Formation of the current sheet in a coronal streamer

Lucia Abbo¹, Ester Antonucci¹ Roberto Lionello², Zoran Mikić², Pete Riley²

¹ INAF-Astronomical Observatory of Turin, 10025, Pino Torinese, Italy, abbo@aoto.inaf.it
² Predictive Science Inc., San Diego, CA 92121, USA

Abstract. The present work is on the study of a coronal streamer observed in March 2008 at high spectral and spatial resolution by the Ultra-violet Coronagraph Spectrometer (UVCS) onboard SOHO. On the basis of a spectroscopic analysis of the O VI doublet, the solar wind plasma parameters are inferred in the extended corona. The analysis accounts for the coronal magnetic topology, extrapolated through a 3D magneto-hydrodynamic model. The results of the analysis show indications on the formation of the current sheet, one of the source regions of the slow coronal wind.

Key words: Sun, corona, solar wind, MHD model

1 Introduction

The origin of the slow solar wind is one of the open problems in solar physics. During solar minimum, the slow solar wind tends to be confined in the equatorial and mid-latitude regions as confirmed by the Ulysses observations in the heliosphere. The main issue is whether the slow wind is coming from open field line regions surrounding the streamer or there is a substantial contribution from the streamer itself: some authors proposed that the low-speed wind could flow between structures present in the inner part of the large equatorial streamers (Noci et al. 1997; Noci & Gavryuseva 2007); for others, the slow wind arises from the streamer bright regions observed in UV identified with streamer stalks (e.g. Habbal et al. 1997, Raymond et al. 1997, Strachan et al. 2002, Uzzo et al. 2003); other papers indicate the open flux tubes in the streamer adjacent regions as the main slow wind sources (e.g. Abbo et al. 2003, Antonucci et al. 2005, Abbo et al. 2010). The analysis presented here concerns data from the recent solar minimum (2006-2008) which has been very peculiar and different in comparison with the previous one (Gibson et al. 2009). In order to investigate signatures of the slow wind sources, we derive the HI and OVI kinetic temperature from the data analysis of the spectral lines observed by UVCS/SOHO and the coronal electron density as a function of the outflow velocity through a diagnostic techniques described in the next session.
2 Diagnostic techniques for the coronal plasma

Outflow velocity and electron density of the coronal wind plasma can be deduced from the emission of intense ultraviolet spectral lines, such as the O VI 1032, 1038 lines. These lines are formed in the extended corona via collisional and radiative excitation processes. The two components have a different dependence on the electron density: the collisional process depends on $n_e^2$, while the radiative process depends linearly on electron density $n_e$. The collisional and radiative components of the O VI 1032, 1038 lines in an expanding plasma can be separated by using the method introduced by Antonucci et al. (2004). The electron density, averaged along the line-of-sight (l.o.s.), $<n_e>$, is proportional to the ratio of the collisional component, $I_c$, to the radiative component, $I_r$, and is a function of the outflow velocity of the wind, $w$: $<n_e> \sim \frac{I_c}{I_r} <\Phi(\delta\lambda)>$, where $<\Phi(\delta\lambda)>$ is the Doppler dimming function which depends on the normalized coronal absorption profile and on the intensity of the exciting spectrum along the direction of the incident radiation, $\mathbf{n}$. The quantity $\delta\lambda = \lambda_0 w \cdot \mathbf{n}$ is the shift of the disk spectrum introduced by the expansion velocity, $w$, of the coronal absorbing ions/atoms along the direction $\mathbf{n}$ and $\lambda_0$ is the reference wavelength of the transition. As the wavelength shift increases, the resonantly scattered emission decreases, giving origin to the Doppler dimming effect (Beckers 1974; Noci et al. 1987). By analysing the O VI doublet lines at 1031.93 and 1037.62 Å, it is possible to measure oxygen ion outflow velocities up to approximately 450 km s$^{-1}$ for the effect of pumping of the CII lines at 1037.02 and 1036.34 Å on the O VI $\lambda$ 1037.61 line (e.g. Dodero et al., 1998).
When the plasma is dynamic, in order to measure the coronal electron density and the outflow velocity at the same time, we impose the constraint of the mass flux conservation along the flow tube connecting the corona to the heliosphere by taking into account the expansion factors of the flux tubes as derived by the MHD model and by considering the mass flux measured in the heliosphere by Ulysses (McComas et al. 2008).

