Oxygen abundance in streamers above 2 solar radii

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Abstract. Oxygen abundance in streamers has been evaluated by several authors [see e. g. 1, 2, 3] who found, in the core of streamers, an oxygen abundance lower by a factor 3-4 than in the lateral branches (legs). All estimates were made at heliocentric distances $h \leq 2.2$ R$_\odot$. In this paper we analyze UVCS observations of two streamers, observed during solar minimum, at altitudes $h \geq 2.4$ R$_\odot$ with the purpose of deriving the oxygen abundance, relative to hydrogen, and its latitude dependence within streamers, in the range $2.4 \leq h \leq 4$ R$_\odot$. To this end, electron densities have been derived from LASCO data, taken at the time of the UVCS observations, and the radial temperature profile has been taken from literature. These parameters allow us, after the collisional contribution to the OVI 1032, 1037 Å line intensities has been identified, to determine the oxygen abundance that reproduces the observed collisional components. Our results are compared with previous abundance determinations and the relationship between coronal and in situ abundances is also discussed.

INTRODUCTION

Observations made with the SOHO/UVCS spectrometer have shown that the streamer morphology in minor ion emission lines can be markedly different from the streamer morphology in H Ly$_\alpha$. Whereas the brightness of the Ly$_\alpha$ peaks in what would be the streamer core, in the case of a global dipolar magnetic configuration, the minor ion emission peaks in structures. These structures, in the dipolar configuration, represent the legs of the streamer, or, in a multipolar magnetic field not identifiable in Ly$_\alpha$ radiation, correspond to lobes of the magnetic configuration. This difference is not always present: whether there are two distinct types of streamers, or whether projection effects mask at times the true streamer morphology, is still an open question.

The O VI depletion in the streamer core, and O VI relative enhancement in the streamer legs, is most easily interpreted in terms of a variation of the oxygen abundance across the streamer [see e. g. 4]. [1, 5], from UVCS data analysis, derived an oxygen abundance higher in the legs, than in the core of streamers. Similar results have been found by [2] and [3]. All these studies are based on data taken at heliocentric altitudes ≤ 2.2 R$_\odot$.

The issue has a strong impact on the problem of the origin of the slow wind. Slow wind emerges from low latitude solar regions, where streamers are mostly rooted. A comparison of the elemental composition of the streamers with the elemental composition of the slow wind may help identifying the site where the slow wind originates.

In this contribution we extend the analysis of the O VI abundance in streamers to altitudes ($2.4 \leq h \leq 4$ R$_\odot$) higher than those addressed by previous works. This will allow us to see whether the oxygen abundance varies across the streamer also at such high levels and whether the decrease of the oxygen abundance with height, found by other authors [see e. g. 2], is still detectable. We also considered two streamers – possibly pertaining to the two classes previously described – with the purpose of checking whether there is any difference in their composition.

DATA AND ANALYSIS TECHNIQUE

The observations

For the present study we selected two streamers observed by UVCS in 1996, on July 6 and 11, in the equatorial region along the East direction. These two streamers are representative of the two classes described above. However, we note that their morphology, as discussed in the following, leaves room for a different interpretation. UVCS data have been acquired in the range 2 to 4.5 R$_\odot$ on July 6, 1996, and 1.6 to 4 R$_\odot$ on July 11, 1996. The slit width was 300 *μm*, a spatial binning of 2 pixels and a six pixel spectral binning was adopted. Spectra have been taken at increasing heliocentric distances, every 0.25, or 0.5 R$_\odot$, with the slit normal to the axis of the streamer.

Images of the two streamers in Ly$_\alpha$ and O VI have been built by integrating over the line width and interpolating between data taken at contiguous altitudes. They are shown in In Figs. 1a and 1b, for the July 6 and 11, respectively. Spectra at each altitude were integrated over 14 spatial bins, to improve the count rate statistics. Data acquired by LASCO/C2 over the same streamers have also been used in this work. Observations of polarized brightness (pB) by C2 start at ≈ 2 R$_\odot$, hence, as we need to use data taken at the same position by UVCS and LASCO, we did not use UVCS observations taken at lower heights.

