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Physical parameters of coronal streamers near the maximum phase of solar cycle

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Abstract. During june 10–17, 2000 the Ultraviolet Coronograph Spectrometer (UVCS) aboard the *Solar and Heliospheric Observatory* observed a streamer complex. Data were acquired at the time of a SOHO–Sun–Ulysses quadrature. We identify two streamers for which we derive electron densities, temperatures and elemental abundances and we point out differences and analogies between the two structures. We also derive the coronal Fe/O, which we consider a proxy for the FIP effect and we compare it with Fe/O values measured *in situ* by SWICS.

Key words. Solar Physics: observations, streamers – Solar Wind: elemental abundances – Spectroscopy: EUV

1. Introduction

In this paper we report on observations acquired by the UVCS spectrograph from june 10 to 17, 2000, near the maximum phase of solar cycle, at the time of a SOHO-Sun-Ulysses quadrature. In this geometrical configuration it is possible to compare the plasma parameters at low heliocentric heights derived from UVCS data with those measured *in situ* by Ulysses instruments. The center of the UVCS slit was placed at a roll angle of about 148° (from North to East) corresponding to the radial direction to Ulysses (see fig.1). The data were acquired alternatively at 1.6 and 1.9 solar radii to evaluate plasma parameters variation with time, heliolatitude and heliocentric height. At each height five UVCS grating positions are used to cover a spectral range from 951 to 1117 Å in the primary OVI channel and from 1180 to 1280 Å in the redundant channel. This spectral range includes Lyman α, Lyman β and Lyman γ lines from neutral hydrogen, the OVI 1032 and 1037 Å doublet lines and several lines from minor ions in different ionization stages, such as MgX, SiXII, FeX, FeXII, CaX, AlXI.

2. The Observed Morphology

We refer the reader to LASCO/C2 coronograph movies wich show the white light corona between 2 and 6 solar radii to get an idea of the streamers evolution from june

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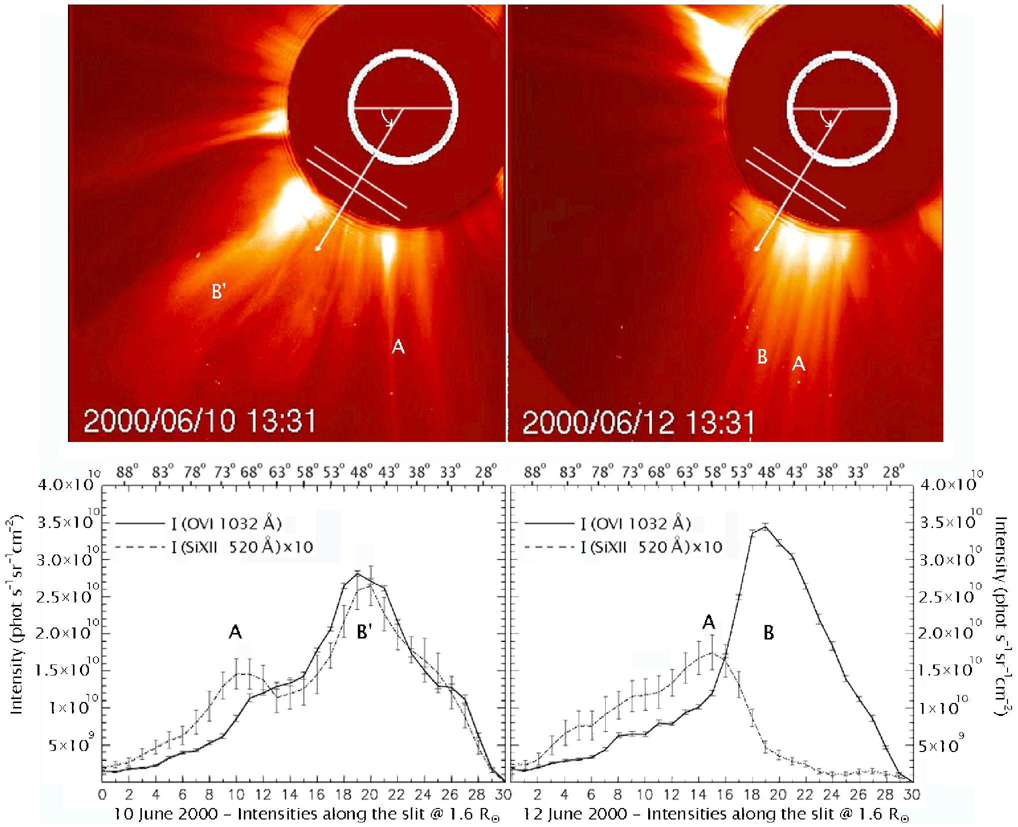

