (STDT) were organized by NASA, all with the goal of sending a spacecraft as close as four solar radii from the center of the Sun. This was motivated in part by the fact that the original Parker solar wind model showed the flow to become supersonic at around five solar radii. The scientific objectives always included understanding coronal heating and solar wind acceleration as well as the origin and release of solar energetic particles. In these first proposals the mission, called Starprobe or Solar Probe (1979–1982) also included gravitational (general relativity) experiments. One interesting study involved a joint NASA-IKI (Space Research Institute of the Russian Academy of Sciences) potential mission, part of a potential cooperative solar system exploration program that was to be developed by the US and Russia named FIRE (Sun) and ICE (Pluto), in addition to Mars Together. The FIRE mission was to consist of two spacecraft, one with a four solar radii perihelion provided by the US, the other with a ten solar radii perihelion provided by Russia. Unfortunately, this program never developed. In the US, further work on the probe with a four solar radii perihelion continued with the STDT reports: A minimum solar mission (chair, Ian Axford, 1995) and Solar Probe: first mission to the nearest star (1999, chair George Gloeckler). A final STDT for a mission to four solar radii was chaired by David McComas (2004). In the meantime, cost as well as technological limitations and scientific drawbacks of a four solar radii mission led to a renewed STDT, also chaired by D. McComas, to examine a new orbit in the ecliptic plane.

One of the main drawbacks of a mission with such a close perihelion was that, to reach it, the mission design required a Jupiter gravity assist to kick it out of the ecliptic plane while at the same time removing much of its angular momentum. This made for a spacecraft that would have to venture into the dangerous environment of the inner Jovian magnetosphere, and then carry a very brief primary mission, lasting only 16 hours in the pole-to-pole transit with perihelion in the ecliptic plane. On the other hand, a mission that used multiple Venus gravity assists, and slowly wound its way into the inner heliosphere over several years, with a somewhat more distant closest approach, 9.87 solar radii from Sun center, would allow a much greater time exploring the inner heliosphere inside Mercury.

The advantages of this design were so many, that even though the perihelion of the probe was further out, the mission was called Solar Probe Plus. Selected by NASA, its name was changed in May of 2017 to Parker Solar Probe, in honor of Eugene Parker. **Figure 10** displays the mission profile and timeline.

Parker Solar Probe

The PSP mission finally launched on 12 August 2018; by the end of 2023, PSP completed 18 of the 24 solar orbits scheduled for its seven-year mission, with the first of five perihelia at a distance of 11.42 solar radii – almost 20 times closer to the Sun than the Earth – completed on 29 September 2023. The primary science objective of the Parker Solar Probe mission is to determine the structure and dynamics of the Sun's coronal magnetic field and to understand how the corona is heated, the solar wind accelerated, and how energetic particles are produced and their distributions evolve. Four suites of instruments are carried: the Electromagnetic Fields Investigation (FIELDS), comprised of magnetometers on the boom behind the heat shield and electromagnetic wave antennae facing the Sun, unobstructed by the heat shield; the Integrated Science Investigation of the Sun, Energetic Particle Instruments (ISIS); the Solar Wind Electrons Alphas and Protons Investigation (SWEAP), including a Faraday cup exposed to the Sun; and the Wide Field Imager for Solar Probe Plus (WISPR), that uses the heat shield as an occulter (see Fox et al., 2016 and the dedicated issue of Space Science Reviews for further details).