How to evaluate oxygen abundances

UV lines in the extended corona form by collisional excitation and resonant scattering of solar disc radiation. Provided the plasma where the lines originate has a low enough flow speed and kinetic temperature, and taking into account that the ratio between the collisional components of the O VI doublet lines is 2, while the ratio between the radiative components is 4, a simple relationship holds between the total intensities of the 1032 and 1037 lines and the radiative component of the 1037Å line:

$$I_{\rm tot,1032} = 2I_{\rm tot,1037} + 2I_{\rm r,1037} \qquad (1)$$

where $I_{\rm tot,1032}$ ($I_{\rm tot,1037}$) is the total intensity of the O VI 1032 Å (1037) line, made up of a collisional $I_{\rm c,1032}$ ($I_{\rm c,1037}$) and a radiative component $I_{\rm r,1032}$ ($I_{\rm r,1037}$). The radiative component (hence, also the collisional component) of the O VI 1037 Å line can be derived from (1) and, as a consequence, also the components of the O VI 1032 Å line can be easily obtained.

The collisional component of the O VI lines is given by:

$$I_{\rm c} = \frac{0.8}{4\pi} h\nu_{k1} A_{\rm el} \int_{LOS} R_{\rm ion}(T_{\rm e}) n_{\rm e}^2 C_{1k}(T_{\rm e}) dx \qquad (2)$$

where $A_{\rm el}$ and $R_{\rm ion}(T_{\rm e})$ are the oxygen and ion abundance; $T_{\rm e}, n_{\rm e}$ are the electron temperature and density; $C_{1k}(T_{\rm e})$ is the collisional excitation coefficient, the indices 1 and k indicate the ground and the upper level of the transition and the integration isextended along the line of sight (LOS).

Relationship (2) allow us to derive the element abundance $A_{\rm el}$, provided we know n_e, T_e and the geometry of the structures where the OVI emission originates. The following subsection illustrates the physical parameters we used in the oxygen determination.

Physical parameters in streamers at $h \geq 2.4 R_\odot$

As we mentioned, in order to apply the method described in the previous subsection, we need to know the density and electron temperature throughout the region where we evaluate the oxygen abundance. Densities have been derived from LASCO/C2 pB data using the standard Van de Hulst inversion technique [6], which is based on the assumption of spherical symmetry. Hence we are modeling a streamer belt, not an isolated feature: this motivated our choice of features observed in 1996, at minimum activity of the solar cycle, when the spherical symmetry assumption is more likely to be tenable.

From LASCO data, densities along a grid of radial directions, 4 degrees apart, have been evaluated throughout the streamers. These are given in the bottom panel of Figs. 2 and 3. Densities at ≈ 2.4 R$_\odot$ seem to be practically constant, throughout the core of the streamer and to decrease towards the streamer legs. All densities decrease with height, with a steeper profile as one moves from the streamer core and enters in the adjacent coronal hole at progressively lower altitudes. Densities in the two streamers at 2.4 R$_\odot$ agree fairly well with those given by [7] for a streamer observed in August 1996 and, at ≈ 4 R$_\odot$, lie on the upper edge of the strip of values given by those authors at that height.

There are a few determinations of electron temperature $T_{\rm e}$ in streamers, at ≈ 1.5 R$_\odot$. In the altitude range we are dealing with, there is only the determination of Fineschi et al. [8] who give $T_{\rm e} = 1.1 \times 10^6 \pm 0.25 \times 10^6 K$, at $r = 2.7$ R$_\odot$. This value is in agreement with the streamer scale height temperature derived by Gibson et al. [7] at that altitude. Hence, we assumed $T_{\rm e}$ to decrease with altitude with the profile given by Gibson et al.

The variation of the electron temperature across a streamer is essentialy unknown. The results of Parenti et al. (these Proceedings) [9] seem to favor an increase of the electron temperature towards the streamer legs. However, Parenti et al. work, which refers to much lower altitudes ($1.6R_\odot$), does not give a profile of temperature across a streamer: it only shows that the electron temperature, evaluated in different days at only one position, is slightly higher at positions which might correspond to the edge of streamers rather than at positions within the streamer core. However, there is no guarantee, so far, that Parenti et al. results, with a very limited statistics, refer to streamers which have a different T_e, possibly constant across the structure. Hence, we assumed T_e to be only a function of r: $T_e = T_e(r)$.

