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The solar wind

PARKER'S THEORY AND THE EARLY MEASUREMENTS OF THE SOLAR WIND

Shortly before the beginning of the space age, Eugene N. Parker of the University of Chicago predicted that interplanetary space would be filled with a plasma flowing rapidly outward from the Sun (Parker 1958). The likelihood that the Sun ejects charged particles that cause auroral and magnetic activity on Earth was generally accepted by that time. The observation that the plasma tails of active comets always point almost radially away from the Sun led Ludwig Biermann (1951) to postulate that the solar corpuscular radiation is continuous, rather than intermittent. It was also known that the outer atmosphere of the Sun, the solar corona, was extremely hot, with a temperature exceeding a million degrees. Sidney Chapman (1957) calculated that if the corona was in hydrostatic equilibrium, it must extend throughout the Solar System and cool off to only $\sim 2 \times 10^5$ K at the orbit of Earth. Parker (1958) put all these ideas together, explaining that the inward pressure of the interstellar medium was too weak to allow the solar atmosphere to be in hydrostatic equilibrium. He coined the phrase "solar wind" to describe the outward flowing solar corona which supplies the pressure required to stand off the local interstellar medium, to exert the necessary force on cometary plasma tails, and to transmit solar disturbances to the geomagnetic field. For a more complete theoretical explanation of Parker's prediction of the solar wind, see Chapter 9.

Parker's theoretical prediction was not uncontested, however. Most notably, Joseph Chamberlain (1960) proposed that rather than Parker's solar wind caused by the hydrodynamic outflow of the solar corona, there was merely a solar breeze, consisting of plasma thermally escaping from the corona. Many of the early space investigations therefore included attempts to determine whether interplanetary space was filled with Parker's supersonic 500 km s^{-1} solar wind or with Chamberlain's subsonic 10 km s^{-1} solar breeze. A summary of those early missions and experiments is given in Table 1.

Not surprisingly, the Soviets were the first in space with instruments capable of measuring the interplanetary plasma. Their "ion traps" were simple Faraday cups with an inner grid held at -200 V to repel interplanetary electrons and to prevent the escape of photoelectrons from the cup and an outer grid at a positive potential to define the minimum energy of the ions entering the cup. Lunik 2 was the most successful of four missions, determining that there was indeed a flux of $\sim 2 \times 10^8$ cm^{-2} s^{-1} of positive ions with energy/charge > 15 eV/charge (Gringauz *et al.* 1960). Because the speed of a proton with energy > 15 eV is > 53 km s^{-1}, the Lunik 2 measurements favored Parker's theory over Chamberlain's, but questions of the extent to which the speed exceeded that limit, the direction of the flow, and its persistence were left unanswered.

With the Explorer 10 mission in 1961, a group from the Massachusetts Institute of Technology (MIT) made the first US measurements of the solar wind (Bonetti *et al.* 1963). Their instrument was an advance over the Soviet ion traps in that it had an additional grid which carried a positive square-wave potential to allow measurement of the ion energy spectrum without confusion between the flux of ions entering the detector (an AC signal) and the flux of photoelectrons knocked out of the negative inner grid (approximately a DC signal). Before the spacecraft batteries died at a distance of ~ 34 Earth radii, the instrument measured an intermittent flux of ions from a direction within a 20° by 80° window which included the direction from the Sun. When the ions (assumed to be protons) were

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Table 1 The earliest attempts (1959–62) to observe the solar wind

Launch date	Spacecraft	Institution	Instrument*	Result
2 January 1959	Lunik 1	USSR	Four ion traps -10 to $+15$ V	No publishable data
12 September 1959	Lunik 2	USSR	Four ion traps -10 to $+15$ V	39–60 R_E Flux $>$ 15 eV $\approx 2 \times 10^8\,\mathrm{cm^{-2}\,s^{-1}}$
4 October 1959	Lunik 3	USSR	Four ion traps -19 to $+25$ V	One observation of flux $>$ 20 eV $\approx 4 \times 10^8\,\mathrm{cm^{-2}\,s^{-1}}$ Other data $<$ threshold ($\sim 10^8\,\mathrm{cm^{-2}\,s^{-1}}$)
12 February 1961	Venus Probe	USSR	Ion traps 0 and 50 V	Very intermittent data One observation of flux $\approx 4 \times 10^8\,\mathrm{cm^{-2}\,s^{-1}}$
25 March 1961	Explorer 10	MIT	Modulated FC	Skimmed magnetopause flank Consistent with flow from Sun Measured n, v, T Supersonic and super-Alfvénic
16 August 1961	Explorer 12	NASA Ames	CPA	Dayside magnetosheath Did not detect any ions
22 August 1961	Ranger 1	JPL	6 CPAs	Failed to get out of parking orbit
18 November 1961	Ranger 2	JPL	6 CPAs	Failed to get out of parking orbit
22 July 1962	Mariner 1	JPL	CPA	Destroyed by range safety
27 August 1962	Mariner 2	JPL	CPA	113 days of data Continuous radial flow High-, low-speed streams n, v, T relations $v_\alpha \approx v_p$; n_α/n_p variable; $T_\alpha \approx 4\,T_p$
2 October 1962	Explorer 14	NASA Ames	CPA	Mostly magnetosheath UV interference

