THE QUIESCENT CORONA AND SLOW SOLAR WIND

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ABSTRACT

This paper discusses the observations of the UltraViolet Coronagraph Spectrometer (UVCS), operating on board the SOHO spacecraft, which concern the quiescent coronal streamers and the slow solar wind. The UVCS started to observe the extended corona at the end of January 1996; it routinely obtains coronal spectra in wavelength intervals around the H\textalpha{} line and the OVI resonance lines at 1032\AA{}, 1037\AA{}. UVCS also obtains polarized radiance data in the visible continuum. Through the composition of slit images it also produces monochromatic images of the extended corona. This paper discusses the streamer characteristics as they result from the UVCS observations, gives values for the physical parameters and suggests a model for the source of the slow solar wind in the inner corona.

1. INTRODUCTION

The Ultraviolet Coronagraph Spectrometer (UVCS) aboard the SOHO spacecraft is described by Kohl et al. (1995). It consists of two parallel coronagraph spectrometer channels which record coronal spectra in the wavelength intervals 1145 \textarcdegree{} - 1287 \textarcdegree{} (Ly-\alpha{} channel) and 984 \textarcdegree{} - 1080 \textarcdegree{} (OVI channel) (extendable to 1100 - 1361 and 937 - 1126, respectively). A third channel measures the coronal polarized radiance in the visible continuum. The instantaneous field of view of the instrument is the slice of the corona whose image is on each spectrometer slit. This is tangent, approximately in its central point, to a circle centered in the center of the solar disk, and can be moved parallel to itself from 1.4 to 10 \( R_S \) of heliocentric distance, and also rotated around Sun's center. Since the instrument axis can be offset from its normal position (pointing at Sun's center) the observable corona extends from 0 to 12 \( R_S \) of heliocentric distance. The operation of UVCS includes a synoptic mode, by which an image of the corona can be obtained for a number of spectral lines by combining nearby slit images.

We will not discuss here in detail the instrument characteristics, which have been studied in the laboratory (Kohl et al. 1995) and in flight (Gardner et al. 1996).

UVCS began to record coronal spectra at the end of January 1996, and has been operating nearly continuously since then. It has recorded an ample amount of data on the extended corona. We discuss, in this paper, some characteristics of the coronal streamers, as they emerge from the recorded data, and their implications for the problem of the origin of the slow solar wind.

2. STREAMER MORPHOLOGY

Streamers appear, in the UVCS pictures of the solar corona, as elongated structures protruding from the Sun towards interplanetary space. At the beginning of the period of observation (end of January 1996) their axis was roughly on the solar equatorial plane, so that the solar corona had the classical shape of the minimum corona. Later on, the picture became less simple: the latitudinal extension of the streamer belt has grown, but not uniformly, around the equator. Sometimes the coronal structure observed has a simple, minimum activity, shape (equatorial streamer) on one side of the Sun, while it is more complex,
and more extended in latitude, on the other side. At other times the complex structure is present on both sides of the Sun. Occasionally the observations show again the simple equatorial belt characteristic of the activity minimum. It is important to add that this description concerns the streamers as seen by UVCS, above 1.5$R_\odot$. A simple structure in Ly-$\alpha$ or in the OVI lines at these heliocentric distances does not imply a dipolar structure of the magnetic field on the solar surface; for example, the simple streamer structure of January 29 is associated with a complex ensemble of three loop systems at the coronal base, as shown by the images obtained with the other SOHO coronagraph, LASCO C1 (Brueckner et al. 1995).

This behaviour of the streamer belt, which is connected to the development and evolution of active regions in the lower atmospheric layers, is not surprising, in this ascending phase of the solar activity cycle, although one could expect a somewhat slower complexity increase.

The most interesting characteristic of the UVCS streamer observations is the discovery of a striking difference, for most, though not all, streamers, between the Ly-$\alpha$ images and those in the OVI lines (Noci et al. 1997). We give, in Figure 1, an example taken from the Noci et al. paper: the OVI streamer appears to consist of two sub-streamers, or rather three at the lower heliocentric distances observed. The Ly-$\alpha$ streamer, on the contrary, has a much simpler structure, particularly above $\approx 2 R_\odot$, with maximum brightness on the axis, where the OVI branches converge with the increase of the heliocentric distance.

Noci et al. (1997) suggest three possibilities to explain the Ly-$\alpha$ /OVI difference: (i) temperature effect: a larger electron temperature in the region of lower OVI emission can affect the OVI population more than that of neutral H; (ii) velocity effect: the OVI lines are more sensitive to Doppler dimming than HI Ly-$\alpha$; (iii) abundance effect: if oxygen is less abundant on the streamer axis than in the surrounding regions its emission on the axis is depressed. We examine, below, these suggestions and also a fourth one: in the discussion we will call region A the one where the OVI brightness is reduced and region B the rest of the streamer.

