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LETTER

Letter to the Editor

Outflow velocity of interplume regions at the base of Polar Coronal Holes

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Abstract. We report on SUMER/SOHO observations at 1.05 $\mathrm{R}_\odot$ of a well identified interplume region in a South Pole Coronal Hole. Combination of Doppler shifts and Doppler dimming measurements allowed to determine, for the first time, the total wind outflow velocity ($\approx 67\,\mathrm{km\,s^{-1}}$) at this height. Our calculations of the outflow velocity benefit from co-spatial and almost co-temporal observations. This large outflow velocity is a *strong* argument in favour of the *interplumes being the main source* of the fast solar wind. We find that the mass flux density through the observed interplume is $4.8\,10^{-10}\,\mathrm{g\,cm^{-2}s^{-1}}$ which yields $10^{-15}\,\mathrm{g\,cm^{-2}s^{-1}}$ at 1 AU with an expansion factor of 11.

Key words: Sun: corona – Sun: solar wind – Sun: UV radiation

1. Introduction

The fast solar wind originates from Coronal Holes (e.g., Krieger et al. 1973) and during periods of sunspot minimum it mainly originates from Polar Coronal Holes (PCH) (e.g., Woch et al. 1997). Coronal Holes are characterized by a large-scale open magnetic field configuration (e.g., Levine et al. 1977). Recent observations of Hassler et al. (1999) suggested the magnetic transition region network in PCH as the source region of the fast solar wind. From Doppler shift measurements they found enhanced outflows of the order of $10\,\mathrm{km\,s^{-1}}$ located at the network boundaries of the observed polar cap. However, observations of this kind actually reveal only a small component of the flow velocity (supposing radial flows), since the line of sight (LOS) forms large angles with the local normal near the poles.

The most prominent structures in PCH, when viewed off-limb, are the plumes (e.g., DeForest et al. 1995; Koutchmy & Bocchialini, 1998). They are bright threads which are presumably rooted in the network in places where small magnetic dipoles merge with the large-scale open magnetic field structures. It is not clear whether the fast solar wind streams out of the Sun from the plumes, the interplume regions or both, though there exists growing evidence favouring the interplumes. This includes (e.g., Wilhelm et al. 1998 and references herein), narrower spectral lines in the plumes than in the interplumes, a lack of significant line shifts in plumes compared to the interplumes, and an enrichment of high First Ionization Potential (FIP) elements (a factor 2–4) in plumes which is not the case for the interplumes (they have similar elemental abundances as solar wind streams observed *in-situ*).

It is clear that the determination of the total flow velocity instead of a single (and small) component for the interplume regions, is an additional and more solid 'test' to confirm that they are the genuine sources of the fast solar wind. Moreover, it is very important to determine the mass flux through interplume regions in order to compare it with data taken at 1 AU. Let us note that realistic solar wind models from the Sun to 1 AU definitely need realistic boundary conditions at the coronal base.

We present here observations of an interplume region in a PCH. They allowed the determination of the total solar wind outflow velocity and the associated mass flux. We also discuss the relevance of interplume regions to the fast solar wind as well as the network structure.

2. Observations

Our observations with the SUMER spectrometer on SOHO (Wilhelm et al. 1995), were made on 26-02-1998 from 19:21-19:46 UT with the center of the 0.3″x120″ entrance slit fixed on the Central Meridian, 970″ from the center of the disk inside the South PCH. In Fig. 1 we indicate the position of the SUMER slit on two images, one taken with the EIT telescope on SOHO (Delaboudinière et al. 1995) in the Fe IX/X channel and the other in White-Light (WL) during the 26-02-1998 total solar eclipse. We estimated the uncertainties of the SUMER pointing to be 1 ″ (from the well-known O VI limb-brightening) and 5 ″ (from SUMER pointing calibrations) in the solar y and x directions respectively. As shown in Fig. 1 where we overlayed the SUMER slit on two different images, our observations were made in an interplume region between two large polar plumes. This can be amply supported by taking into account the above pointing uncertainties and the fact that we estimate the width of this interplume region to be about 25 ″. The corresponding intensity contrast between plume and interplume can be seen both in the EUV emission (depending on the square of elec-