3 Extrapolations of the coronal magnetic field

In order to get a detailed description of the magnetic topology in the outer corona and derive the magnetic field expansion factors of the flow tubes, the coronal magnetic fields have been extrapolated from photospheric longitudinal fields on the basis of the three-dimensional MHD model of Mikić et al. (1999). The code integrates the time-dependent MHD equations in spherical coordinates \((r, \theta, \phi)\) until the plasma and magnetic fields settle into equilibrium. The photospheric magnetic field data (obtained from synoptic observations at Kitt Peak National Solar Observatory on the days of observation considered in the analysis) are used to specify the boundary condition on the radial component of the magnetic field, \(B_r\). Other boundary conditions on the velocity, temperature and density of plasma are determined with constraint values at the solar surface.

4 Observations and data analysis

We have analyzed UVCS observations of a streamer performed in the period 14-20 March 2008, characterized by a good spatial coverage (heliodistances of the slit center from 1.7 to 3.5 \(R_\odot\)).

Fig. 2. Composite image: visible light in corona from LASCO C2, magnetic field lines as derived by the MHD model and UVCS field of view (yellow lines).
The pointing of UVCS was carefully studied, in order to center the cusp of the streamer in the part of the slit which still has the maximum spatial resolution after the OVI detectors electronic problems since January 2006. For this observation, the spatial resolution is 28 arcsec and the slit width corresponds to 100 $\mu$m up to 2 $R_\odot$, to 150 $\mu$m from 2.1 to 2.5 $R_\odot$ and to 200 $\mu$m from 2.7 to 3.5 $R_\odot$. The magnetic field line map is shown in Figure 2 overlapped with the coronal image in visible light from LASCO C2 and the field of view of UVCS indicated by yellow lines. The streamer boundary is derived on the basis of the MHD model and divided two regions considered in the analysis: region 1 characterized by closed magnetic topology and region 2 with open magnetic field lines (labeled in Fig.2). In order to derive the plasma conditions within the streamer and in the external region, the intensities of the O VI doublet lines are integrated in the two regions by applying the radiometric calibration of UVCS data. The electron density and the outflow velocity are derived from the ratio of the collisional to radiative component of the oxygen O VI 1032 line, with the constraint of mass flux conservation, according to the method discussed in the previous section. The expansion factors of the flux tubes connecting the corona and heliosphere, are derived from the extrapolations of the coronal magnetic fields of the MHD model.

5 Results and conclusions

We would like to study the variation of the coronal plasma physical parameters in open and closed magnetic field lines regions in order to recognize possible signatures of the slow wind sources and of the current sheet formation. The kinetic temperature of ions, expressed in terms of the spectral line width observed by UVCS, $T_k \propto \sigma^2/\lambda$, is a measure of the velocity distribution of the ions along the line of sight. The left panel of Figure 3 shows the kinetic temperature of HI atoms (diamonds) and OVI ions (dots) as a function of heliodistance for the two regions defined in Fig.1 (blue points for region 1 and orange for region 2). It is worth to note that, on the one hand, the $T_k$ of HI Ly$\alpha$ values are around $1.5 \times 10^6$ K and there is a slight decrease starting at 2.6 $R_\odot$, for both regions 1 and 2; on the other hand the oxygen ion kinetic temperatures show a rapid increase from 2.6 $R_\odot$ in region 1 and from 1.9 $R_\odot$ in region 2. The broadening of the spectral lines can be a signature of energy deposition in the extended corona, which causes the solar wind acceleration, as suggested by the interpretation of coronal hole observations (e.g. Antonucci et al. 2000). Therefore, above 2.6 $R_\odot$, where probably the transition from closed to open magnetic field lines occurs, energy deposition may take place also in the internal parts of the streamer and this is also a possible signature of the current sheet formation. We have also derived the electron density for the two regions inside and outside the streamer and the results are shown in the right panel of Figure 3 as a function of heliodistance. The electron density values relative to the inner part of the streamers (region 1, blue dots) are compatible with a configuration of static plasma up to 2.6 $R_\odot$ and the values are comparable to those derived in streamers by Gibson et al. (1999).
Fig. 3. Left panel: Kinetic temperature of HI Lyα (diamonds) and OVI 1032 (dots) as a function of heliocentric distance for the two regions considered in the analysis. Right panel: Electron density as a function of heliocentric distance relative to the internal part of the streamer (region 1) and the adjacent part (region 2). The dashed line shows the values derived by Gibson et al. (1999) from visible light observations for streamers and the dotted line shows results obtained by Guhathakurta et al. (1999) for coronal holes.