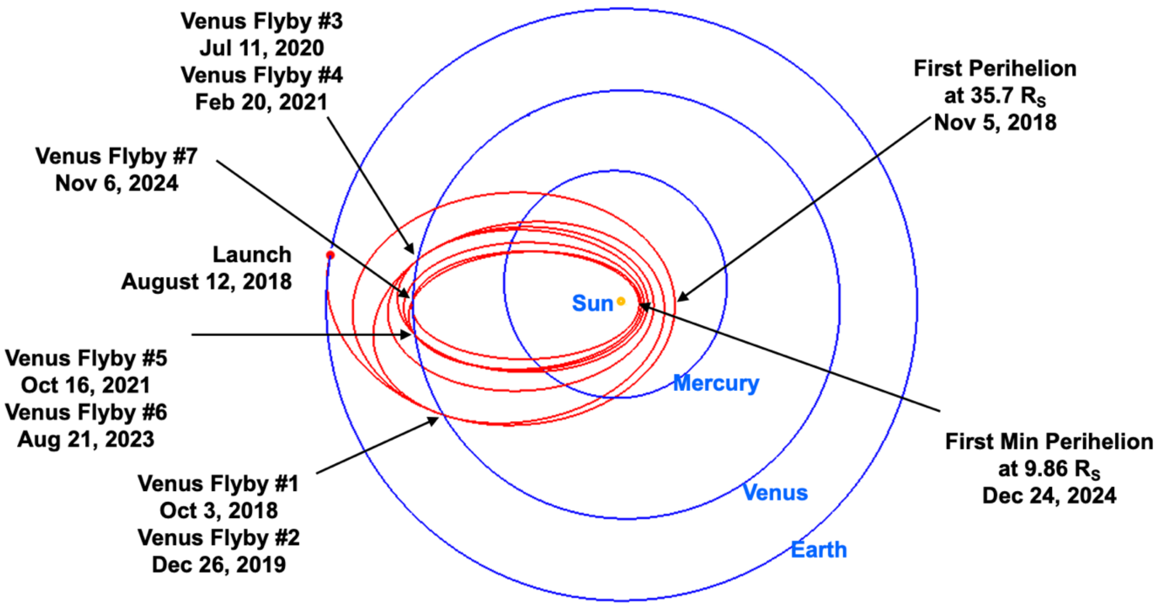

Figure 10. *Parker Solar Probe (PSP) mission timeline. At the time of writing PSP has completed its first orbit with a perihelion at a distance of 10.42 solar radii from the Sun's photosphere, more than 20 times closer than the Earth.*