A further relevant parameter is the plasma flow speed. This parameter affects the identification of the collisional component of the OVI line intensities, and makes the identification of I_c from eq. ((2)) inaccurate.

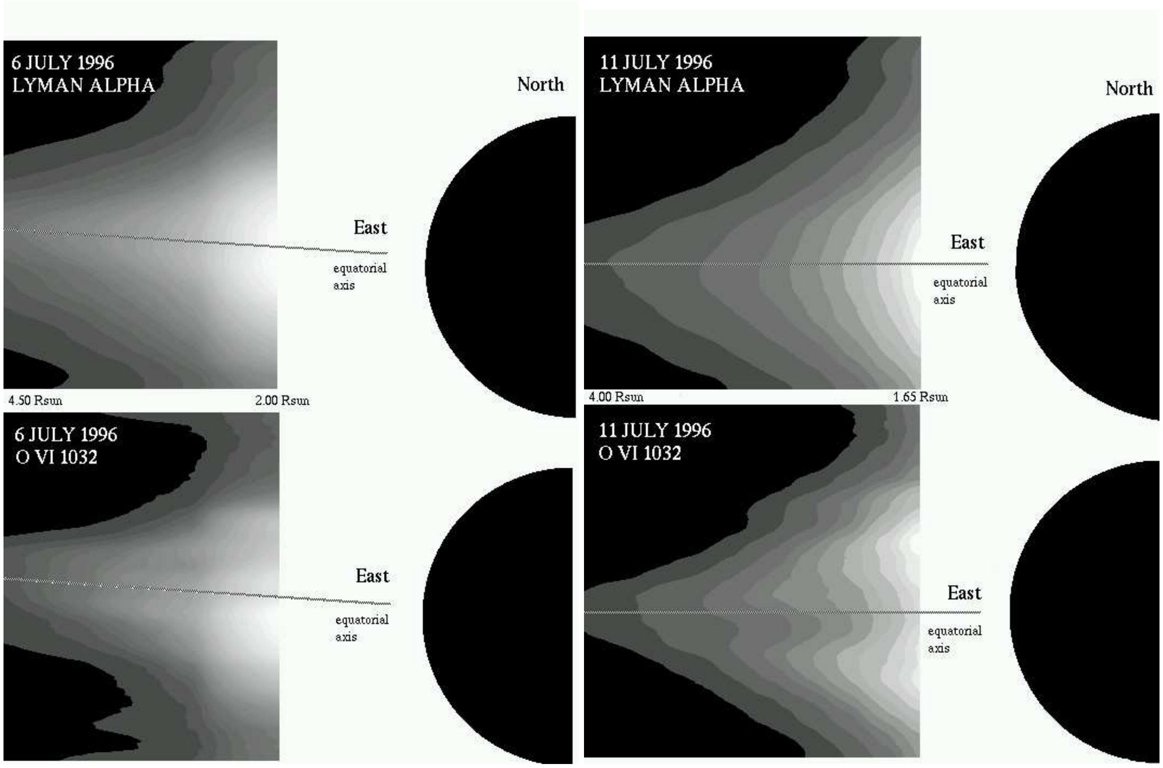

FIGURE 1. Images of the two streamers in Ly_{α} and O VI for 6 and 11 July, 1996. The spectral images for 6 July have been taken with the slit axis 5° above the equator. The dotted lines indicate the position of the equator.

Another parameter affecting the identification of I_c is the line width. This because the percentage contribution of the radiative component to the total line intensities (hence also the collisional contribution) depends also on the width of the absorption profile. The present observations have been acquired with too large a slit width, and too coarse a spectral resolution, to allow us to measure line widths from the data: hence in the following we took the OVI lines width from literature [10]. Then, we calculated, from the above densities, temperature and line width the plasma speed which reproduces the observed R, taking into account the dimming effect. Once the plasma speed is known, we may also calculate the error made deriving I_c from eq. (2) and recalculate the oxygen abundance from the revised value of I_c.