Fig. 1. Top: LASCO/C2 images for june 10 and 12 showing the position of the UVCS slit, which was centered on the radial direction to Ulysses at 1.6 and 1.9 solar radii. Bottom: profiles of the OVI 1032 Å and SiXII 520 Å line intensities along the UVCS slit at 1.6 solar radii. The latitude corresponding to the slit bins are given at the top of the UVCS panels.

10 to 17. If we consider only what's happening in the South-East quadrant of the corona, we can see on june 10 two streamers, labeled B' and A: later in the day B' goes through a disruption and disappears. On the next day a new structure labeled B appears, while streamer A seems to move slowly eastward. From june 12 to 17 we can follow the evolution of the two streamers A and B which move apparently in opposite heliolatitude directions. It is possible to understand this displacement if we suppose that streamer A, rooted on the back side of the Sun, is dragged eastward by solar rotation, while streamer B, rooted on the front side of the sun, is dragged westward; the two streamers superpose along the line of sight on june $13-14$. These processes result in a shift, along the UVCS slit, of the position of the line intensity maxima which correspond to the streamer peak emission. However we don't expect a very good agreement between LASCO movies and UVCS data, both of possible differences in the white light *vs* UV structure, and because the axes of streamers A and B are not radial, as shown by the only image available for this week from Mauna Loa Observatory. In fig. 1 we make a comparison between two images from LASCO movies (on 10 and 12 june 2000) and profiles of the OVI 1032 Å

and $SiXII$ 520 Å line intensities along the UVCS slit, for the same days, at 1.6 solar radii. We point out that on june 10 there is a good agreement between the radial projection of the streamer's axis and the position of OVI and SiXII intensity maxima. On the contrary on june 12 there is no SiXII countepart to the white light emission of streamer. Because OVI and SiXII lines originate from ions forming at quite different temperatures (in ionization equilibrium OVI ions peak at a temperature of $\sim 3 \cdot 10^5 K$, while SiXII ions peak at $\sim 2 \cdot 10^6 K$), we conclude that different positions along the slit of the OVI and SiXII peak emission correspond to coronal regions with different plasma temperatures. Hence we consider streamer A – whose LASCO eastward time displacement corresponds to the displacement along the UVCS slit of maximum SiXII emission – to be a streamer with higher temperature than streamer B, whose LASCO westward time displacement corresponds on the UVCS slit to the displacement of the OVI emission peak.

3. Data Analysis

To support quantitatively this conclusion, we have derived streamer's temperatures. Because we have spectra that include FeX, FeXII and FeXIII ions, we derived electron temperatures from the ratio of the intensities of these lines, under the hypothesis of ionization equilibrium. Once electron temperatures are known, following Noci, Kohl and Withbroe (1987), we can evaluate the electron density from the ratio between the radiative and collisional component of the OVI 1032 Å line:

$$\frac{I^{1032}_{rad}}{I^{1032}_{coll}} = K\, \frac{\lambda^2 \sqrt{T_e}\, e^{\left(\frac{E}{k_B T_e}\right)} \int I_{ex}(\lambda) d\lambda}{\bar{g}\, N_e \sqrt{\Delta\lambda^2_{cor} + \Delta\lambda^2_{ex}}}\, \frac{\Omega_0}{\pi}$$

where $K = 5.75 \cdot 10^2$, I_{ex} is the OVI 1032 Å disk intensity, Ω_0 is a geometrical factor, $\bar{g}$ is the Gaunt factor and other symbols have their usual meaning. This equation is correct only under the hypothesis of static plasma, which is certainly the case for streamers at 1.6 and 1.9 solar radii (see Strachan et al. (2002)). Following the method described by Raymond et al. (1997), valid only for static plasma, we derive the absolute oxygen abundance from the radiative $[N(O)/N(H)]_{rad}$ and collisional components $[N(O)/N(H)]_{coll}$ as follows:

$$\left[\frac{N(O)}{N(H)}\right]_{rad} = C\, \frac{I_{rad}(OVI)}{I_{rad}(Ly\beta)}\, \frac{b_{Ly\beta}}{b_{OVI}}\, \frac{f_{Ly\beta}}{f_{OVI}}\, \frac{\delta\nu_{OVI}}{\delta\nu_{Ly\beta}}\, \frac{\nu_{Ly\beta}}{\nu_{OVI}}\, \frac{I_{disk}(Ly\beta)}{I_{disk}(OVI)}$$

$$\left[\frac{N(O)}{N(H)}\right]_{coll} = C\, \frac{I_{coll}(OVI)}{I_{coll}(Ly\beta)}\, \frac{b_{Ly\beta}}{b_{OVI}}\, \frac{q_{Ly\beta}}{q_{OVI}}$$

where $C = \frac{N(HI)/N(H)}{N(OVI)/N(O)}$ is the ratio between HI and OVI ion concentrations, I_{disk} are the disk intensities, I_{rad} and I_{coll} are the radiative and collisional components of the intensity, f is the oscillator strength, b the branching ratio, $\delta\nu$ the line width and q the collisional excitation rate. We notice that C is costant within 10% in our temperature range ($6.0 < \log T < 6.2$). Because UVCS spectra include lines from many other ions, it is also possible to evaluate absolute abundances of the elements responsible for those line emission. To this end it is sufficient to calculate the ratio between the line intensities and the intensity of the collisional component of hydrogen Lyman β, which is a function only of electron temperature and element abundance, and compare the "observed" ratio with values predicted for ratio by standard codes (here the Chianti 3 code) at the temperature we derived.

4. Results

4.1. Electron Temperature and Density

Temperature profiles along the UVCS slit show, as anticipated, that streamer A is hotter by about 0.1 dex than streamer B (i.e. $\log T_A = 6.12 \pm 0.04$ and $\log T_B = 6.01 \pm 0.03$ for june 11). Data don't show any evidence, within the error bars, for a temperature decrease from 1.6 to 1.9 solar radii. Also, data don't allow us to come to definite conclusions about the temperature evolution with time: however, the temperature of streamer A seems to keep constant with time, while the colder streamer B possibly warms up. The two streamers have about the same electron density, constant with time until june $16-17$, when the density of streamer A increases by about a factor 2 (see later); densities on june 11, 12 and 13 are about a factor 3 higher than streamer densities at the minimum phase of solar cycle (see e.g. Gibson et al. (1999)). On june $16-17$ the streamer A, dragged by solar rotation, lies onto the plane of the sky and is at the center of the UVCS slit: this allows us to derive plasma parameters across the streamer. The temperature profile shows a decrease from the center toward the edges of the streamer, in agreement with Parenti et al. (2001): locating the streamer's edge where $I_{edge}^{1032} \simeq 1/e\, I_{peak}^{1032}$, we found T to decrease by $10-15\%$ with respect to the temperature at the center of the streamer. Also the electron density decreases from the center toward the edges, as expected.

4.2. Elemental Abundances

Our determination of the oxygen abundances shows that the cooler streamer B is overabundant with respect to streamer A. We remind the reader that streamer A is an older structure, while B reforms on june 11 after the disruption of streamer B' on the previous day. We can hypothesize that in younger streamer B gravitational settling had not enough time to reduce the oxygen abundance from photospheric to coronal values. This happens also with others elements, overabundant in streamer B.
On june 17, we have been able to check the behavior of the oxygen abundance across streamer A: in the edge abundance is higher than in the center. However, we notice that we don't observe two lobes in the OVI intensity across the streamers as observed in the minimum phase of the solar activity cycle. Perhaps we can justify this apparent contradiction as a consequence of the strong density increase between streamer's legs and center.
In order to find some indications about the origin of slow wind, we also compared coronal Fe/O values with those acquired *in situ* by the SWICS experiment onboard Ulysses spacecraft. To this end, we need to know the geometry of fieldlines that extend from the coronal levels sampled by UVCS to the distances sampled by SWICS. The magnetic field configuration as been derived via an MHD extrapolation model, which makes use of the photospheric magnetic field measurements of the Wilcox Solar Observatory. It turns out that UVCS and SWICS values are in good agreement (for example $(Fe/O)_{UVCS} = 0.12 \pm 0.03$ and $(Fe/O)_{SWICS} = 0.09 \pm 0.04$ for june 11). However the fluctuations in the *in situ* values are so large that a comparison can be made only between time–averaged values, giving little evidence in favor of an association between abundances in the streamer legs and slow wind.

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