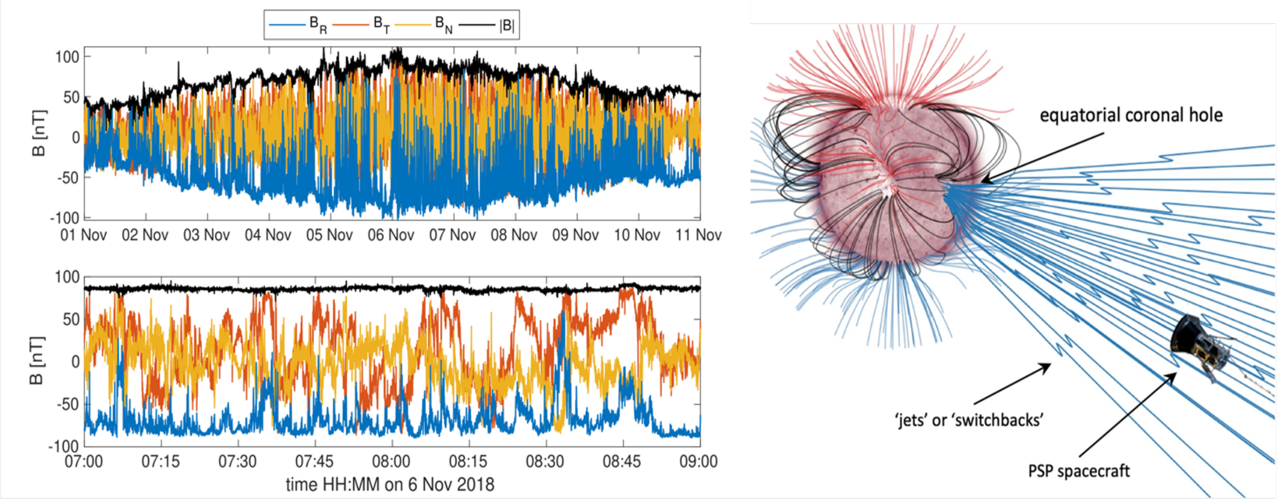

Figure 11. *Left panel, the three components of the magnetic field, with the radial component in blue, the component (roughly) normal to the ecliptic plane in yellow, and the component in the sun-spacecraft orbit plane in the direction of motion in orange. The field magnitude is in black. Right panel: an artist impression of the implication of the measurements: large amplitude outwardly propagating folds in the field, or switchbacks, are the most prominent feature of Alfvénic turbulence in the inner heliosphere. Adapted from Bale et al. (2019).*

PSP has already made a number of important new discoveries covering all of its objectives. One of the first surprises observed immediately at Parker's first encounter with the Sun came from the magnetic field measurements shown in **Figure 11**: on the left, the time series of the three components of the magnetic field are plotted as a function of time, with the radial component in blue, as well as the magnetic field magnitude (in black). The top panel shows data over the whole encounter, 10 days, with the first perihelion occurring close to midnight between the 5th and 6th of November. One immediately notices the remarkable oscillations from negative to positive of the radial field, from around -90 nT to +90 nT at perihelion continuously occurring throughout the encounter. These apparent changes of polarity of the magnetic field were quickly understood not to be spacecraft crossings of the heliospheric current sheet separating the dominant northern and southern polarities of the field, but rather kinks in the field lines as displayed on the right-hand side of **Figure 11**. The bottom panel on the left-hand side shows an inset, where one can see how the oscillations in magnetic field magnitude, in black, are less than 5 % of the oscillations in field components. These huge oscillations are nothing but very large-amplitude Alfvén waves propagating away from the Sun. Though they had been observed already, very rarely by Ulysses, in very fast solar wind streams, and somewhat more commonly by Helios and Wind, one remarkable aspect was that the overall solar wind speed was extremely slow, below 300 km/s. On top of this flow, the large-amplitude Alfvén wave, called switchback, displays a velocity imprint in the form of outwardly propagating jets, perfectly correlated with

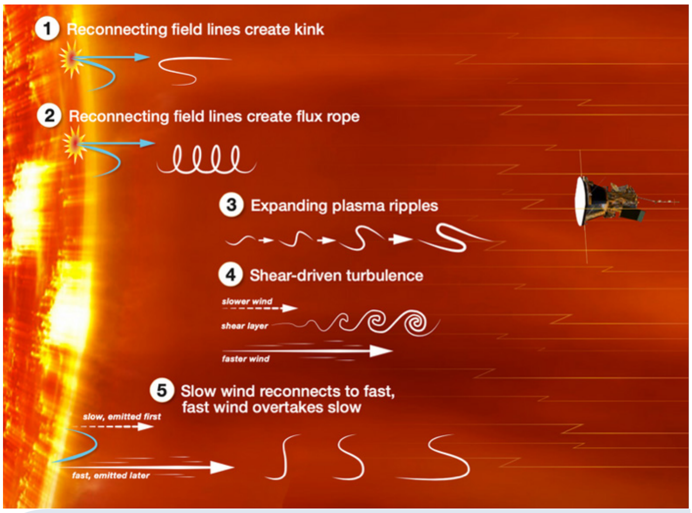

Figure 12. *Schematic of switchback formation mechanisms. Adapted from https://www.nasa.gov/feature/goddard/2021/switchbacks-science-explaining-Parker-solar-probe-s-magnetic-puzzle.*

the radial magnetic field, and speeds of order 100 km/s, comparable with local Alfvén speed.