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**a) Temperature effect**

Let us assume that the electron temperature in region B is above $10^6 K$. A possibility to be examined is that of a larger temperature in region A than in region B. If so, the larger temperature in region A would correspond to a decreased population of the OVI ions in it (Figure 2, Dere et al. 1997), and, therefore, explain the lower emission in the OVI lines. However, a higher temperature will affect also the neutral hydrogen population, which would also be reduced, with a consequent brightness decrease, in contrast with what is observed. A combination of temperature and density increase cannot produce the desired effect, because the curves which give, as a function of the electron temperature, the OVI and HI populations run almost parallel in that interval (Figure 2), and the OVI lines, having a significant contribution from collisional excitation, are more sensitive to density than Ly-$\alpha$. An electron temperature above $\approx 3 \times 10^6 K$ in region B (and larger in region A) accompanied by a larger density in A could explain the observed trend, but it would produce too low an OVI emission (Figure 2). Another argument against the temperature explanation is that a brightness depletion is observed also in the lines of other ions, such as MgX ($\lambda$ 625), SIXII ($\lambda$ 499), FeXII ($\lambda$1242). Again, an electron temperature above $3 \times 10^6 K$ would be a possible explanation of the observed trend, but it would have a FeXII brightness much lower than observed.

Let us examine, now, the possibility of an electron temperature below $10^6 K$. Between $3 \times 10^5$ and $10^6 K$ one could find a combination of higher temperature and density in region A to explain the observations in the HI and OVI lines, but not those in the lines of other ions, whose abundances, at these temperatures, are very low (Figure 2).

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**b) Velocity effect**

The Ly-$\alpha$ line is produced by resonance scattering (Gabriel et al. 1971) and is therefore subject to Doppler dimming (Hyder and Lytes 1970, Beckers and Chipman 1974). The two lines of the OVI resonance doublet are excited in part by collisions with free electrons, in part by transition region radiation (Kohl and Withbroe 1982), therefore their radiative components can be affected by Doppler dimming. The OVI ions, because of their larger mass and thus much narrower absorption profile, are much more sensitive to this effect than the HI atoms. An outflow speed in the 50 - 60 km/sec range, would Doppler dim the radiative component of the OVI lines, but it
would not affect the Ly-α line (Withbroe et al. 1982), so that an intensity decrease of the OVI lines would arise, but not of the Ly-α line.

It would then be possible to explain the OVI/HI brightness difference by suitable temperature, velocity and density distributions along the line of sight. However, this explanation is ruled out by the fact that the Fe XII line (λ1242) behaves similarly to the OVI lines. For this line the radiative contribution is negligible, and thus it can not be Doppler dimmed.

c) Abundance effect

This is an obvious possibility, which has been, in fact, confirmed by the analysis accomplished by Raymond et al. (1997) for a quiescent coronal streamer. We will describe their results in the next section.

d) Drift of neutral hydrogen

We examine now the possibility that it is neutral hydrogen, rather than OVI and other ions, to have a peculiar behaviour. Neutral hydrogen, differently from the charged ions, can, in fact, drift across the magnetic field lines and modify the equilibrium concentration if inhomogeneities are present.

The analyses accomplished up to now on the UVCS data have assumed the atmosphere to vary slowly and regularly (e.g. following spherical symmetry) along the line of sight. This is based on the fact that our preliminary studies of the effect of inhomogeneities on our diagnostic tools (e.g. line widths; the OVI λ1037/λ1032 ratio) show that it is small (≤ 10%), if we exclude extreme or very complicated configurations. Also inhomogeneities large enough to be resolved by UVCS, like plumes in coronal holes, give a rather weak signal in our data. Therefore we believe that a better line of reasoning is the one which tries to interpret the UVCS data without assuming complicated non-observed structures along the line of sight. However, in the problem posed by the observed morphology difference between OVI and HI streamers, the consideration of inhomogeneities appears a priori, a viable solution, even if their distribution and structure are not too complicated.

Let us consider a model in which the streamer, rather than being homogeneous, is constituted of elements of higher density, with dimensions smaller than a resolution element, embedded in a thinner atmosphere. Taking into account the observations reported by Koutchmy et al. (1994), Woo et al. (1995), Woo and Habbal (1997) we assume the more dense elements to have a filamentary structure, probably parallel to the magnetic field. We will calculate the average motion of the neutral hydrogen atoms and show that they can drift out of the threads and bring the density of the neutrals in the space between the threads at the same level as in them. For simplicity we take the same temperature and abundances in the dense elements and in the surrounding plasma. While the ions are confined by the magnetic field and thus have the same density contrast as protons between threads and surrounding plasma, this is not so for neutral hydrogen, which can move away from the denser elements into the ambient atmosphere. To calculate the distance covered by hydrogen atoms during their lifetime two characteristic times are relevant, the charge exchange time, \( t_c \), and the ionization time, \( t_i \), the first being slightly smaller than the second (see below). If \( v = \sqrt{2kT_h/m} \) \( (T_h \) being the kinetic temperature of neutral hydrogen, \( m \) its mass and \( k \) the Boltzmann constant) is the mean (thermal) speed of an hydrogen atom, this shall move, on average, the distance \( l_v = vt_c \) before exchanging its electron with a passing proton. This process, however, does not change the number of neutrals; its effect is that the newly created atom moves in a different direction with respect to the previous one. The ensuing motion of the neutral particle is a random walk which is constituted by as many steps as occur before a real ionization takes place. Their number is, on the average, \( n \approx t_i/t_c \). The average total distance covered by an hydrogen atom is, therefore:

