Investigation of the sources of the slow solar wind

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Abstract. Aim of this analysis is to study the variation of the physical conditions of the coronal plasma across the streamer boundary in order to identify the coronal sources of the slow solar wind during the minimum of solar activity. The analysis is based on the observations of equatorial streamers, obtained in the outer corona during the years 1996 and 1997 with the Ultraviolet Coronagraph Spectrometer (UVCS) onboard SOHO. The outflow velocity, the electron density and the oxygen abundance relative to hydrogen of the coronal plasma have been determined, in the range between 1.6 and 3.5 solar radii (R☉), by means of a spectroscopic analysis of the OVI 1032, 1037 Å and the HI Lyα 1216 Å lines. Coronal expansion at low velocity, in the range 80–100 km/s, is observed along regions 15°–20° wide, surrounding the streamer boundary. Evidence for coronal plasma outflows at low velocity is also found further out in the region along the streamer axis. In this case the outflows become significant beyond 2.7 R☉. Hence, the slow solar wind during solar minimum flows just outside the denser and brighter zone of a streamer, characterized by closed magnetic field lines and in a lane around the heliospheric current sheet, forming just above the closed field line region.

INTRODUCTION

According to the Ulysses observations, during solar minimum the slow solar wind tends to be confined in the equatorial streamer belt, whereas the fast wind fills most of the heliosphere. This study is an attempt to identify the coronal regions where the heliospheric slow wind originates, by analyzing the observations obtained with the Ultraviolet Coronagraph Spectrometer (UVCS) onboard SOHO. The most probable sources of the slow wind are the regions of open magnetic field lines at the border of the large quiescent equatorial streamers observed during solar minimum. Therefore we focus on the comparison of the dynamical conditions observed in the central brightest streamer region, corresponding to plasma predominantly confined by closed field lines, and in the dim lanes running along the borders of these bright regions. The UVCS observations of the outer corona, extending from 1.5 R☉ to a few solar radii, provide a set of spectroscopic data apt to identify plasma outflows by means of the Doppler dimming analysis of the resonantly scattered coronal emission.

DIAGNOSIS OF THE CORONAL ULTRAVIOLET EMISSION

The spectroscopic diagnostic technique used in this study (Antonucci et al., 2002) allows us to determine the electron density and the outflow velocity of the OVI ion component of the coronal plasma uniquely on the basis of the OVI 1032, 1037 doublet, and to compute the abundance of oxygen relative to hydrogen by including also the HI Lyα 1216 line data. The technique fully accounts for the effect of Doppler dimming in an expanding corona. The ultraviolet lines emitted in the extended corona are formed both via collisional and radiative excitation. The radiative contribution becomes predominant in low density conditions. The collisional and radiative components are separated by considering a pair of lines emitted from the same ion, such as the OVI 1032 and 1037 Å lines. The electron density is then derived from the ratio of the collisional to radiative component of a spectral line, being proportional to this ratio multiplied by a factor depending on the outflow velocity. Therefore in order to derive electron density and outflow velocity, at the same time, we need a further constraint given by the mass flux conservation along the flow tube connecting the corona and the heliosphere: $n_e \cdot w \cdot A = \text{const}$, where $n_e$ is the electron density, $w$ is the outflow speed, $A = F(r) \cdot r^2$ is the cross section of the flux tube and the quantity $F(r)$ takes into account the deviation from radial expansion. The abundance of oxygen relative to hydrogen is computed from the ratio of the radiative components of the OVI 1032 line and the HI Lyα 1216 line, both functions of the outflow velocity (Antonucci and Giordano, 2001), by assuming conditions close to ionization equilibrium.
OBSERVATIONS AND DATA ANALYSIS

The present analysis is based on a set of six streamers, observed with UVCS at high spectral resolution. They are detected at mid and low latitudes during the solar minimum period 1996–1997. Table 1 reports the following quantities: date of observation, position angle (PA, in degrees, counterclockwise from the North Pole) of the streamer axis, range of the UVCS fields of view, in solar radii (\(R_\odot\)).