While the origin of magnetic switchbacks in the solar wind has not been fully resolved, several dynamical processes have been proposed, summarized in **Figure 12**. One idea is that reconnection between closed and open field lines produces an outwardly propagating kink. This kink may either be a switchback directly (cases 1 and 2 in the figure) or provide an initial radial field modulation that develops into a switchback during the expansion from the Sun (case 3). Shear in the flow of localized or large-scale streams, or a variant, the Kelvin-Helmholtz instability[6], might also lead to switchbacks (cases 4, 5). In any case, the

6 A shear instability occurring in a fluid at the interface between two parallel streams of different velocities and densities.

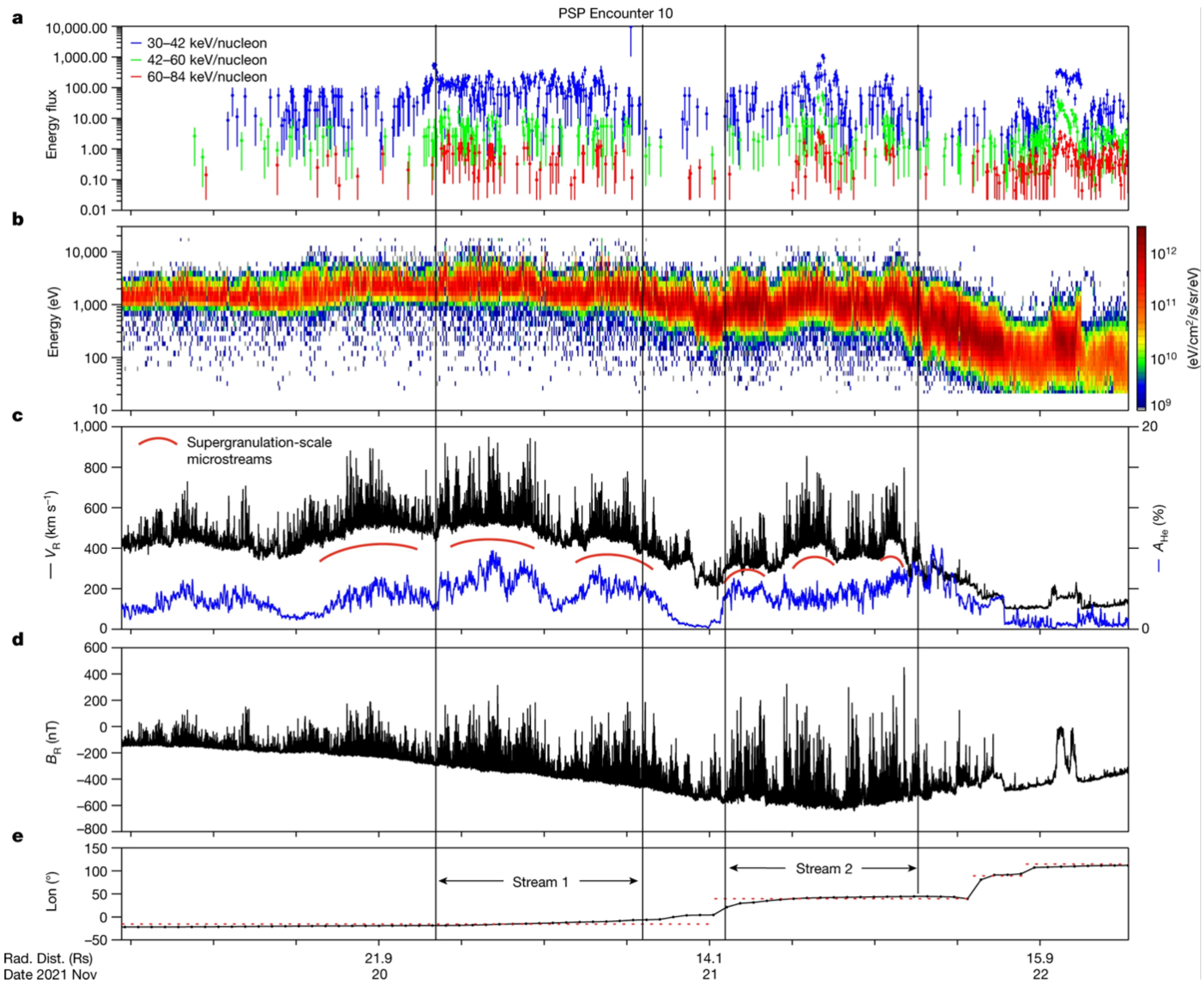

Figure 13. *Hot solar wind ions in (a) extend in energy to greater than 85 keV as suprathermal tails on the proton particle distribution in (b). In (c), red arcs mark the solar wind radial velocity (VR) microstream structure that is organized in Carrington longitude at angular scales associated with supergranulation convection and the photospheric network magnetic field. These microstreams become shorter in duration as the spacecraft accelerates through perihelion near the center of this figure and sweeps more rapidly through Carrington longitude. The thermal alpha particle abundance (A_{He}, blue trace in (c)) is similarly modulated by the microstream structure. The alpha particle abundance is frozen-in at the base of the corona. (d) Reversals of the radial magnetic field (BR) 'switchbacks', are organized by the microstreams and are linked to the radial flow bursts by the Alfvénicity condition. Photospheric footpoints from a simple potential field model for the magnetic field indicate two distinct coronal hole sources well separated in Carrington longitude (Lon), dotted line in (e). From Bale et al. (2022).*

energy and pressure content of such fluctuations is compatible with the requirements of fast solar wind acceleration.