RESULTS

Oxygen abundances have been derived along four radial directions through the streamers bodies. In Figs. 2 and 3 we show the results of our analysis for, respectively, the July 6 and 11, 1996, streamers. In both figures the upper panel gives isophotes of the intensity of the OVI 1032 Å line, integrated over the line width, as a function of latitude and heliocentric distance. The morphology of the streamers, at least above $\approx 2R_{\odot}$, shows that the July 11 feature has a double peaked appearance which disappears at $\approx 3R_{\odot}$: above this altitude the OVI intensity peaks at the latitude where, at lower levels, the intensity has a local minimum in between the two peaks. The July 6 isophotes, on the contrary, do not provide any clear evidence of a double peaked structure, although we cannot discard the hypothesis that the small secondary intensity enhancement, which appears at southern latitudes, is the remnant of a peak which is partially masked because of projection effects.

In the top panel, different symbols, drawn at different heliocentric distances along radials through the northern latitudes $2, 6, 10°$ and the southern latitude 2°, indicate the positions where the oxygen abundance has been evaluated. In the July 11 streamer, the radial at 2° cuts through the OVI intensity drop, while the radials through $-2°$ and 6° cut through the OVI intensity peaks sideways of the intensity minimum. Values of the oxygen abundance at these positions are given in the middle panel of Figs. 2, 3 and the bottom panel shows the density values adopted in the oxygen abundance determination. The error in oxygen abundances, taking into account only uncertainties originating from the count rate statistics, is

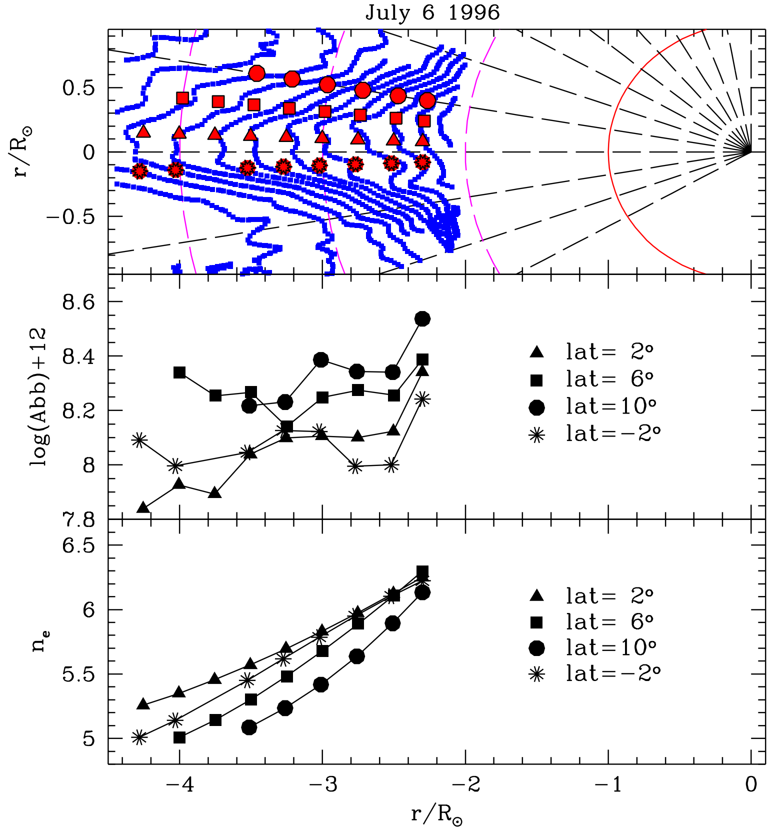

FIGURE 2. Oxygen abundance for the July 6, 1996 streamer. Top panel: isophotes of the OVI 1032 total line intensity vs. latitude and heliocentric distance. The lowest isophote corresponds to $logI_{ovi,1032} = 9.0$, the highest isophote corresponds to $logI_{ovi,1032} = 6.8$. Symbols drawn along different radials indicate the positions where the oxygen abundance has been evaluated. Middle panel: oxygen abundance at the positions given in the top panel. Bottom panel: densities at the positions given in the top panel.