(dashed line). From 2.6 to 3.4 $R_\odot$, we obtain values (blue triangle) by assuming a radial expanding coronal plasma achieving outflow velocities between 160 and 180 km/s. This result confirms that at these heights the current sheet is already formed. For what concerns the region external to the streamer (region 2), we have computed the electron density taking into account the magnetic topology of the flux tubes as derived by the MHD model and the results are shown as orange dots in the right panel of Fig. 3. They are intermediate between those derived for streamers by Gibson et al. (1999) (dashed line) and for coronal holes by Guhathakurta et al. (1999) (dotted line). The outflow velocity values found in this region are in the range of 130-240 km/s. The results of kinetic temperature and electron density values lead to the identification of the sources of the slow coronal wind that is found to flow adjacent to the streamer boundary in the open magnetic field line region. Moreover, the presence of outflowing plasma has been accurately detected where the heliospheric current sheet is forming, about at 2.6 $R_\odot$. This implies that a contribution to the slow wind comes also from the cusp of the streamer above the closed magnetic field lines. 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.

6 Acknowledgments

UVCS is a joint project of the National Aeronautics and Space Administration (NASA), the Agenzia Spaziale Italiana (ASI) and Swiss Founding Agencies. The
research of LA has been funded through the contract I/023/09/0 between the National Institute for Astrophysics (INAF) and the Italian Space Agency (ASI) and by Italian Embassy within Egypt Italy Science Year (EISY) 2009 program.

References

1. Abbo, L., Antonucci, E., Dodero, M.A., et al.: Investigation of the sources of the slow solar wind. In: Proceedings of the Tenth International Solar Wind Conference. AIP Conference Proceedings, Vol. 679, pp. 238-241 (2003)
2. Abbo, L., Antonucci, E., Mikić, Z., et al.: Characterization of the slow wind in the outer corona. Adv. in Space Research, in press (2010)
3. Antonucci, E., Dodero, M.A. & Giordano, S.: Fast Solar Wind Velocity in a Polar Coronal Hole during Solar Minimum. Sol. Phys., 197, 115–134 (2000)
4. Antonucci, E., Dodero, M.A., Giordano, S., et al.: Spectroscopic measurement of the plasma electron density and outflow velocity in a polar coronal hole. A&A, 416, 749–758 (2004)
5. Antonucci, E., Abbo, L. & Dodero, M.A.: Slow wind and magnetic topology in the solar minimum corona in 1996-1997. A&A, 435, 699–711 (2005)
6. Beckers, J.M. & Chipman, E.: The Profile and Polarization of the Coronal La Line. Sol. Phys., 34, 151–161 (1974)
7. Dodero, M.A., Antonucci, E., Giordano, S., et al.: Solar Wind Velocity and Anisotropic Coronal Kinetic Temperature Measured with the O VI Doublet Ratio. Sol. Phys, 183, 77–90 (1998)
8. Gibson, S.E., Fludra, A., Bagenal, F., et al.: Solar minimum streamer densities and temperatures using Whole Sun Month coordinated data sets. JGR, 104, 9691–9700 (1999)
9. Gibson, S., Kozyra, J.U., de Toma, G., et al.: If the Sun is so quiet, why is the Earth ringing? A comparison of two solar minimum intervals. JGR, 114, CiteID A09105 (2009)
10. Guhathakurta, M., Fludra, A., Gibson, S.E., et al.: Physical properties of a coronal hole from a coronal diagnostic spectrometer, Mauna Loa Coronagraph, and LASCO observations during the Whole Sun Month. JGR, 104, 9801–9808 (1999)
11. Habbal, S.R., Woo, R., Fineschi, S., et al.: Origins of the Slow and the Ubiquitous Fast Solar Wind. ApJ, 489, L103 (1997)
12. McComas, D.J., et al.: Weaker solar wind from the polar coronal holes and the whole Sun. Geophys. Res. Let., vol.35, L18103 (2008)
13. Mikić, Z., Linker, J.A., Schnack, D.D, et al.: Magnetohydrodynamic modeling of the global solar corona. Phys.of Plasmas, 6, 5, 2217–2224 (1999)
14. Noci, G., Kohl, J.L. & Withbroe, G.L.: Solar wind diagnostics from Doppler-enhanced scattering. ApJ, 315, 706–715 (1987)
15. Noci, G., Kohl, J.L., Antonucci, E., et al.: The quiet corona and slow solar wind. In: Fifth SOHO Workshop, The Corona and Solar Wind near Minimum Activity, (ESA SP-404; Noordwijk: ESA), pp. 75–84 (1997)
16. Noci, G. & Gavryuseva, E.: Plasma Outflows in Coronal Streamers. ApJ, 658, L63–L66 (2007)
17. Uzzo, M., Ko, Y.-K., Raymond, J.C., et al.: Elemental Abundances for the 1996 Streamer Belt. ApJ, 585, 1062–1072 (2003)
18. Wang, Y.-M., Sheeley, N.R., Jr., Socker, D.G., et al.: The dynamical nature of coronal streamers. JGR, 105, 25133–25142 (2000)