Mem. S.A.It. Vol. 74, 733

**Memorie** della

# Acceleration region of the slow solar wind in corona

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**Abstract.** We present the results of a study concerning the physical parameters of the plasma of the extended corona in the low-latitude and equatorial regions, in order to investigate the sources of the slow solar wind during the minimum of solar activity. The equatorial streamer belt has been observed with the Ultraviolet Coronagraph Spectrometer (UVCS) onboard SOHO from August 19 to September 1, 1996. The spectroscopic diagnostic technique applied in this study, based on the OVI 1032, 1037 Å lines, allows us to determine both the solar wind velocity and the electron density of the extended corona. The main result of the analysis is the identification of the acceleration region of the slow wind, whose outflow velocity is measured in the range from 1.7 up to 3.5 solar radii.

**Key words.** SOHO; solar wind; Sun:corona

## 1. Introduction

The origin and the acceleration of the solar wind is one of the most interesting problems in solar physics. The existence of two kinds of solar wind, fast and slow, has been known since the 70's, but the identification of the source regions was clear only for the fast wind. The aim of this study is to investigate the source regions of the slow wind in the extended corona with the Ultraviolet Coronagraph Spectrometer (UVCS) onboard SOHO, during the solar minimum. Several hypotheses, concerning the coronal origin of the slow wind, propose the inner part of streamers or the streamer cusp as source regions (e.g. Noci et al., 1997; Sheeley et al., 1997; Wang et al., 2000; Wiegelmann et al., 2000). In other cases, the external regions close to the streamer or the lateral parts of the streamer called 'legs' are suggested as sources of the slow wind (e.g. Raymond et al., 1997; Fisk et al., 1999; Ofman 2000; Wang et al., 2000; Marocchi et al., 2001). Therefore, to identify the location where the slow wind originates and accelerates, we investigate the transition between the streamer and

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the adjacent coronal hole region in the extended corona.

## 2. Diagnostic techniques of the OVI lines ratio

The information on the physical parameters of the coronal plasma is inferred from the observation of the most intense coronal lines, emitted in the ultraviolet region via collisions and resonance scattering. The spectroscopic technique developed by Antonucci et al., 2003 provides a means to calculate the outflow velocity of OVI ions and the electron density at the same time, on the basis of the OVI doublet. First, the collisional and the radiative components are separated by considering the two lines emitted from the same ion OVI at $\lambda$ 1031.93 and 1037.62 Å. The electron density is then derived from the ratio of the collisional to radiative component of a spectral line and depends on the outflow velocity, since the expansion of the corona induces a Doppler dimming of the resonant scattering component of line intensity. In order to apply this method, information on the magnetic configuration of the solar corona is required, since a physical constraint is given by the mass flux conservation along the flow tube connecting the corona to the heliosphere. The emission of the OVI doublet is observed in the extended corona with UVCS. The magnetic topology and the expansion factors of the flux tubes have been reconstructed, for the dates of the UVCS observations considered in this study, using the 3D-MHD model of the global corona developed by Mikić et al., 1999 at Science Applications International Corporation (SAIC).

## 3. Observations and data analysis

We have analyzed UVCS observations at mid and low latitudes of the equatorial regions, at high spectral resolution (the slit width of the spectrometer was selected to be 50 $\mu$m corresponding to 0.18 Å) during the solar minimum of the activity cycle 23 (1996). The dates and the altitude ranges of the UVCS fields of view are given in Table 1. In three of the seven streamers considered in the analysis, the UVCS instantaneous field of view (FOV) was centered on the regions of closed magnetic field lines defining the core of the structures, as derived on the basis of the 3D-MHD model by Mikić et al., 1999. These streamers, observed on August 20, 21 and 31, 1996, are then selected for the analysis of the physical parameters within the streamer. The other four cases of the UVCS observations (August 19, 22, 30 and September 1, 1996) are considered only to analyze the transition between open and closed field line regions. This is because the center of the FOV of UVCS, in these cases, was closer to the border of the streamer. In order to define the streamer boundary by taking into account the coronal magnetic topology, we consider it coincident with the interface between closed and open field lines obtained from the magnetic extrapolations. The intensities of the OVI 1032 and 1037 lines are then integrated both over the region within the streamer boundaries and over the external region, adjacent to the streamer boundary. The plasma inside the boundaries is considered to be static. When analyzing the plasma inside the streamer, we assume an isotropic distribution of the oxygen ion velocity, that is the width of the velocity distribution along the radial di-