\[
\begin{align*}
\text{distance covered} & = \sqrt{n} \times l_v = \sqrt{2kT_h/m} \sqrt{t_i/t_c}.
\end{align*}
\]

In a static atmosphere, starting with a situation where the threads and the ambient plasma have the hydrogen ionization ratio which corresponds to the equilibrium value, there will be a net flux of neutrals out of the threads. This flux is maintained by the fact that the number of recombinations per unit time and volume inside the threads remains unchanged, since it depends on the electron and proton density there. This expansion of the cloud of neutrals out of the threads makes the density roughly constant inside a cylinder of radius \( d \) centered around a thread. Hence, if the mean distance between the dense threads were not larger than \( d \), all the atmosphere, for what concerns the neutrals, would reach equilibrium having a roughly constant density. The value of this density depends on how fast neutrals are produced by recombination (mainly in the threads) compared with how fast they are lost by ionization (outside and inside). Since the number of recombinations per unit volume and time remains constant.
(note that this process does not alter the total density of the threads, given the very small neutrals to protons ratio \((\approx 10^{-7})\), and the number of ionizations is proportional to the electron density, a large density contrast between threads and ambient can keep the neutral density almost unchanged at the initial thread value. In the extreme case of a negligible proton and electron density in the ambient atmosphere, the density of neutrals, in a static situation, has the same value, the thread equilibrium value, both in these features and outside them. Therefore, if we introduce the filling factor, \(f\), to represent the fraction of volume in a resolution element, occupied by the dense features, we can say that the average density of neutrals in a resolution element is a growing function of \(f\), which becomes independent of it if the density in the ambient atmosphere is much smaller than that in the dense elements. These considerations are also true in the real, non-static, case, since the time \((t_i)\) for an atom to move the distance \(d\) is significantly smaller than the expansion time, even in coronal holes (Withbroe et al. 1982). The expressions for \(t_i\) and \(t_e\), that we take from Holzer et al. (1983), are, in c.g.s. units:

\[
\begin{align*}
t_i^{-1} &= 6.2 \times 10^{-11} N_e^\prime T_e^{-1/2} \exp(-\chi/kT_e) \\
t_e^{-1} &= 2.7 \times 10^{-10} N_p^\prime (T_p + T_e) \left(\frac{T_p + T_e}{2}\right)^{1/2} \\
&\times \left[1 - 8.3 \times 10^{-2} \log_{10} \left(\frac{T_p + T_e}{2}\right)\right]^2,
\end{align*}
\]

where \(\chi\) is the hydrogen ionization potential, \(T_p\) and \(T_e\) are the proton and electron temperatures, respectively, and \(N_p^\prime, N_e^\prime\) the proton and electron densities in the thin atmosphere. (We do not use the density inside the threads because we assume their width to be smaller than \(t_e\).) Therefore, with \(T_p = T_e = T_h = 2 \times 10^6 K\) (see section 3), \(N_p^\prime = N_e^\prime = 1 \times 10^6 \text{ cm}^{-3}\), which are appropriate for a streamer at \(r \approx 2 R_0\) (Allen 1973), we get \(d = 2.2 \times 10^3 \text{ km}\). This means that, with the temperatures and densities used, a neutral atom moves away from its initial position by \(2200 \text{ km}\), on the average, before being ionized. However, we believe that there is no observational evidence, at present, against a model with an ambient atmosphere ten times thinner, at least in region A, which makes \(d = 2.2 \times 10^3 \text{ km}\). If these conditions apply and the filamentary structures of the streamer have an average spacing not larger than \(d = 2.2 \times 10^3 \text{ km}\), the density of the neutrals will vary little across the streamer. Therefore the Ly-\(\alpha\) line will not show a significant brightness decrease in region A, even if \(f\) is smaller there than in the rest of the streamer. (It can even show an increase if the density is larger in the regions of A.) The OVI lines, on the contrary, show a strong dependence on \(f\) if the density contrast between threads and ambient is large. For the collisional components we have:

\[
I = a_1 [f \int N_0 N_e dx + (1 - f) \int N'_e N'_e dx],
\]

where \(a_1\) is a constant, \(N_0\) the density of the OVI ions, \(N_e^\prime\) the electron density in the thread like structures and the integrations are along the line of sight. Putting \(c = N'/N\), this becomes:

\[
I = a_1 [f + c^2(1 - f)] \int N_0 N_e dx.
\]

Analogously the radiative components have the intensity:

\[
I = a_2 [f + c(1 - f)] \int N_0 N_e dx.
\]

To produce an intensity drop, for the ion lines, in region A, we need a filling factor smaller in this region. If, for example, \(f_A = 0.1, f_B = 0.0\) and, as suggested by Koutchmy et al. (1994), \(c = 0.1, I_B \approx 6I_A\) for the collisional components of the OVI lines, \(I_B \approx 3I_A\) for the radiative ones, which would explain the intensity drop in region A for the OVI lines.

