The source region of the solar wind

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The Sun is continually emitting a stream of charged particles, namely protons, alpha particles (fully ionized helium), heavy ions and electrons flowing out into the interplanetary medium from its hot outer atmosphere, the solar corona. This is the solar wind. Spacecraft measurements show that the solar wind has two components which may be described as 'slow' and 'fast'. The slow wind has a speed of about 400 km/s while the fast wind travels twice as fast.

The first indication of a wind came from comet tails. Observations showed that comet tails always point away from the Sun, no matter whether a comet is headed towards or away from the Sun. In the early 1600s, Kepler speculated that comet tails are driven by the solar radiation pressure which still holds true for the many comet tails consisting of dust (see Figure 1).

Comets, however, also have ion tails, shining in their own spectral lines, not just in scattered sunlight. Such tails may point in slightly different directions, and are at times observed to accelerate quite suddenly, causing them to become kinked or bent. Comet Hale–Bopp, a prominent comet which was at its brightest in March–April 1997, clearly exhibited such twin tails. While the dust tail was much brighter, the plasma tail had a different colour, tending towards the blue.

How can solar radiation pressure explain such behaviour? In 1951 Biermann postulated that apart from sunlight, the Sun also emitted a steady stream of particles, a 'solar corpuscular radiation' which pushed the ions. We did not know then why this 'particle radiation' should exist? However, in 1958 Parker gave the first clue to understand this. He showed that even though the Sun’s corona is strongly attracted by solar gravity, it is such a good conductor of heat that it is still very hot at large distances. Since gravity weakens as distance from the Sun increases, the outer coronal atmosphere escapes into interstellar space. Not everyone accepted Parker’s theory of the solar wind when it was first published in 1958, and it was hotly debated. This hypothesis was confirmed when the solar wind was first detected in 1962 by the Mariner II spacecraft. However, the acceleration of the fast wind is still not understood and cannot be explained by Parker’s theory. The solar wind shapes the Earth’s magnetosphere and supplies energy to its many processes. Its density at the Earth’s orbit is about 6 ions/cm$^3$ which means that the solar wind plasma is more rarefied than the best vacuum laboratory on Earth.

Coronal holes

The Ulysses spacecraft confirmed the earlier results from Skylab and Helios in the 1970s that the fast wind escapes from holes in the corona near the poles. Coronal holes are well-defined regions of strongly-reduced extreme-ultraviolet and X-ray emission in the solar atmosphere (see Figure 2). Ulysses also characterized two kinds of solar wind at solar minimum conditions. At high latitudes, the Ulysses observed a relatively smooth solar wind originating from coronal holes in the polar regions. The fast wind departed very little from a velocity of about 750 km/s. Slow speed winds at about 400 km/s and originat-
ing in the streamer belts were observed in a relatively narrow latitude band on the either side of the ecliptic plane.

That the solar wind is emanating from coronal holes (open magnetic field regions in the corona) has been widely accepted since the Skylab era. But there was little additional direct observational evidence to support this view. Hassler et al. found the Ne VIII emission blue shifted in the north polar coronal hole along the magnetic network boundary interfaces compared to the average quiet-Sun flow (cf., Figure 3). These Ne VIII observations reveal the first two-dimensional coronal images showing velocity structure in a coronal hole, and provide strong evidence that coronal holes are indeed the source of the fast solar wind.

**Solar wind origin in coronal funnels**

Tu et al. have now successfully identified the magnetic structures in the solar corona where the fast solar wind originates. Using images and Doppler maps from the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrograph and magnetograms from the Michelson Doppler Imager (MDI) on the space-based Solar and Heliospheric Observatory (SOHO), they have reported the solar wind flowing from funnel-shaped magnetic fields which are anchored in the lanes of the magnetic network near the surface of the Sun. This landmark research leads to a better understanding of the magnetic nature of the solar wind source region.

The heavy ions in the coronal source regions emit radiation at certain ultraviolet wavelengths. When they flow towards Earth, the wavelengths of the ultraviolet emission become shorter, a phenomenon called the Doppler effect, which is well known in its acoustic variant, for example, from the change in tone of the horn of a police car while approaching to or receding from the listener. In the solar case, plasma motion towards us, which means away from the solar surface, is detected as blue shift in the ultraviolet spectrum.

**Figure 3.** The solar corona and polar coronal holes observed from EIT and SUMER instruments on SOHO. The 'zoomed-in' or 'close-up' region in the image shows a Doppler velocity map of million degree gas at the base of the corona where the solar wind originates. Blue represents blue shifts or outflows and red represents red shifts or downflows. The blue regions are inside a coronal hole or open magnetic field region, where the high-speed solar wind is accelerated. Superposed are the edges of 'honeycomb'-shaped patterns of magnetic fields at the surface of the Sun, where the strongest flows (dark blue) occur. (Image Credit: Science, 1999, 283, 810, SUMER/SOHO, EIT/SOHO, ESA/NASA).