For each streamer we define the streamer boundary as the contour level corresponding to the 1/e value of the OVI line intensity maximum (different definitions of streamer boundary are discussed by Abbo and Antonucci, 2001). The intensities of the OVI 1032, 1037 and HI Ly \(\alpha\) 1216 lines are then computed by integrating the line emission in two regions: within the streamer boundaries and in the external region, approximately 15\(^\circ\)–20\(^\circ\) wide, adjacent to the boundary. The integrated emissions are then fitted with a gaussian curve to obtain the line intensity and width, that can be expressed in terms of the kinetic temperature, \(T_k\), quantity that measures the velocity distribution of the emitting particles along the line-of-sight (l.o.s.).

The kinetic temperatures derived from the OVI 1032 line profiles are plotted in Figure 1 as a function of heliocentric distance (the values found for streamers are reported as full dots and those relative to the regions surrounding streamers as full triangles). This quantity is clearly increasing with height and the values found outside are significantly higher than inside streamers (Antonucci et al., 1997).

The diagnostic technique to be applied to the UVCS data is based on the computation of resonance absorption along the direction of the incident radiation coming from the disk, within a solid angle subtended by the solar disk itself. Therefore the analysis has to include the distribution of the oxygen ion velocity in three dimensions, whereas only the distribution along the l.o.s. is observed. Within the streamer, that is, in higher density conditions, we assume an isotropic maxwellian velocity distribution with the width defined by the observed \(T_k\). Outside the streamer, in the thinner regions adjacent to the streamer boundary, we assume a bi–maxwellian velocity distribution of the ions, with a kinetic temperature equal to the observed one in the plane perpendicular to the radial direction, and equal to the electron temperature along the radial direction. This assumption is dictated by the fact that line broadening in the regions close to streamers is about twice larger than in the streamer itself, thus representing an intermediate condition between closed field regions and the core region of coronal holes, where the ion velocity distributions are found to be highly anisotropic (e.g., Kohl et al. 1998, Cranmer et al. 1999, Antonucci et al., 2000).

The coronal electron temperature, \(T_e\), assumed in the analysis of streamers is that derived by Gibson, et al. 1999. In the open field line regions it is inferred from the coronal hole measurements by David, et al. 1998 (see Antonucci et al. 2000).

In order to define the constraint imposed by mass flux conservation in the hypothesis of coronal expansion, the flux tube geometry has been modeled by assuming the expansion factor of the magnetic field lines as derived by Wang and Sheeley (1990) for the regions immediately adjacent to a streamer. In this model the magnetic field is taken to be potential everywhere except in an equatorial current sheet (with the inner boundary of the current sheet located at 2.5 \(R_\odot\)), where the magnetic field radial component changes sign discontinuously and the latitudinal component vanishes. In this model the open magnetic field lines adjacent to the streamer are characterized by a maximum expansion factor, \(F(r)_{max} = 13.5\), much larger than that expected in the core of coronal holes, where \(F(r)_{max} = 4\). In a previous analysis (Abbo and

<table>
<thead>
<tr>
<th>Date</th>
<th>Streamer axis (PA,°)</th>
<th>Altitude range ((R_\odot))</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 Aug</td>
<td>120</td>
<td>1.6 – 3.5</td>
</tr>
<tr>
<td>22 Aug</td>
<td>60</td>
<td>1.6 – 3.5</td>
</tr>
<tr>
<td>30 Aug</td>
<td>240</td>
<td>1.6 – 3.5</td>
</tr>
<tr>
<td>1 Sep</td>
<td>280</td>
<td>1.6 – 3.5</td>
</tr>
<tr>
<td>30 Apr</td>
<td>280</td>
<td>1.7 – 3.3</td>
</tr>
<tr>
<td>5 May</td>
<td>80</td>
<td>1.8 – 3.3</td>
</tr>
</tbody>
</table>
is predominantly static out to 2.7 R⊙. Hence, we conclude that the plasma in the bright emission regions located outside the streamer, is dominated by open magnetic field lines.

