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# Solar Wind Acceleration

**Ruth Esser**

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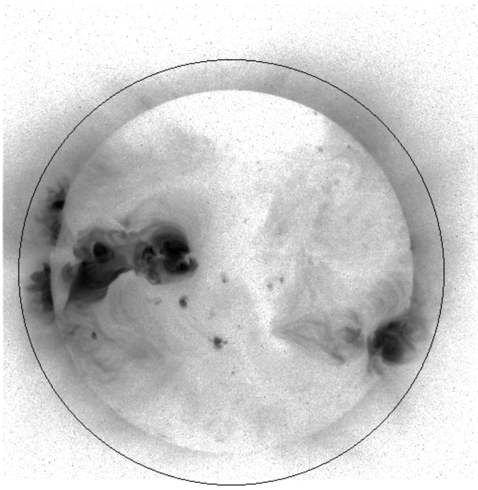

**Figure 1.** Soft x-ray Yohkoh image from 12 April 1993. The image shows a very distinct low-emissivity coronal hole region (large white area surrounding the north pole and stretching all the way to the equator). There is also a coronal hole present at the south pole, but this is veiled by denser material from surrounding regions and is therefore not visible at the time of the observation (see YOHKOH.)

# Solar Wind Acceleration

Solar wind acceleration is the increase of the flow speed of the solar wind plasma from close to zero in the lower SOLAR ATMOSPHERE to the values observed in interplanetary space, which can range from 200 km $s^{-1}$ for the slowest speeds in the ecliptic plane to 750 km $s^{-1}$ for streams originating in the large polar CORONAL HOLES. The exact height in the solar atmosphere at which the plasma starts its outflow is still being debated. Until recently it was thought that the solar atmosphere was more or less static out to distances of 5 to 10 solar radii. With new observations from both ground and space based instruments, it has become clear that at least the fast solar wind streams accelerate at much lower heights in the solar atmosphere than previously thought, starting their outflows probably even below the TRANSITION REGION.

### Properties of solar wind streams

Solar wind streams that differ significantly in speed will also differ in other plasma properties such as density and temperature. Different parts of the global solar magnetic field seem to give rise to streams with different properties. The large-scale magnetic field on the Sun can be approximated to first order by a dipole. Near the dipole equator inside of 1.5 to 3 solar radii the magnetic field is strong enough to withstand the outward plasma pressure, the magnetic field lines are therefore closed, and the plasma is confined in these regions called CORONAL STREAMERS. Further away from the Sun the magnetic field becomes weak compared with the plasma pressure, and the plasma forces the field lines to open, permitting a steady outflow of plasma into interplanetary space. These open field lines fill the space between the streamer boundaries and the solar poles. Plasma conditions in the open field regions differ from the conditions in the streamers. Observations show that electron densities and temperatures as well as emission at visible, UV and x-ray wavelengths are lower in the open field regions. Regions of extremely low emission are called coronal holes. The fastest solar wind originates from the large polar coronal holes which, particularly during solar minimum activity, might have extensions all the way to the solar equator (see figure 1, white areas on the solar disk). Measurements in interplanetary space show that this high-speed solar wind has rather constant plasma properties. At the Earth's orbit the flow speed is 750 km $s^{-1}$ (which is $2.7 \times 10^6$ km $h^{-1}$), the proton density is about $2 \times 10^6$ $m^{-3}$, and the electron and proton temperatures are $(1–2.5) \times 10^5$ K respectively. The abundance of alpha particles relative to protons is about 4.5%. The alpha particles are almost six times hotter than the protons and exceed their speed by about 50 km $s^{-1}$, which is close to the local Alfvén speed. The small traces of other heavy ions, such as $O^{6+}$, $C^{5+}$ and $Mg^{10+}$, that are also found in the solar wind, flow with the same speed as the alpha particles. The increase in the flow speed between 0.3 and 1 AU was determined during the HELIOS I and II era to be of the order of 1% in the high-speed wind. Generally plasma properties of the fast solar wind originating from the polar coronal holes vary by less than 10%. (For a more detailed description of the HELIOS I and II solar wind probes see Schwenn and Marsch (1990, 1991).)

In reality the large-scale magnetic field is more complicated than a pure dipole field and several closed field regions can be present at the same time (see SOLAR WIND: MAGNETIC FIELD). The slower solar wind originates from the open magnetic field regions on top of the different streamers, the edges of the streamers and the regions between streamers and coronal holes. These slower streams have plasma properties that are extremely variable. Their speed ranges from 200 to 600 km $s^{-1}$, their density from $2 \times 10^6$ to more than $10 \times 10^6$ $m^{-3}$, the electron and proton temperatures range from $(10–20) \times 10^4$ and $(2.5–15) \times 10^4$ K respectively. Heavy ions in these streams flow either with the same speed as the protons or are slightly slower. The ratio of the alpha to proton temperature is reduced to 3, and the abundance of alpha particles relative to protons ranges from close to 0% to almost 20%. The increase of the flow speed between 0.3 and 1 AU is of the order of 10%, thus larger than in the high-speed wind.