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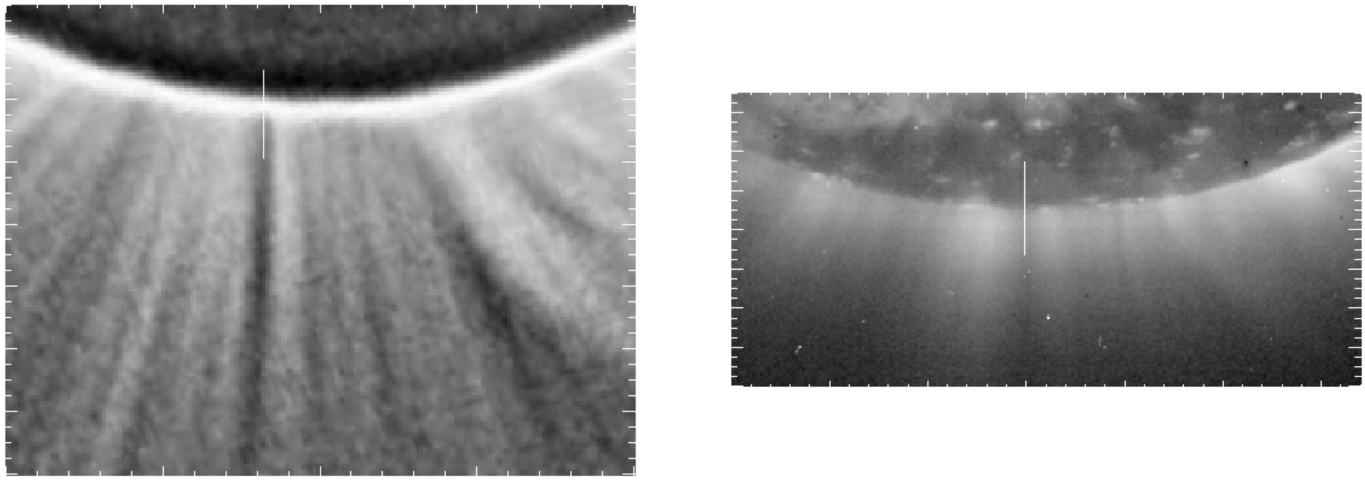

Fig. 1. Views of the South PCH, with the SUMER slit superimposed on the two images as a vertical line. Solar North is upward, solar East is leftward. Left panel: WL image taken around 18:33 UT the 26-02-1998 during 1998 total solar eclipse. Right panel: EIT Fe IX/X image taken around 21:00 UT the same day. No image manipulation was applied.

tron density $n_{\rm e}$ and the temperature $T_{\rm e}$) and in the WL emission (depending on $n_{\rm e}$).

Our dataset includes 16 readouts of the SUMER detector B with an exposure time of 95 s in the wavelength range 1020–1060 Å. The doublet of O VI lines at 1031 and 1037.2 Å and the C II line at 1037.02 Å lie within this spectral interval. We first applied the normal suite of corrections to the raw data (i.e. flat-fielding, destretching and intensity as well as wavelength calibration).

Preliminary results of the analysis (Patsourakos et al. 1999) can be summarized as follows. They refer to the average over the outer part of the slit corresponding to distances 50–60 ″ ($\approx$ 1.05 $\rm R_\odot$) above the photospheric limb position as well as to the average over the whole duration of our observations. We found for the O VI 1037.2 Å line an average Doppler velocity of about 7 km s^{-1} directed *away* from the observer and an average Full Width at Half Maximum ($FWHM$) of about 250 mÅ. The value of the integrated intensity ratio of the O VI lines at 1032 and 1037.2 Å was 2.54 ± 0.04. Finally, since the stray-light contribution was less than 9 % of the observed signal, it was neglected.

Inspection of EIT images the day of our observations and about 15 days before (for structures on the other side of the observed polar cap) showed that large-scale bright structures did not extend high enough in latitude to cause contamination of the LOS signal.

3. Determination of the radial velocity

The exploitation of the Doppler dimming effect (e.g., Withbroe & Kohl, 1982; Noci et al., 1987; Li et al. 1998) is one of the few consistent methods to infer the plasma bulk outflow radial velocity υ_r in the corona. For our case, we calculated the integrated intensity ratio ρ_{int} of the O VI lines at 1032 and 1037.2 Å as a function of υ_r, which has the advantage of being independent of the oxygen abundance and ionization. The O VI lines we used are formed in the corona by collisional excitation and by resonant scattering of disk photons. In the presence of a plasma outflow, the disk profile is redshifted with respect to the coronal absorption profile leading to a dimming of the resonantly scattered component (Doppler dimming effect). However, the radiative component of the 1037.2 Å line can increase by the pumping of C II line photons at 1037.02 Å for outflow velocities between 100–250 km s^{-1} (in this case the ratio is lowered). The intensity ratio (when Doppler pumping is not taken into account) yields values between 2 and 4, with the above two values corresponding to collisionally and radiatively dominated emission. The significantly larger than 2 value of the observed intensity ratio demonstrates that an important part of line emission resulted from resonant scattering.