As noted, the wind speed over the first PSP perihelion was very slow, and the reason has to do with the corresponding solar wind source region, which was found to be located in a small, extremely rapidly expanding coronal hole of negative polarity near the equator. The quasi-ubiquitous presence of strongly Alfvénic turbulence measured by the Parker probe in the inner heliosphere is strongly suggestive of the fact that all solar wind streams develop with an outwardly propagating fluctuation component. Apparently, evolution in the outer corona and heliosphere then proceeds to destroy these highly-correlated states more easily in slow wind streams, especially in the neighborhood of the heliospheric current sheet, or other locations where the structuring of the solar wind is significant and the inhomogeneity of the medium leads to a stronger decay of correlation.

Another very significant PSP finding concerns the distribution of switchbacks, their connection to the source regions of the solar wind, and velocity structures seen in the heliosphere. As shown in Bale et al. (2023) with measurements from Encounter 10, fast solar wind streams confirm that the photospheric supergranulation structure, reflected in the magnetic network at the base of the corona, remains imprinted in the near-Sun solar wind. As a result, switchbacks come in patches. That the magnetic field switchbacks were organized in patches was visible already in **Figure 11**, from encounter 1, but is shown more evidently in **Figure 13**. The patches in panel (d) in the figure correspond to bursty wind streams identified by the arcs in panel (c), that also show power-law-like energetic ion spectra to beyond 100 keV (panels, a, b). Computer simulations of interchange reconnection at the coronal base support key features of such observations, including the ion spectra. The process of magnetic reconnection in the low corona is collisionless and the energy release rate seems to be sufficient to power the fast wind. Parker Solar Probe therefore seems to confirm the fundamental role of magnetic reconnection – Parker's nanoflare scenario (Parker, 1988) – in the formation of the corona and solar wind. Interestingly, the slowest solar wind streams appear to be consistent with a wind driven almost entirely by electron heat flux, essentially as described by the isothermal Parker fluid theory from 1958 (**Figure 14**). The colored pixels in the figure refer to individual measurements of speed, with color going from black to blue to red with increasing number of measurements of the given speed and distance. These measurements include microstreams and switchback jets that require supplemental energy deposition and acceleration.