**Table 1.** Observation date and altitude range (in solar radii, $R_\odot$) of the solar minimum (1996) coronal streamers observed with UVCS-SOHO.

| Date | Altitude range ($R_\odot$) |
|---|---|
| 19 Aug | 1.6 – 3.5 |
| 20 Aug | 1.6 – 3.5 |
| 21 Aug | 1.6 – 3.5 |
| 22 Aug | 1.6 – 2.6 |
| 30 Aug | 1.6 – 2.6 |
| 31 Aug | 1.6 – 2.6 |
| 01 Sep | 1.6 – 2.6 |

rection (perpendicular to the line-of-sight, l.o.s.) is equal to that observed along the l.o.s., as deduced from the line broadening. For the analysis of the regions adjacent to streamers, we assume an anisotropic velocity distribution of the ions with a kinetic temperature equal to the electron temperature (derived by Gibson et al., 1999 and by David et al., 1998) along the radial direction. This assumption is justified by Abbo et al., 2003, on the basis of a comparison of the conditions in open magnetic field line regions close to streamers and in coronal holes, where the ion velocity distributions are found to be highly anisotropic (Antonucci et al., 2000).

## 4. Results

The electron density has been computed by applying the spectroscopic techniques described in section 2. When calculating the electron density for the regions inside the streamer we obtain the results shown as full dots in Figure 1. The values are the average of the results obtained for the three streamers observed on August 20, 21 and 31 (Table 1). The error bars are calculated according to the standard deviation of the mean value. The electron density values are consistent with those derived in streamers from the visible light coronal observations by Gibson et al., 1999 (dashed line). This result is also in agreement with the analysis of a previous study by Abbo et al., 2003. In the case of the observations on August 20 and 21, at 3.5 $R_\odot$ the density result, obtained by relaxing the hypothesis on the static conditions of the plasma (asterisk in Figure 1), is compatible with the curve derived by Gibson et al., 1999. The corresponding outflow velocity values are in the range of 85-110 km/s. On the basis of the inferred coronal field lines, this height corresponds approximately to the formation of the interplanetary current sheet. For the regions external to the streamer boundaries, the electron density results are shown in Figure 2 (full triangles). They are compared both with those derived for streamers by Gibson et al., 1999 and for coronal holes by Guhathakurta et al., 1999. The density results outside streamers have intermediate values. Figure 3 illustrates the results of the outflow velocity relative to the external re-

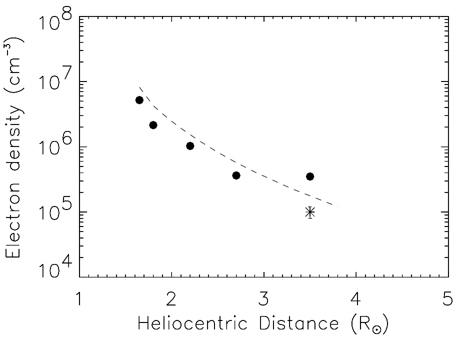


**Fig. 1.** Streamer electron density as a function of heliodistance derived by considering static conditions (full dots). The asterisk indicates the result obtained in the case of an expanding corona. The values are compared with those derived by Gibson et al., 1999 (dashed line) from visible light observations.

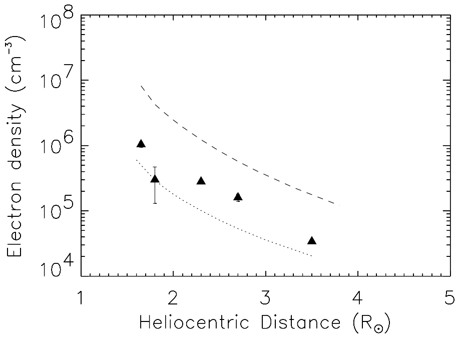


**Fig. 2.** Electron density as a function of heliodistance derived by considering dynamic conditions in the region external to the streamer boundaries. The values are compared with those derived by Gibson et al., 1999 (dashed line) and by Guhathakurta et al., 1999 (dotted line).