**Figure 4.** This picture was constructed from measurements which were made on 21 September 1996 on SOHO with the SUMER for Doppler spectroscopy of the coronal plasma, with the MDI for magnetograms of the Sun’s surface, and the EIT for the context image of the Sun. The SUMER spectrometer scrutinized ultraviolet light which is emitted by the hot gas in the Sun’s atmosphere, and is ideally suited for studying atmospheric motions. Careful data analysis, involving subtle wavelength calibration and coronal magnetic-field extrapolation was required before the slow outward motions could be identified at various heights above the solar surface, and their links with the magnetic field guiding the flow could be established. The figure illustrates location and geometry of three-dimensional magnetic field structures in the solar atmosphere. The magenta-coloured curves illustrate open field lines, and the dark gray solid arches show closed ones. In the lower plane, the magnetic field vertical component obtained at the photosphere by MDI is shown. In the upper plane, inserted at 20,600 km, the Ne VIII Doppler shift is compared with the model field. The shaded area indicates where the outflow speed of highly charged neon ions is larger than 7 km/s. Note the funnel constriction by pushing and crowding of neighbouring loops. The scale of the figure is significantly stretched in the vertical direction. The smaller figure in the lower right corner shows a single magnetic funnel, with the same scale in both vertical and horizontal directions. (Image Credit: Science, 2005, 308, 519, SUMER/SOHO, EIT/SOHO and ESA/NASA).
work lanes by magneto-convection, where the funnel necks are anchored. The plasma, while still being confined in small loops, is brought by convection to the funnels and then released there, like a bucket of water is emptied into an open water channel.

Previously it was believed that the fast solar wind originates on any given open field line in the ionization layer of the hydrogen atom slightly above the photosphere. However, the low Doppler shift of an emission line from carbon ions shows that bulk outflow has not yet occurred at a height of 5000 km. The solar wind plasma is now considered to be supplied by plasma stemming from the many small magnetic loops, with only a few thousand kilometers in height (between 5 and 20 Mm), crowding the funnel. Through magnetic reconnection plasma is fed from all sides to the funnel, where it may be accelerated and finally forms the solar wind. The fast solar wind starts to flow out from the top of funnels in coronal holes with a flow speed of about 10 km/s. This outflow is seen as large patches in Doppler blue shift (hatched areas in the image) of a spectral line emitted by Ne$^+$ ions at a temperature of 600,000 Kelvin, which can be used as a good tracer for the hot plasma flow. Through a comparison with the magnetic field, as extrapolated from the photosphere by means of the MDI magnetic data, it has been found that the blue-shift pattern of this line correlates best with the open field structures at 20,000 km. It is to be further noted that this result is obtained by a correlation of the Doppler-velocity and radiance maps of spectral lines emitted by various ions with the force-free magnetic field as extrapolated from photospheric magnetograms to different altitudes. Ne VIII mostly radiate around 20 Mm where they have outflow speeds of about 10 km/s, while C IV with no average flow speed mainly radiate around 5 Mm.

**Deep roots of the solar wind**

Magnetic fields dictate the transport of charged particles. Thus solar wind particles flow along invisible magnetic field lines much like cars on a highway. When the magnetic field lines bend straight out to the solar surface, like the pattern of iron filings around a bar magnet, the solar wind acts like cars in city traffic and emerges relatively slowly. Scientists have known this for over thirty years and used it to give a crude estimate for the speed of the solar wind – either fast or slow.

In the new work, the speed and composition of the solar wind emerging from a given area of the solar corona are estimated from the characteristics of the chromosphere underlying that piece of the MDI data. Using SOHO’s Extreme ultraviolet Imaging Telescope (EIT) as a ‘finder’, McIntosh and Leamon isolated regions of the solar corona with open magnetic field lines (coronal holes) and closed fields (active regions). Then, using the earth-orbiting TRACE to measure the time sound waves took to travel between the heights of formation of two chromospheric continua, they were able to demonstrate that sound travel time predicted not only solar wind speed measured by ACE but its isotopic composition as well. The conditions in the ambient solar wind determine whether a coronal mass ejection will drive a shock wave in front of it. Shocks accelerate most of the energetic particles that can damage spacecraft and endanger spacefarers unshielded by a planetary magnetosphere. Knowledge of the state of the solar wind throughout the heliosphere is, therefore, essential to the exploration of the solar system. This work could extend solar wind predictions from the earth–Sun line (where ACE, WIND, and SOHO measure solar wind parameters) and a few planetary probes (such as the Voyagers) that also carry solar wind plasma packages, to cover the half of the heliosphere influenced by the visible hemisphere of the Sun.


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