In the regions adjacent to streamers, on the other hand, the results obtained for a static plasma are unrealistic, whereas those obtained for a dynamic expanding corona (triangles in Figure 2) are acceptable, implying that the narrow region, 15°–20° wide, along the streamer boundary, is dominated by open magnetic field lines.

It is interesting to note that all along the streamer border (that in the present set of data starts at 1.8 R⊙, height corresponding to a portion of the spectrometer slit, set to 1.6 R⊙, far from the center) and around the streamer axis above 2.7 R⊙, the oxygen ions kinetic temperatures are higher than within the inner part of the streamer (Figure 1). If this large increase in kinetic temperature is interpreted as energy deposition as suggested by the coronal hole observations (Antonucci et al. 1997b, Kohl et al. 1997, Noci et al. 1997), these regions where the plasma expands are regions of energy dissipation. Such an effect, however, occurs only beyond 2.7 R⊙ along the streamer axis, presumably in coincidence with the transition from closed to open magnetic field lines, that is, close to the inner boundary of the heliopsheric current sheet.

In the regions where coronal expansion is found to be compatible with the OVI emission data, we find an outflow velocity ranging from 90 km/s to 100 km/s along the streamer border and a value about 80–90 km/s above 2.7 R⊙ along the streamer axis. These values are compatible with a regime of fast wind. In fact in coronal holes between 1.8 R⊙ and 3.5 R⊙, the fast wind expands much more rapidly with a speed that varies typically from about 100 km/s to 400 km/s.

A distinctive feature of the heliospheric slow and fast wind, besides the wind speed, is the plasma composition. Therefore we also derive the oxygen abundance relative to hydrogen, although, being a high FIP element, oxygen does not show a marked variation between slow and fast wind. The oxygen abundance is plotted in Figures 4, inside (full dots) and outside streamers (full triangles), as a function of heliocentric distance. The abundance decreases with increasing heliolatitude, as found in quiescent streamers (Marocchi et al. 2001). In streamers it ranges from values close to the photospheric abundance,
6.7 × 10⁻⁴, to 1 × 10⁻⁴, abundance found in the core of a streamer (e.g. Raymond et al., 1997). This supports the interpretation given by Marocchi et al. that the abundance of the wind close to the heliospheric current sheet might derive by open field lines existing within the streamer, and separating substreamers not always resolved in the outer corona (following the hypothesis of slow wind formed between substreamers formulated by Noci et al. 1997). In the regions surrounding the streamer border where the decrease of abundance tends to be less marked. Since also the slow wind oxygen abundance tends to be lower than the fast wind abundance, the trend found in Figure 4 for the regions adjacent to the streamer border (full triangles) is supporting the conclusion that these are sources of slow wind.

This study, based on the OVI coronal emission, leads to the conclusion that the regions running along the streamer boundaries are sites of coronal outflows at low velocities and therefore these are the likely sources of the slow wind. In addition, coronal expansion at low velocities is also likely to occur beyond 2.7 R☉ along the streamer axis, presumably where the transition between closed and open magnetic field lines takes place and the interplanetary current sheet forms. The values of the outflow velocity found, in the range between 80 km/s and 100 km/s, are consistent with the results obtained by Sheeley et al., 1997 and Wang et al., 1998 for the outward motions of the density inhomogeneities detected with LASCO (SOHO), which originate at the cusp of streamers. They are also consistent with the results found by Strachan et al., 2002, obtained by analyzing, with the traditional Doppler dimming technique, the coronal visible and ultraviolet emission of an equatorial streamer observed with UVCS. At last, considerations on the oxygen abundance in the regions of plasma outflows do support the interpretation of these regions as sources of the slow wind. The resulting scenario is compatible with the model proposed by Wang et al., 2000, of a two–component slow wind: one component flowing along the rapidly diverging open magnetic field lines adjacent to the streamer boundary, and the second one confined to the region of the denser equatorial plasma sheet.