In this picture, clearly, the brightness drop from region B to region A is not to be attributed to an abundance drop, the abundances in the streamer having been assumed uniformly distributed. The effect is caused by a decrease of the filling factor from region B to region A, which results in a decreased average density of the protons in region A. This allows an observational test, but we do not have conclusive data on the streamer densities yet, since the entrance aperture of the UVCS polarimeter, being much smaller than that of the UVCS channels, does not cover both regions during an observation. We have, however, other UVCS observations to test the model. In particular, we mention a result which is already in the literature, which concerns the two components of the OVI lines. According to the calculation given above, the radiative component is lowered, by the inhomogeneities, much less than the collisional one; therefore, if one separates the two components to determine the OVI abundance from each, one would derive, to explain the brightness drop in region A, a lower abundance from the radiative component than from the collisional one. This is in contrast with Raymond et al. (1997) analysis of these components in streamers, which gives the opposite result.

We conclude that drift of HI atoms across the magnetic field can not explain the brightness drop observed in region A.

This analysis confirms our previous results which have found the effect of inhomogeneities on the UVCS data to be small. However we believe that drift of neutral hydrogen across magnetic field lines should have some effect, in presence of inhomogeneities, particularly in regions where the density is low. Indeed, this phenomenon is a good candidate to explain why all the UVCS images of coronal features in Ly-\(\alpha\) show a lower contrast than in the OVI lines.

3. PHYSICAL PARAMETERS IN STREAMERS

We have studied a number of streamers starting with our more direct diagnostic tools, consisting of the line widths and of the OVI doublet ratio. Some of these results have been reported already in recent works (Kohl et al. 1997a, Kohl et al. 1997b, Noci et al. 1997).
3.1. Kinetic Temperatures

The line widths, once corrected for the instrument profile, contain information on the velocity distributions in the plasma along the line of sight. Even in a constant temperature atmosphere the emergent intensity would not have a Gaussian profile, because the radiatively excited component of a line depends on the spectral profile of the exciting radiation and on the scattering angle. However, these effects are small in a corona with spherical symmetry (Withbroe et al. 1982). In case the line of sight passes through a dense feature which is out of the plane of the sky, the contribution of this can affect the shape of the line observed. We have made some calculations of the effect of such a situation, with the result that it is in the 10% range, if extreme and unlikely cases are excluded. Therefore we have used the simple Doppler transformation \( \Delta \lambda / \lambda = \Delta v / c \) to determine, from the wavelength width of the lines, the width of the velocity distribution function of the emitting ions. Beyond the thermal motions of the individual ions, other random motions (turbulence, waves) can contribute to the line broadening, and thus the kinetic temperatures that we obtain include these contributions (see Kohl et al. 1997a for a more extended discussion). However, it does not appear likely that they play a very important role, mainly because the random motions of the plasma elements, whichever the cause, involve particles of different masses, therefore the resulting r.m.s. velocities are independent of the particle mass and the kinetic temperatures proportional to it. This is not the case in our data.

According to Noci et al. (1997) the spatial distribution of the r.m.s. velocities of the OVI ions, in streamers, is characterized by the fact that in the brightest regions (the streamer core, around the axis, at the lowest heights) the r.m.s. velocity is the smallest. The r.m.s. velocity is roughly constant in the core, while, outside it, it increases, both moving in radial distance and in heliolatitude. For example, in the June 5, 1996 streamer observation, the r.m.s. velocity is about 40 km/sec in the core (from 1.5 \( R_\odot \)), lower limit of the observation, to 1.8 \( R_\odot \), and 60 km/sec at 2.5 \( R_\odot \) on the streamer axis. Values similar to the latter were measured 30° away from the axis at 1.5 \( R_\odot \). Analogously, the r.m.s. velocities measured in the October 12, 1996 west limb streamer are 40 km/sec at \( r = 1.5 R_\odot \), 70 km/sec at \( r = 2.5 R_\odot \) and 124 km/sec at \( r = 5 R_\odot \). Quite similar velocities have been found for the February 5, 1997 streamer. (Kohl et al. 1997a).

The analysis of the Ly-\( \alpha \) observations for the three streamers mentioned above gives values of the r.m.s. velocity in the range 115 - 140 km/sec between 1.5 and 2 \( R_\odot \), decreasing to \( \approx 100 \) km/sec at \( r = 8 R_\odot \). (Noci et al. 1997, Kohl et al. 1997a).