### Flow speeds in the near Sun regions

The sound speed in the solar wind plasma is about 40 to 70 km $s^{-1}$ at the Earth's orbit. In solar wind, even the slowest streams are therefore highly supersonic. The transition from sub- to supersonic occurs somewhere close to the Sun, probably between 1.5 to 3.5 solar radii in the high-speed polar wind, and between 3.5 and 8 solar radii in the slower streams. The exact distance from the Sun at which the solar wind speed reaches the

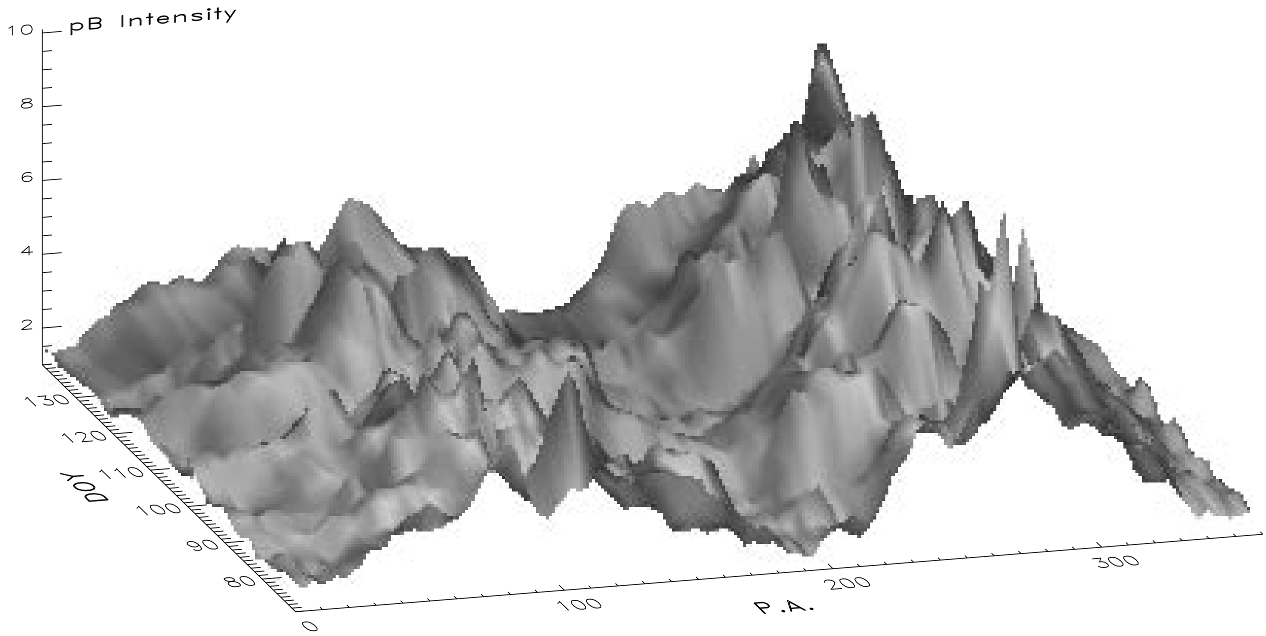


**Figure 2.** Polarized white light intensity measurements carried out every 3° along the circle shown in figure 1. These ground based measurements are made daily with the Mauna Loa K-coronameter, operated by the High Altitude Observatory (NCAR/HAO). The intensities are normalized to the lowest coronal hole intensity. Position angle 0 corresponds to heliographic north. Shown here are the measurements from 12 March to 19 May 1993. The low intensities from position angle 120° to 220° correspond to the southern coronal hole. Note the large daily intensity variations both inside the hole and in the surrounding regions.