* FC is Faraday cup and CPA is curved-plate analyzer.

detected, their flux was in the range 1.0–2.5 $\times 10^8\,\mathrm{cm^{-2}\,s^{-1}}$, their speed was $\sim$280 km s^{-1}, and their flow was supersonic, as predicted by Parker's theory. In retrospect, the ion fluxes detected by Explorer 10 were not in the solar wind proper, but downstream of the Earth's bow shock, in the flank of the magnetosheath.

A group at the NASA Ames Research Center attempted to measure the solar wind with instruments on Explorers 12 and 14 in 1961 and 1962 (Bader 1962, Wolfe and Silva 1965). These instruments were curved plate analyzers with a voltage applied perpendicular to the ions' direction of motion to bend their trajectories onto a detector. On Explorer 12 there was a problem that the field of view of the instrument did not include the solar direction, and on Explorer 14 there was a problem with contamination of the ion signal by solar ultraviolet radiation when the instrument did face the Sun. Furthermore, on both missions, the spacecraft trajectories were almost entirely downstream of the bow shock.

About the same time as the unsuccessful attempts by Bader and Wolfe at NASA Ames, one of the authors (MN) and her colleague, Conway W. Snyder, flew solar wind detectors on four different missions. The first two of those spacecraft, Rangers 1 and 2, failed to get out of low-Earth orbit, while the third spacecraft, Mariner 1, went astray and was destroyed by ground command. Finally, after some hair-raising misadventures (Neugebauer 1997), Mariner 2 was safely placed on a trajectory to Venus. The Mariner 2 instrument was a curved-plate analyzer which measured the ion current reaching a collector at each of 10 voltages on the deflection electrodes. Mariner 2 obtained a spectrum of the solar wind every 3.7 minutes almost continuously for 113 days. There was no longer any doubt that Parker had been correct; the solar wind exists.

Although the ion spectra obtained by Mariner 2 were very crude by today's standards, with measurable currents in no more than five energy/charge channels at any time, a lot of information about the properties of the solar wind could be gleaned from the data (Neugebauer and Snyder 1966). The solar wind blew continuously from within a 10° cone centered on the Sun. The wind was organized into low- and high-speed streams (velocities of $\sim$350 and 700 km s^{-1}, respectively), each of about 7 days' duration. The speed *versus* time profiles were steepened on the leading edges of the fast streams where the increased density indicated a snowplow effect. The proton temperature varied directly with the speed. These features are illustrated in Figure 1,