The lower variability of the Ly-\( \alpha \) width, with respect to the OVI line width, inside the streamer, is in agreement with a similar behaviour from streamer to coronal hole, and within coronal holes (Kohl et al. 1997a). If these velocities are transformed into kinetic temperatures, we get, for oxygen, \( T = 3.1 \times 10^9 K \) in the streamer core and \( T = 29.8 \times 10^9 K \) at 5 \( R_\odot \). Even higher temperatures have been determined for FeXII (Kohl et al. 1997a). For hydrogen we get \( T = 1.6 - 2.4 \times 10^9 K \) in the core, and \( T = 1.2 \times 10^9 K \) at 5 \( R_\odot \). Although not so high as the kinetic temperatures measured by UVCS in coronal holes (Kohl et al. 1997a), these ion temperatures are much higher than expected. They indicate the presence of a process which accelerates preferentially the higher mass particles. The temperature differences at low heights, where the density is larger, are reduced by the collisions.

Theories have been proposed, which can account for the very high ion temperatures observed by UVCS/SPARTAN and UVCS/SOHO in coronal holes (Axford and McKenzie 1992, McKenzie et al. 1995. Marsch and Tu 1997). The temperatures that we have obtained in streamers indicate that the same mechanism is probably operative also in streamers.

It is important to stress that these r.m.s. velocities and kinetic temperatures refer only the line-of-sight motions of the ions. We do not have direct information on the velocity distributions in the perpendicular direction. We have indirect information, however, for the OVI ions, coming from the study of the OVI \( \lambda 1037/\lambda 1032 \) ratio: the fact that this ratio shows strong evidence of Doppler pumping of the \( \lambda 1037 \) line at large heights, gives an upper limit for the kinetic temperature of the OVI ions relative to the motions along the radial direction (see next section). For the February 5, 1997 west limb streamer, this was \( T \approx 3 \times 10^8 K \) (Kohl et al. 1997a).

3.2. Outflow Velocities

The OVI \( \lambda 1037/\lambda 1032 \) ratio permits the determination of the outflow velocity in the solar corona (Noci, Kohl and Withbroe 1987), because the two lines have a different contribution of radiative excitation, and this depends on the bulk velocity in the corona (Doppler dimming): if collisions are the dominant excitation mechanism the ratio is 0.5, while it is 0.25 if radiative excitation is dominant. Furthermore, the \( \lambda 1037 \) line is pumped by a nearby chromospheric CII line for a sufficient Doppler shift of the coronal absorption profile (Doppler pumping), which pushes the line ratio above 0.5 if the bulk speed is above \( \approx 94 \) km/sec. The radiative contributions depend on the width of the coronal absorption profile, which is set by the velocity distribution of the absorbing ions in the direction of the incoming radiation, wider distributions corresponding, clearly, to less efficient pumping. This has permitted to establish the upper limit for the kinetic temperature in the radial direction given in the previous section.

For the June 4 east streamer, the value of the OVI \( \lambda 1037/\lambda 1032 \) ratio, according to Noci et al. (1997), is between 0.3 and 0.4, slightly decreasing with heliocentric distance from 1.5 \( R_\odot \) to 3 \( R_\odot \). This is consistent with a small or zero plasma velocity in the core of the streamer, which remains small (\( \leq 50 \) km/sec, Noci, Kohl and Withbroe 1987) even outside the core, where the r.m.s. velocity is significantly larger than in the core, as described above (the decrease of the OVI \( \lambda 1037/\lambda 1032 \) ratio with height is in agreement with the fact that the radiative components become dominant as the heliocentric distance increases because the density decreases and Doppler dimming is still small). In other words, above the
core, characterized by low kinetic temperature and low or absent outflow velocity, there is a region of increased kinetic temperature with still small (or zero) outflow velocity. For a different streamer (3 February 1997) observations were made up to 8 R⊙; they show that Doppler pumping of the 1037 Å line becomes evident above ≈ 4R⊙, and dominant at greater heights, which implies an outflow velocity increasing well above 100 km/sec. The value reached by the OVI λ1037/λ1032 ratio at 7 R⊙(≃ 1) is quite similar to the value reached at 2.2 R⊙in the northern polar hole in January 1997: outflow speeds of the same order as those in coronal holes occur also above streamers, although at larger heights.

Perhaps more interesting is the fact that the quoted value of the OVI λ1037/λ1032 ratio at 7 R⊙puts also an upper limit to the outflow speed, which is ≈ 250 km/sec (Noci, Kohl and Withbroe 1987).

Doppler pumping of the 1037 Å line becomes evident also in the regions surrounding the streamer.