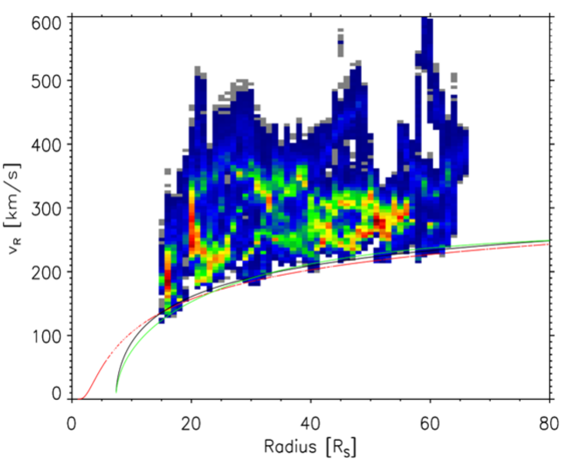

Figure 14. *A histogram of all solar wind speed measurements (colors denote increasing number of measurements from black to blue to red) from PSP over the first ten orbits. Courtesy S. Bale.*

PSP has also provided significant advances in our knowledge on slow wind sources. While faster wind streams typically originate in the large (often polar) coronal holes, slow wind emerges from different regions of the corona. PSP has shown unequivocally how Alfvénic slow wind, i.e., slow wind with the turbulence characteristics of faster wind, emerges from rapidly expanding coronal holes. It also has observed the effects of reconnection in the forming heliospheric current sheet, the large-scale boundary region separating magnetic polarities in the heliosphere, both in-situ and in the white light images taken by the WISPR telescopes. A composite image showing a chain of plasma blobs, or plasmoids, originating in the heliospheric current sheet, and strikingly resembling the expectations from models of current sheet reconnection instabilities as well as numerical simulations is shown in **Figure 15**.

Another source of slow wind comes from regions where the magnetic field mapping from the lower corona into the solar wind displays high complexity and non-monotonic expansion, i.e., boundary re-