gions of streamers. The values up to 3.5 $R_\odot$ (full dots) are obtained from the present study. They are extended to higher altitudes by including the LASCO results at 10 $R_\odot$ (Sheeley et al., 1997) from the white-light observations. The velocities are much lower than those of the fast wind, shown by the solid curve, obtained from the UVCS observations of coronal holes up to 3 $R_\odot$. The dashed curve shows the extrapolated values by considering a constant acceleration of $\sim 6\times10^{-2}$ km s$^{-2}$, calculated in the altitude range of 1.8-3 $R_\odot$ (Antonucci et al., 2000). The average acceleration of the slow wind obtained from the present analysis results to be $\sim 4.8 \times10^{-3}$ km s$^{-2}$, one order of magnitude lower than the acceleration found in the fast wind regions. This value is comparable with that derived by Sheeley et al., 1997, from the white-light observations of LASCO between 2 $R_\odot$ and 30 $R_\odot$. The outflow velocity results of the present analysis are consistent with those found by Strachan et al., 2002, by analyzing the visible and ultraviolet coronal emission of an equatorial streamer at 2.3 $R_\odot$, using the Doppler dimming technique.

In conclusion, the slow solar wind accelerates in the coronal region of open field lines, adjacent to the streamer. Moreover, outflowing plasma is also detected where the heliospheric current sheet is forming. This implies that a contribution to the slow wind comes also from the cusp of the streamer above the closed magnetic field lines (Abbo, 2003).

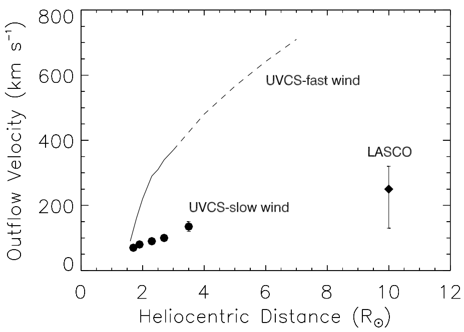


**Fig. 3.** Outflow velocity of the slow wind obtained from the present analysis (full dots) as a function of heliodistance. The point at 10 $R_\odot$ is obtained by LASCO (Sheeley et al., 1997). The solid curve up to 3 $R_\odot$ represents the values of the fast wind obtained from the UVCS data and the dashed curve shows the extrapolated values by considering constant acceleration (Antonucci et al., 2000).

## References

Abbo, L. 2002, Ph.D. Thesis, University of Torino

Abbo, L., Antonucci, E., Dodero, M.A. & Benna, C. 2003, AIP Conf. Proc., in press

Antonucci, E., Dodero, M.A. & Giordano, S. 2000, Solar Phys., 197, 115

Antonucci, E., Dodero, M.A., Giordano, S., et al. 2003, A&A, submitted

David, C., Gabriel, A. H., Bely-Dubau, F., et al. 1998, A&A, 336, L90

Fisk, L.A., Zurbuchen, T.H. & Schwadron, N.A. 1999, ApJ, 521, 868

Gibson, S. E., Fludra, A., Bagenal, F., et al. 1999, JGR, 104, 9691

Guhathakurta, M., Fludra, A., Gibson, S.E., et al. 1999, JGR, 104, 9801

Marocchi, D., Antonucci, E. & Giordano, S. 2001, Ann. Geophys., 19, 135

Mikič , Z., Linker, J.A., Schnack, D.D, et al. 1999, Phys. of Plasmas, 6, 5

Noci, G., Kohl, J.L., Antonucci, E., et al. 1997, ESA SP–404, 75

Ofman, L. 2000, Geophys. Res. Let., 27, 18, 2885

Raymond, J.C., Kohl, J.L., Noci, G., et al. 1997, Solar Phys., 175, 645

Sheeley, N.R., Jr., Wang, Y.-M., Hawley, S.H., et al. 1997, ApJ, 484, 472

Strachan, L., Suleiman, R., Panasyuk, A.V., et al. 2002, ApJ, 571, 1008

Wang, Y.-M., Sheeley, N.R., Jr., Socker, D.G., et al. 2000, JGR, 105, 25133

Wiegelmann, T., Schindler, K. & Neukirch, T. 2000, Solar Phys., 191(2), 391