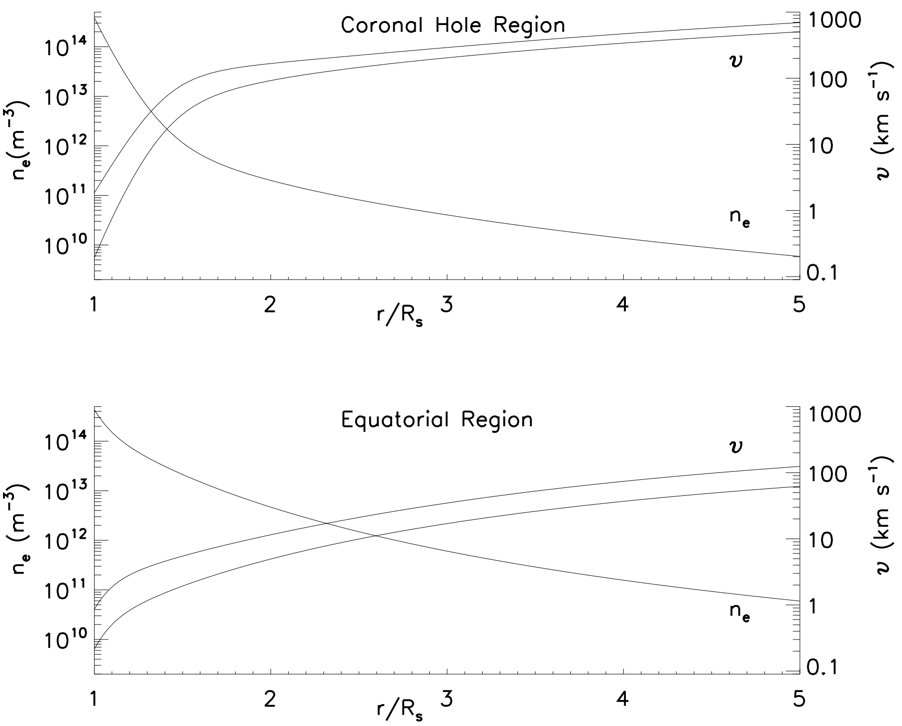


**Figure 3.** Electron densities derived from polarization brightness measurements in the inner corona ($n_e$) and estimates of the flow speed ($v$) derived from the mass flux measured *in situ*, these densities and the law of mass flux conservation for a radial expansion of the flow tubes (lower limits) and an expansion seven times more than radially.

sound speed is not yet known, partly because we are not sure of the flow speeds in the inner corona, but also because we do not know the particle temperatures (sound speed) very accurately. Given the different properties of streams in interplanetary space one has to assume that their acceleration, as well as other characteristics in the inner corona, are different. The only means to determine these characteristics is by remote observations since no spacecraft has approached the Sun closer than about 60 solar radii. (A spacecraft to probe the solar wind plasma at distances of 5 to 10 solar radii is being planned.) The analysis of remote observations always requires a series of assumptions and approximations, and the results are therefore often a question of interpretation. For example, remote observations of the coronal plasma are always intergrated measurements along a line-of-sight. An example is given in figure 2. This figure shows Thompson scattered polarized white light intensity measured clockwise along the circle shown in figure 1, as a function of position angle, where 0 corresponds to the Sun's north pole. These measurements were carried out daily from day 75 to 135, 1993. The southern polar coronal hole extends roughly from position angle 120° to 220°. It can be seen that the intensity measured inside that region varies significantly both along the time axis and along the position angle, even though the plasma properties measured *in situ* in the high-speed solar wind are rather constant. The intensity changes seen when observing coronal holes remotely are mostly due to changes in the regions surrounding them. At times these surrounding denser regions can veil the coronal holes completely or partially, as in figure 1 at the southern pole. Parameters derived from remote observations represent the plasma properties averaged along the line-of-sight. Thus, particularly measurements carried out in coronal holes will be biased by surrounding regions, and the measurements can only serve as guidelines. Figure 3 shows the electron densities, $n_e$, derived for a coronal hole region (upper panel) and an equatorial region (lower panel) using polarized white light observations (e.g. Fisher and Guhathakurta 1995).

An estimate of the lower limit on the outflow speed of the electron–proton plasma close to the Sun can be obtained from the mass flux measured *in situ*; these electron densities and the law of mass conservation which states that the flux of protons must be conserved from the solar surface into interplanetary space where *in situ* measurements can be carried out. (The proton flux is defined as the number of protons per $m^3$ times the proton flow speed times the area expansion of the flow tubes, which is the ratio between the flow tube area on the solar surface, where the stream originates, and the area that this stream covers at a given distance from the Sun.)

The lower limits of the flow speed, $v$, shown in figure 3, are for the smallest possible flow tube expansion (radial), and the upper limits are for a very large expansion (seven times more than radially). The flow speeds derived from this estimate show that the solar wind accelerates very rapidly in the inner corona, and achieves its almost final flow speeds between 5 and 10 solar radii. This is in agreement with the *in situ* Helios observations which show that there is basically no acceleration of the flow at large distances from the sun. Observations from SOHO indicate that the heavy $O^{5+}$ ions already flow faster than the protons in the inner corona. It seems that, at least in the high-speed wind, the differences between minor ions and protons, seen in the *in situ* measurements, originate in the inner corona with subsequent modification in interplanetary space.

Solar wind speeds of 200 km $s^{-1}$ can be achieved by the pressure gradient force alone. To accelerate the wind to higher speeds, additional energy is needed that has to be deposited in the corona. At present it is not well understood where this additional energy comes from. It is usually assumed that plasma waves play a significant role (see SOLAR WIND: THEORY and CORONAL HEATING MECHANISMS).

## Summary

The acceleration of the solar wind plasma to the speeds measured in interplanetary space happens close to the Sun, below 5 solar radii in the fastest streams and at slightly larger distances in the low-speed wind. During this acceleration process the solar wind passes from subsonic to supersonic speeds. The energy source necessary for the acceleration to happen is not yet known but is thought to be high-frequency plasma waves originating either in the lower solar atmosphere or higher up in the corona via a cascade from lower-frequency waves or via locally generated microinstabilities.

*Bibliography*

Fisher R and Guhathakurta M 1995 Physical properties of the polar coronal rays and holes as observed with SPARTAN 201-01 coronagraph *Astrophys. J.* **447** L139–L143

Schwenn R and Marsch E 1990 *Physics of the Inner Heliospehere* vol 1 (Berlin: Springer)

——1991 *Physics of the Inner Heliospehere* vol 2 (Berlin: Springer)

*Ruth Esser*