3.3. Electron Temperature and Densities

A parameter, whose knowledge is very important to understand the physical processes which take place in the coronal streamers is the electron temperature T_e. UVCS has the capability to make a direct measurement of this quantity by determining the width of the Ly-α line scattered by the coronal free electrons. Since the total intensity of this line is ≈ 10^-3 smaller than that of the resonant component and the width forty times larger, its measurement is very difficult. A preliminary analysis of an observation to determine T_e with this method is given in these proceedings (Fineschi et al. 1997).

It is possible to determine the electron temperature indirectly, through the hydrogen ionization ratio, either by a comparison of the Ly-α total intensity with the intensity in the visible continuum, or by a comparison of the collisional and radiative components of Ly-β. We give some details on the latter technique, which seems promising.

The emissivity of a coronal line excited from the ground level, integrated over the line width, has the expression

\[ j_{\text{rad}} = \int \int \int \Omega p(\phi) d\omega' \int_{-\infty}^{\infty} I_D(\nu'[v_p], n') (B_{12}/4\pi) N g_p(v_p) dv_p, \]

for the radiative component (Noci, Kohl and Withbroe 1987), and

\[ j_{\text{coll}} = (h\nu/4\pi) b q_{\text{coll}} N N_e, \]

for the collisional one. Here h is Planck constant, ν the frequency of the line considered, ν' the frequency at which the absorption occurs, which depends on the velocity, νp, of the absorbing ions in the direction, n', of the incident radiation, gp(vp) the distribution function of the velocities of the absorbing ions along the direction n', that we assume Maxwellian, p(φ) the scattering function, Ω the solid angle subtended by the solar disk at the point of scattering, I_D(ν'[v_p], n') the intensity from the solar disk, B_{12} the Einstein coefficient for absorption, N the density of the absorbing ions in the ground level, N_e the electron density and b the branching ratio for radiative de-excitation. The quantity q_{coll} has the expression:

\[ q_{\text{coll}} = 2.73 \times 10^{-17} f_{12} \tilde{g} e^{E_{12}/kT_e} e^{E_{12}/E_{12}/\sqrt{T_e}}, \]

where f_{12} is the oscillator strength, \tilde{g} an effective Gaunt factor, E_{12} the energy of the transition and c.g.s. units are used (Seaton 1964).

Doppler dimming of the hydrogen lines is important only for outflow speeds larger than ≈ 80 km/sec (Withbroe et al. 1982), therefore it can be neglected in streamers at the heliocentric distances where this method can be applied (lower than ≈ 2R⊙, see below). In this case an approximate form of Equation (1) is:

\[ j_{\text{rad}} \approx b h\nu (B_{12}/4\pi) N g_p(0) \times \int \int \int \Omega p(\phi) d\omega' \int_{-\infty}^{\infty} I_D(\nu'[v_p], n')(dv_p/d\nu') dv', \]

from which:

\[ j_{\text{rad}} \approx b h\nu (\Omega/4\pi) (B_{12}/4\pi) N g_p(0) I_D^2, \]

(3)

where I_D^2 is the total (integrated over the line profile) intensity from the disk of the line considered, and the scattering function has been approximated with 1/4π. We apply Equation (3) to the Ly-α and Ly-β lines:

\[ j_{\text{rad}}^\alpha = b_\alpha f_\alpha \alpha_\alpha I_D^2, \]

and

\[ j_{\text{rad}}^\beta = b_\beta f_\beta \alpha_\beta I_D^2, \]

where I_D^\alpha and I_D^\beta are the total intensities of the two lines on the disk, \alpha_\alpha, \alpha_\beta their wavelengths, and f_\alpha, f_\beta the oscillator strengths of the transitions. From this and from Equation (2), by integration along the line of sight, we obtain the total intensity of the coronal Ly-β line:

\[ I_\beta = \frac{b_\beta f_\beta \alpha_\beta I_D^2}{b_\alpha f_\alpha \alpha_\alpha I_D^2} I_\alpha + (h\nu/4\pi \alpha_\alpha) b_\alpha q_{\text{coll}} \int N_e N_h dx, \]

where N_h is the number density of the hydrogen atoms and q_{coll} is a value averaged over the line of sight. For the total intensity of the coronal Ly-α line an approximate form can be obtained from Equation (3):

\[ I_\alpha = K I_D^2 \alpha_\alpha f_\alpha \frac{b_\alpha}{\sqrt{T_h}} \int_{lo\delta} N_h dx, \]

where K is a constant and \Omega, T_h are values averaged over the line of sight. Here we have neglected the collisional contribution to the Ly-α line (Gabriel et al. 1971). Because the dependence of q_{coll} on T_e is small, we can use a first approximation value for T_e and T_h, so that the above equations have, as unknowns, the integrals along the line of sight. Solving for them, one obtains:

\[ \int_{lo\delta} N_h dx = A \]

(4)

\[ \int_{lo\delta} N_e N_h dx = B, \]

(5)
where $A$ and $B$ contain known constants or quantities measurable with UVCS.