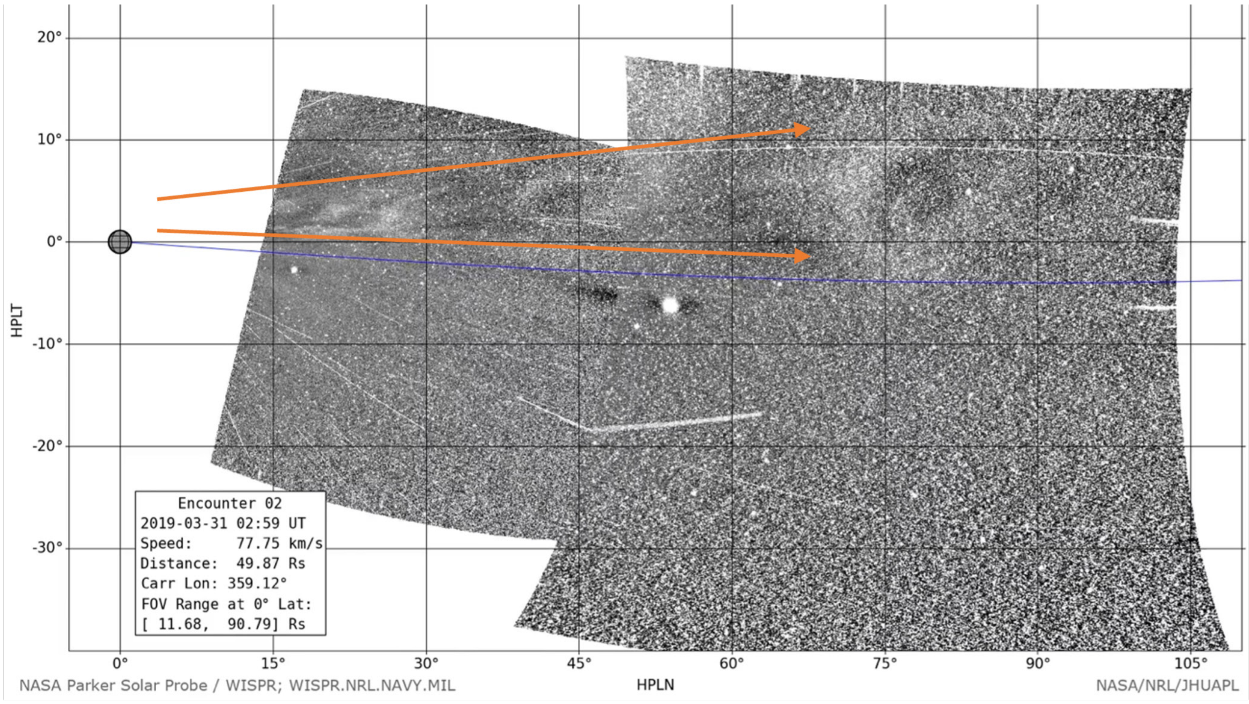

Figure 15. *Reconnection in the forming heliospheric current sheet as seen from a white-light image taken by the two WISPR telescopes on Parker Solar Probe during the second encounter on 31 March 2019, while the spacecraft was about 50 solar radii from the Sun, shown as a circle to the left of the image. Three distinct structured plasma blobs are highlighted by the two orange arrows. Dots are stars and bright circles planets. Striations are from small clouds generated by dust impacts. Courtesy of the Wide field Imager for Parker Solar Probe (WISPR).*

gions separating different types of flux systems, the so-called S-web or pseudostreamer arcs.

In addition to results concerning the macroscopic structure and acceleration of the solar wind, Parker Solar Probe has opened a fascinating window into the kinetic physics of the magnetized plasma of the inner heliosphere, measuring distribution functions with exotic shapes very far from equilibrium created by the interaction of waves, turbulence and current sheet electric fields with the particles themselves. PSP has also contributed to our understanding of the dust environment of the inner heliosphere, confirming the existence of an inner dust-free zone as well as to a broader understanding of the different sources of populations of zodiacal dust. As the solar cycle is approaching maximum, PSP has also directly crossed large CMEs, and new studies on the magnetic structure, energetic particle sources and acceleration in the inner heliosphere are under way.

Solar Orbiter, DKIST and the future of solar and heliospheric exploration

Parker Solar Probe is not alone in exploring the heliosphere from new vantage points. The present decade has also seen the launch of the joint ESA-NASA mission Solar Orbiter (Müller 2020) that is exploring the inner heliosphere carrying both in-situ and remote sensing instruments. Thanks to the multiple conjunctions and quadratures between Solar Orbiter and Parker Solar Probe (Velli 2020), joint studies are quickly increasing our knowledge of the origins and evolution of individual solar wind streams, enhancing our understanding of heliospheric plasma turbulence and energetic particle acceleration. Solar Orbiter's capability of measuring solar magnetic fields from points of view separated widely in longitude, and, in the near future, in latitude, promise a greater understanding both of the 3D structure of the heliosphere as well as of the large-scale circulation on the photosphere, essential to understand the dynamo at the source of solar magnetic activity. The inauguration in 2019 of the Daniel K. Inouye Solar Telescope (DKIST) has allowed the highest-resolution measurements – below 100 km – of small-scale motions and magnetic activity in the photosphere and chromosphere, and perhaps also resolving active current sheets at the source of the solar corona. This truly seems to be a golden age for exploring solar magnetic activity, holding the promise for understanding the role of magnetic fields and plasmas not only in our near environment, the heliosphere, but more generally in the environments of planets embedded in other astrospheres, with all its consequences, including habitability and the potential for life.

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The Author

Marco Velli is the Johannes Geiss Fellow 2022 and Professor of Space Physics at the Earth, Planetary and Space Sciences Department, University of California, Los Angeles, USA. A student of the University of Pisa and Scuola Normale Superiore, he has spent research periods at the University of St. Andrews, Scotland, the Observatoire de Paris, France, Università della Calabria, Italy, and the Smithsonian CfA, Cambridge, MA, as well as the Jet Propulsion Laboratory, California Institute of Technology, where he remains a Senior Scientist.

SPATIUM