0.05 dex, at heliocentric distances $\leq 3R_\odot$ and 0.1 dex at higher distances. Although, as we already mentioned, densities are about constant, within the streamer core (at the lowest heliocentric altitude), the bottom panel hints to a decrease of densities with latitude while the opposite behavior is shown by the oxygen abundance, which increases as one moves away from the streamer axis. The anticorrelation between densities and oxygen abundance has already been suggested by [1] and by [3], who derived abundances with a completely different technique than we adopted.

The average value of the oxygen abundance in the streamers' cores at $r/R\odot = 2.5$, for latitudes within $\pm 2°$ from the equator, is 1.28×10^8. Marocchi et al. [3] give $1.1 \times 10^8 \pm 0.2$ at 2.2 $R_\odot$. We point out that Marocchi et al. used a temperature of $1.58 \times 10^6 K$, while we have, at $r/R\odot = 2.5$, $T = 1.18 \times 10^6 K$. The two determinations appear to agree, within the error uncertainties, and seem to indicate that the abundance is constant with altitude, with no evidence for gravitational settling. The same conclusion seems to be consistent with the results we obtained at higher altitudes, at least within the streamer cores. Qualitatively, we may say that T_e should decrease slower than implied by the profile we chose, to yield a decrease of oxygen abundance with height. This, because the OVI emissivity is higher at lower temperatures, and a less steep decrease of temperature with height would require, in order to comply with the observed OVI line intensities, a lower oxygen abundance.

The average value of the oxygen abundance in the streamers lateral branches – latitudes $\geq 6°$ from the equator, is on the order of $2 \times 10^8 - 2.25 \times 10^8$, with an $\approx 70\%$ increase, with respect to the streamer core. A higher variation has been found by Raymond et al. [1], who give a factor 5 increase, at an altitude of $\approx 1.5R_\odot$, and Marocchi et al. [3], who find an increase slightly larger than a factor 2, from the streamer core to the legs, at an altitude of 2.2 $R_\odot$.

Abundances in the streamer of July 6, 1996, are slightly lower than abundances in the July 11, 1996

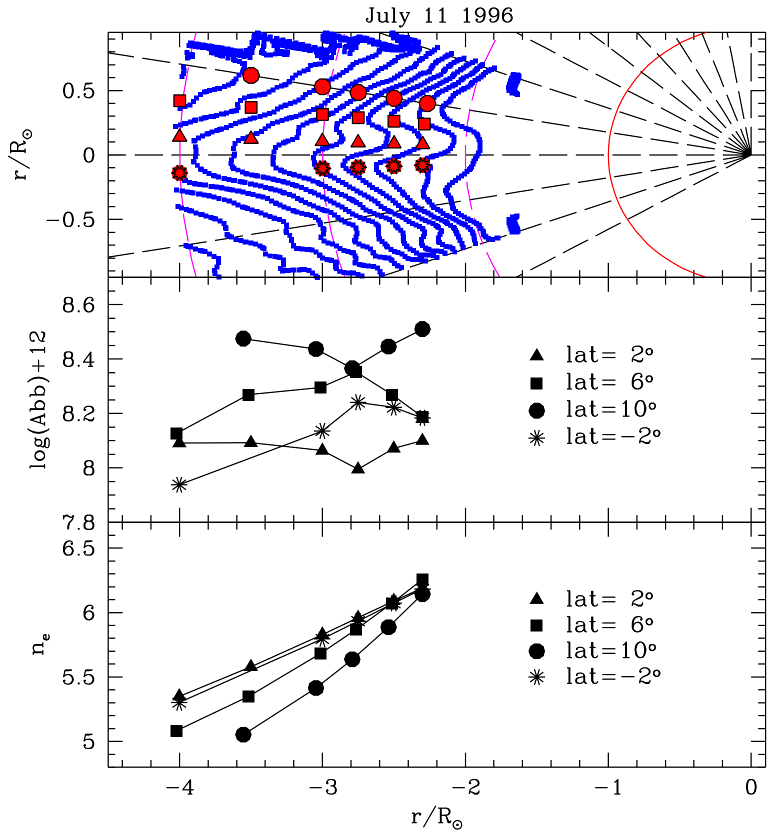

FIGURE 3. Same as Fig. 2 for the July 11, 1996 streamer. Top panel: isophotes of the OVI 1032 total line intensity vs. latitude and heliocentric distance. The lowest isophote corresponds to $logI_{ovi,1032} = 9.0$, the highest isophote corresponds to $logI_{ovi,1032} = 6.8$. Symbols drawn along different radials indicate the positions where the oxygen abundance has been evaluated. Middle panel: oxygen abundance at the positions given in the top panel. Bottom panel: densities at the positions given in the top panel.

streamer, although values are within the estimated uncertainties. Hence, there is apparently no difference, in this respect, between the two class of streamers although we stress once more that the two streamers do not unambiguously belong to different classes.