In order to estimate the electron and HI densities we need to invert the above integrals, on the basis of some assumptions on the run of the densities along the line of sight. Finally, one can obtain the electron temperature $T_e(r)$ from the ratio between $N_e(r)$ and $N_e(r)$.

The main limits of this method are: (i) the effect of the integration along the line of sight, which produces an error, difficult to estimate, in the inversion of the integrals (4) and (5), and also it makes it necessary to use, for some quantities (e.g. $\varphi_{col}$), values averaged with respect to the line of sight; (ii) the rather slow dependence of the hydrogen ionization fraction on the electron temperature in the region of interest ($T_e \approx 1 - 3 \times 10^4 K$, see Figure 2).

This method works only for heliocentric distances lower than $\approx 2R_\odot$, because the collisional component of the Ly-$\beta$ line becomes negligible for larger heights. Therefore, to get the quantities $A$ and $B$ over a wide enough range of $r$, for a correct inversion of the integrals in Equations (4) and (5), observations below $r = 1.5 R_\odot$ are required, which means offsetting the instrument and operating in manual mode. This has been done rather seldom, up to now, so that we do not have enough data, yet, at these low heights to apply this method. We will have suitable data in the near future.

3.4. Abundances

Raymond et al. (1997) have studied the UVCS observations of a quiescent coronal streamer characterized by a HI/OVI morphology difference of the kind described in section 2. The main result of Raymond et al. (1997) is that the ionization state was close to that of a $\log T = 6.2$ plasma and that oxygen and other high-FIP (first ionization potentials) elements were depleted by an order of magnitude in region A, compared with the photosphere, while they were depleted by a factor of three only in region B. Low-FIP elements were also depleted, though slightly less than the high-FIP ones, with the same trend (roughly a factor of two more in region A). In section 4 we will discuss this point further, for its solar wind implications.

4. SOLAR WIND FROM STREAMERS

The picture which emerges from the UVCS observations of streamers is that of a stationary or quasi-stationary core (low heights), outside which r.m.s. velocity and outflow speed show a transition to the values of the adjoining coronal holes (north and south). The observed depletion of high FIP elements in streamers, compared with the photosphere, is an argument in favor of the origin of the slow solar wind from streamers, since high-FIP elements are depleted in the slow solar wind (Meyer 1983, Geiss et al. 1995). However, the fact that also low-FIP elements are depleted in streamers is puzzling, as is the difference in this phenomenon from region A to region B.

In past years it has been a common opinion that the flanks of the streamers were the source of the slow solar wind (see, e.g., Noci 1996), an opinion based essentially on the observation that the slow wind is associated with the interplanetary current sheet which is a continuation of the solar streamer belt (Hundhausen 1977, Gosling et al. 1981). In this view the solar wind was a continuous steady flow in the inner corona, along the open field lines on either side of the closed magnetic region, and then, above the cusp, on either side of the current sheet. The understanding of why the sides of the streamers would be the origin of slow, rather than fast, solar wind is one of the primary objectives of the SOHO mission. Recently it has been suggested that the slow wind comes from a process of loop destabilization (Uchida et al. 1992) or plasmoid expulsion (Bochsler 1994). Lately, observations of interplanetary scintillation (Woo et al. 1995, Woo and Habal 1997, Habal et al. 1997) and of coronal irregularities’ motion (Sheeley et al. 1997) have shown that the slow wind, at low heliocentric distances, flows along the streamer stalk (the tail of the streamer, above the cusp, which stretches out towards interplanetary space). These important results are a confirmation of the old view, since the current sheet is inside the stalk, but also indicate a non-steady character of the wind flow, with a wind-current sheet interaction at low heliocentric distances. However they do not concern the part of the streamer which is below the stalk. We now propose a model for the source of the slow solar wind at the coronal base, and also a mechanism to explain the difference in speed between slow and fast wind.

In the model that we propose the slow wind originates in the unipolar regions which exist, at the coronal base of streamers, in a complex loop system as that present at the east solar limb on January 29, 1996. If one looks at the shape of the coronal features, as they appear in the LASCO C1 image, an ensemble of three loop systems is clearly visible; hence we deduce that the magnetic field has the structure shown schematically in Figure 3. Three current sheets, which come close together at $r \approx 4 R_\odot$, divide the region above the loop systems in two similar sections, one of which appears less bright in the OVI lines (region A). According to Figure 3 there should be two regions A in the January 29, 1996 streamer, and it is indeed the conspicuous region A is visible, in the right position, in that streamer, and, also, in that of May 4 (Figure 1). An accurate examination of the morphology of other streamers has not yet been made.

The slow wind, flowing between the loops, goes through the regions A, where the flux tubes widen, and then moves upwards between the two external current sheets inside flux tubes which become narrower and narrower with height. We suggest that it is the narrowing of the flux tubes in the inner corona that causes the wind to be slow, and, at the same time, determines a depletion of the abundance of the heavy ions.