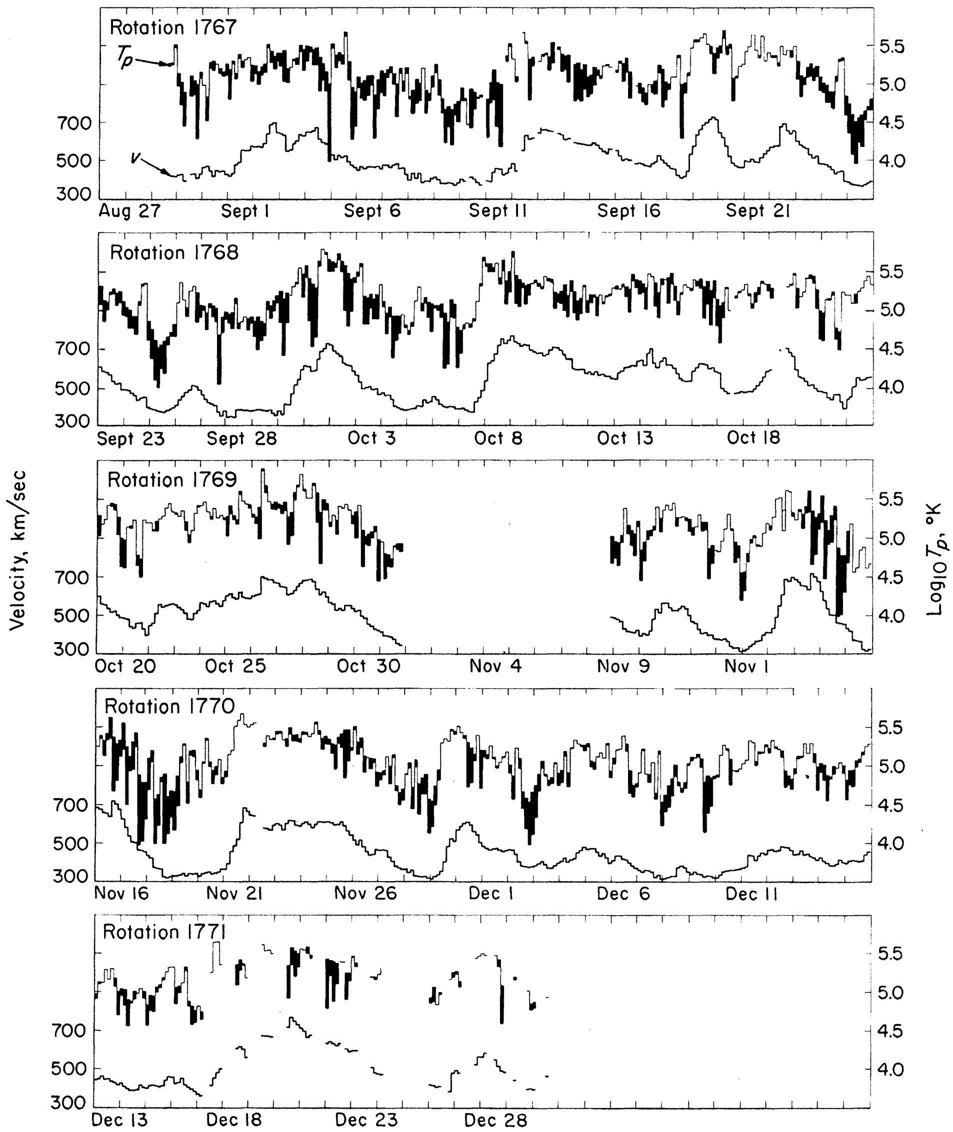

Figure 1 Three-hour averages of solar wind speed (bottom line) and proton temperature with upper and lower limit bars (top) observed by Mariner 2 in 1962. (From Neugebauer and Snyder 1966.)

which is a plot of three-hour averages of the solar wind speed and temperature over five 27-day rotations of the Sun. The pattern roughly repeated from one rotation to the next. On average, the ion flux and density varied as the inverse square of heliocentric distance between 1.0 and 0.7 AU.

It was often possible to detect a second spectral peak which was interpreted as being caused by alpha particles (helium nuclei) moving with approximately the same speed as the protons. This second peak could not, however, be fit to a model in which the alpha particles had the same temperature as the protons; instead, equal thermal speeds were indicated. The abundance of the alpha particles relative to the protons was sometimes highly variable from day to day.

Parker predicted not only the existence of the solar wind, but also the configuration of the interplanetary magnetic field (Parker 1958). Because of the very high electrical conductivity of the solar corona, the plasma and the magnetic field must move together. That is, the solar field is frozen into the solar wind. But at the same time that the field is being dragged nearly radially into space by the solar wind, it is still tied to the rotating Sun, with the result that the interplanetary field should have a spiral pattern with an angle to the radial direction of ~45° near 1 AU. The predicted spiral pattern of the field could be discerned in the data of the magnetometer on Mariner 2; this is illustrated in Figure 2, where each point represents a running average of five-hour averages. Although there is a great deal of scatter, the points are distributed in the quadrants predicted by the Parker spiral model. The properties of the fluctuations about the spiral direction continue to be studied intensively