DISCUSSION AND CONCLUSIONS

A comparison of our with other studies support previous results indicating that streamers show an enhanced oxygen abundance in their lateral branches. On this basis, because the oxygen abundance in slow wind is higher than the oxygen abundance in the streamer core, Raymond et al. [1] suggested streamer legs as the site where slow wind originates. On the theoretical side, Ofman [11] recently showed, through a 2.5 D numerical MHD model, that the enhanced oxygen OVI emission in the legs of streamers may be caused by Coulomb friction with outflowing protons and thus may trace the source regions of slow wind.

From our results the difference between abundances in core and legs of streamers appears to decrease with altitude, as the abundance values seem to converge, along different radials, towards the same value. The core depletion is usually ascribed [1, 5] to gravitational settling: the core of the streamer, being made of closed loops, may constitute an ambient where oxygen ions, trapped for a long time, settle down. In the streamer legs plasma outflows may make this mechanism less efficient. In this case, we may surmise that, as we move to higher heights, we enter regions where loops tend to open up and, as a consequence, the difference between legs and core gradually disappears. We notice, however, that this scenario implies that the oxygen abundance at high levels is approximately the same as in the legs of the streamer, but there is no indication for such a behavior in our data.

Although we have examined only core data, at high levels, and hence we need first to extend our analysis to other positions within the streamer, we like to call the attention of the reader to a different issue. The results we, and other authors, obtained are based on the assumption of ionization equilibrium: an hypothesis which is fairly often adopted (even in recent coronal hole models) without being adequately tested. However, a comparison between the expansion time of the coronal plasma in our streamer with the OVI ion recombination time, shows that ionization equilibrium probably breaks below 2 solar radii. However, we point out that, independently of whether ionization equilibrium is tenable or not, the behavior across the streamer is obviously maintained, because it depends on the assumption of a constant electron temperature across the streamer, rather than on the absolute value of T_e. Only large variations in the plasma outflow speed within the streamer may affect the profile of abundances normal to the streamer's axis.

As a first, crude, attempt to guess how abundances would behave, in a non-equilibrium ambient medium, we re-calculated oxygen abundances assuming the electron temperature ($T_e = 1.18 \times 10^6 K$) at $r = 2.3\ R_\odot$, to be the freezing-in temperature of OVI ions. Results from such a calculation lead to a slight increase of the abundance of oxygen with height.

Whether oxygen is frozen-in in streamers, and at which level oxygen starts being frozen-in, has a potentially strong impact on the relationship between oxygen abundance in the slow wind and oxygen abundance in streamer legs. Marocchi et al. [3] pointed out that the slow wind is richer in oxygen than streamers, the difference being not significant possibly only if streamers abundances at 1.5 $R_\odot$ are considered. Our calculations show, although in a very approximate way, that non-equilibrium may act in the correct direction, that is, keeping up abundances at a value possibly consistent with that measured in slow wind.

The analysis presented in this paper is preliminary. The problems we plan to address for a better data analysis include a study of the ionization equilibrium in the streamer and an extension of the analysis to the whole structure of the streamer. This implies the evaluation of the plasma flow speed in streamers through a technique which is at present under development. A further check of the behavior of T_e in the streamer may be given by simulating the intensity of the H Ly_α and Ly_β lines and comparing them with the measured values. This is especially relevant for the problem of the variation of the electron temperature across the streamer. Although at low heliocentric altitudes the oxygen core depletion is too large to be attributed to a variation of the electron temperature across the streamer, at higher levels where possibly the depletion is lower, the issue deserves further studies.

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