We can deduce some characteristics of the critical solution in flux tubes of this kind by comparison with the critical solution of a wind which expands radially. We call $r_c$ the heliocentric distance of the critical point of the latter and $r_1$ the one which corresponds to the maximum of the cross sectional area, $A(r)$, of a generical flux tube which goes through region A.
We consider the equation for the critical point,

\[ \frac{2kT}{m} \left( \frac{1}{r} + \frac{1}{F} \frac{dF}{dr} - \frac{1}{T} \frac{dT}{dr} \right) - \frac{GM}{r^2} = 0, \quad (6) \]

where \( m \) is the proton mass, \( T \) the temperature, \( G \) the gravitational constant, \( M \) the solar mass and \( F(r) \) describes the deviation of the expansion from the radial case,

\[ A(r) = F(r)r^2. \]

Equation (6) is satisfied at the critical point. Hence, in the radial expansion case (\( dF/dr = 0 \)), the left hand side of the above equation is zero at \( r = r_c \), while in our case it is, at that point, negative, since \( dF/dr < 0 \) at \( r_c \) if we assume that \( r_c > r_1 \) (Figure 3). (The temperature is affected very little by the area variation since the density also is not affected, see below.) Since the left hand side of Equation (6) is negative below the critical point, we conclude that the decrease of \( A(r) \) with height pushes the critical point upwards and then lowers the outflow speed below it. We suggest that this is the reason why the outflow speed of the plasma which moves within the two external current sheets of a system like the one of Figure 3 (slow wind) is smaller than that of the plasma flowing from coronal holes (fast wind), where no narrowing of the flux tubes occurs.

We now discuss the effect of the magnetic field topology on the abundances, still comparing our case to the radial expansion one. Starting from \( r_c \) and going downwards, we note that: (i) the proton density, \( N_p \), is the same in the two cases, because, in the subsonic region, it is determined essentially by gravity (we assume the same density and temperature at the coronal base); (ii) the velocity varies as \( (A_N p)^{-1} \), as a consequence of the continuity equation. Therefore, because of (i) and (ii), the velocity decreases more rapidly in our case than in the radial expansion one, going downwards, from \( r_c \) to \( r_1 \). The result is that in our case we have a smaller speed than in the radial expansion case in the interval \( r_1 < r < r_c \), but the same density. Therefore the proton flux \( N_p r \) is also reduced in that interval.

It has been shown (Geiss et al. 1970) that Coulomb collisions with protons are the main mechanism to drag the ions into the solar wind, which makes the dragging force proportional to the proton flux; hence we suggest that the proton flux reduction in the flux tubes which go through region A causes the ion abundance drop which is observed in that region.

Region B is divided in two by the current sheet; in its internal part, the one towards the streamer axis, an effect similar to the one described above should occur, which explains the abundance decrease that is observed also in this region.

It is worth noting that this model predicts an abundance depletion of heavy ions at the sector boundary in the interplanetary space, which is, at least for helium, observed (Borrini et al. 1981).

Note that the mass flux reduction occurs essentially in the interval \( r_1 \), \( r_c \). Above \( r_c \) the narrowing of the flux tubes modifies the situation. Hence the model does not necessarily predicts a mass flux lower in the slow wind than in the fast one, which would be in contrast with the observations.

5. CONCLUSIONS

The UVCS observations of streamers allowed us to determine several physical parameters which have noticeably increased our understanding of these features. They have also revealed some unexpected and intriguing new phenomena, in particular the ion r.m.s. velocities much higher than expected and the OVI/HI morphology difference. We have said a few words, in section 3.1, about the interpretation of the former; we have dealt more with the latter, because it is more specific to the argument of this paper. We have proposed, in section 4, a model for the source of the slow solar wind, which also explains the OVI/HI difference. In this model the slow solar wind originates from within streamers, as shown in Figure 3, rather than from their flanks, as previously believed. Its source region is well separated from the source region of the fast wind, in the inner corona, by the two lateral current sheets which mark the boundary of the region where the cross-sectional area of the flux tubes decreases with height from that where it increases. These current sheets may well be the sharp boundary between slow and fast wind, evidence of which has been found with the Ulysses interplanetary data (Geiss et al. 1995).

At some heliocentric distance the current sheets appear to come close together, so that instabilities and interactions are likely to develop (Dahlburg and Karpen 1997). The result could be blobs of plasma, trapped in closed magnetic field lines, moving out towards the interplanetary space, as the observations of LASCO suggest (Sheeley et al. 1997). It is also possible that magnetic reconnection takes place in one or two current sheets, not necessarily involving the three of them.

We owe this new picture of the source of the slow solar wind to the diagnostic capabilities of the UVCS.
instrument, combined with those of the LASCO coronagraph. We believe that the data which are being continuously collected by these coronagraphs and by the other coronal and in situ SOHO instruments are producing a real breakthrough in our understanding of the origin of the slow solar wind.

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