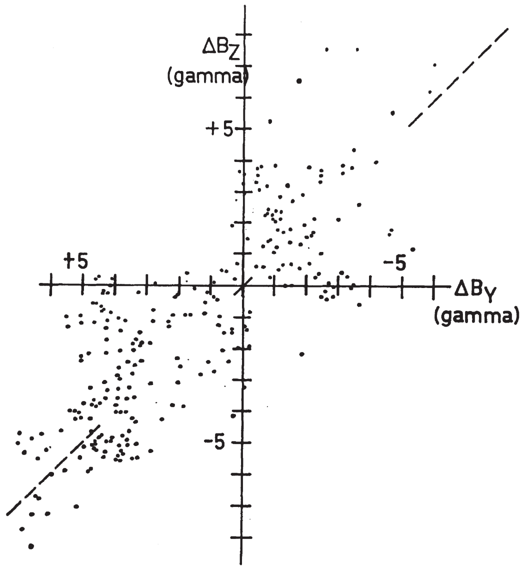

Figure 2. Five-hour sliding averages of hourly averages of the radial (ΔB_Z) and in-ecliptic transverse (ΔB_Y) components of the interplanetary magnetic field measured by Mariner 2. The dashed line shows the expected relation for the Parker spiral. (From Smith 1964.)

to reveal some of the fundamental processes occurring in the solar wind. A change in the direction of the interplanetary field from the first to the third quadrant in Figure 2, or the reverse, indicates a reversal of the polarity of the interplanetary field with the field sometimes pointing in toward and sometimes pointing out from the Sun. Week-long periods of persistent polarity were named "magnetic sectors" by Wilcox and Ness (1965).

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The solar wind has probably been blowing for at least the past 3×10^9 years with essentially the same strength, as can be estimated by comparing the flux of xenon ions in today's solar wind with that deduced from the xenon content of the lunar regolith (Geiss 1973). Observations of comet tails reveal that the solar wind did not stop blowing even during the Maunder minimum, from about 1645 to 1715 when there were essentially no sunspots.

It thus seems that the solar wind is a ubiquitous and continuous phenomenon, but it is not a structureless one. Its density, speed, temperature, ion charge states, elemental composition, and other properties all vary with time and position on timescales from minutes (or less, but knowledge of fast fluctuations is limited by the typical time resolution of today's ion sensors) up to decades (or more, limited by the short duration of the space era). The large-scale structures of the solar wind are conveniently divided into recurrent or quasi-stationary streams and transient flows.

The discovery of a 27-day (the synodic period of solar rotation) modulation of cosmic rays by Forbush in 1938 was conclusively traced to dynamical phenomena in the interplanetary medium and related to recurring coronal "active regions" (in the terminology of those days) by Simpson in 1954 (Simpson 1998). As shown in Figure 1, such recurrent structure was indeed found in interplanetary space in the form of alternating high- and low-speed streams, each lasting several days. The polarity of the interplanetary magnetic field tended to remain constant throughout each of the high-speed streams, with consecutive streams having opposite polarities. It is important to note that there is not a one-to-one correspondence between fast streams and magnetic sectors. There need not be a fast stream within every magnetic sector, and the position of a fast stream relative to its magnetic sector boundary does not remain fixed in interplanetary space. The leading edge of each fast stream, where the solar wind speed increases, is now commonly called a corotating interaction region (CIR). Such interaction regions are an inevitable consequence if streams of sufficiently different speeds are emitted from the Sun at the same heliographic latitude. The effect of solar rotation is to eventually ram fast solar wind into slower wind emitted from more westerly heliographic longitudes. Figure 3 shows an early schematic and a newer version of this scenario. The newer version also shows how the CIR develops in interplanetary space to engulf the magnetic sector boundary.

As a general rule, two magnetized plasmas cannot intermix without the benefit of magnetic reconnection or other types of plasma instability. Therefore, the fast and the slow solar wind streams remain separated out to large heliographic distances. Discontinuities separating the two wind types were first studied by Belcher and Davis (1971) using Mariner-5 data.[1] Burlaga (1974) introduced the term "stream interface" for this boundary which is characterized by a decrease in density by a factor of $\sim$2, accompanied by a similar increase in kinetic temperature. Sometimes, in order to enhance the signal, these two signatures are conveniently combined into the specific entropy argument, $T/n^{1/2}$, where T is temperature and n is density. As the solar wind expands to 1 AU and beyond, the stream interaction becomes progressively more pronounced. The leading (slow) plasma becomes accelerated and the trailing (fast) plasma becomes decelerated, building up hydromagnetic stresses which ultimately lead to the development of a pair of interplanetary shocks, a forward shock at the leading edge of the CIR and a reverse shock at the trailing edge.

[1] Mariner 5: a NASA Venus flyby mission launched on 14 June 1967 and operated to 21 November 1967.

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