We used the formalism given in Noci et al. (1987). To note here, that these authors did not apply their calculations to the very low altitudes of our observations. The intensity ratio was calculated at the point of minimum approach of the LOS with respect to the Sun ($1.05\,\rm R_\odot$), since the electron density $\rm n_e$ declines very fast with distance and moreover the major part of the line emission results from collisions with free electrons (with an n_e^2 dependence). For our calculations, we took into account the C II Doppler pumping of the 1037.2 Å line.

Since $\rho_{\rm int}$ (apart from $\upsilon_{\rm r}$) depends also on $T_{\rm e}$, $T_{\rm ion}$ (the oxygen ion temperature parallel to the flow direction), $n_{\rm e}$, and the profile of the exciting disk and lower corona radiation, we will constrain all of the above parameters from observations to finally express the intensity ratio as a function of the radial flow velocity only. These empirical constraints are given in Table 1.

The electron density that we used was obtained from polarization brightness eclipse observations corresponding to the observed region, made on 26-02-98 at 18:33 UT by Gabryl, Cugnon, & Clette (1998). For $T_{\rm e}$, we used the upper limit inferred by the failure to detect the Fe XI line at 7892 Å in observations on the same date and in the same region as ours (Wood et al. 1999). The $T_{\rm e}$ they deduced agrees well with interplume

Table 1. Empirical constraints used for the calculation of Doppler dimming (C II pumping included).

r	$1.05 R_\odot$
n_e	$1.8\,10^7$ cm^{-3}
T_e	$9.0\,10^5$ K
T_{ion}	0.9–1.8 10^6 K
I_{max} (O VI 1031.9 Å)	$2.7\,10^3$ erg cm^{-2}sr^{-1}s^{-1}Å^{-1}
I_{max} (O VI 1037.2 Å)	$1.68\,10^3$ erg cm^{-2}sr^{-1}s^{-1}Å^{-1}
I_{max} (C II 1037.02 Å)	$0.25\,10^3$ erg cm^{-2}sr^{-1}s^{-1}Å^{-1}
$FWHM$ (O VI 1031.9 Å)	233 mÅ
$FWHM$ (O VI 1037.6 Å)	208 mÅ
$FWHM$ (C II 1037.02 Å)	268 mÅ

temperatures ($\approx 8.1\,10^5$ K) derived from more elaborated diagnostics (Wilhelm et al. 1998). The determination of $T_{\rm ion}$ is more ambiguous since we have no direct means of measuring the temperature of the oxygen ions. As such, we considered two limits which bound the acceptable values of $T_{\rm ion}$. The first limit occurs when the oxygen ions are in thermal equilibrium with electrons. This is a lower limit, since there exists significant evidence from UVCS of ions being hotter ($\approx$ 100 times) than the electrons and the protons in the inner corona from distances of about 2.0 $R_\odot$ (e.g., Kohl et al. 1998). The upper limit is set by attributing the entire observed line $FWHM$ to the effective temperature of the oxygen ions. This is an upper limit because the observed line $FWHM$ not only results from the contribution of thermal motions but also from unresolved bulk motions (turbulence and waves) along the LOS. Finally, for the determination of the exciting profile we used time and space averaged profiles for each of the two O VI lines. The spatial average was carried out on the part of the slit lying on the disk and that corresponding to an approximately 4 arcsec-wide bright ring where the O VI line emission peaks off-limb. This ring corresponds to the heights where the LOS intersects the formation layers of the O VI line. The above averaged profiles represent the exciting radiation profiles since (a) at the observation point mainly regions very close to the limb contribute photons and (b) these source locations all lie within the Coronal Hole. We used our SUMER observations to derive the characteristics of the profile of the exciting C II (1037.02 Å) line in the same way as above. Hence, our calculation of ρ_{int} uses the above realistic physical parameters which are co-spatial and co-temporal (or almost co-temporal) with our observations.

Fig. 2 shows the variation of the ratio $\rho_{\rm int}$ as a function of v_r using the parameters of Table 1. The two Doppler dimming curves (one for each $T_{\rm ion}$ that we used) are quite close to each other, which renders less ambiguous the determination of the radial velocity. Note that for large outflow velocities the line ratio takes values lower than 2 due to the C II Doppler pumping. We found the average value of the outflow velocities for each of the two curves plotted in Fig. 2 to be $v_{\rm r} = 67^{+16}_{-14}$ km s^{-1}. The uncertainties arise from quadratically combining (1) the consideration of photon-counting statistics and the uncertainties of radiometric calibration into the intensity ratio determination

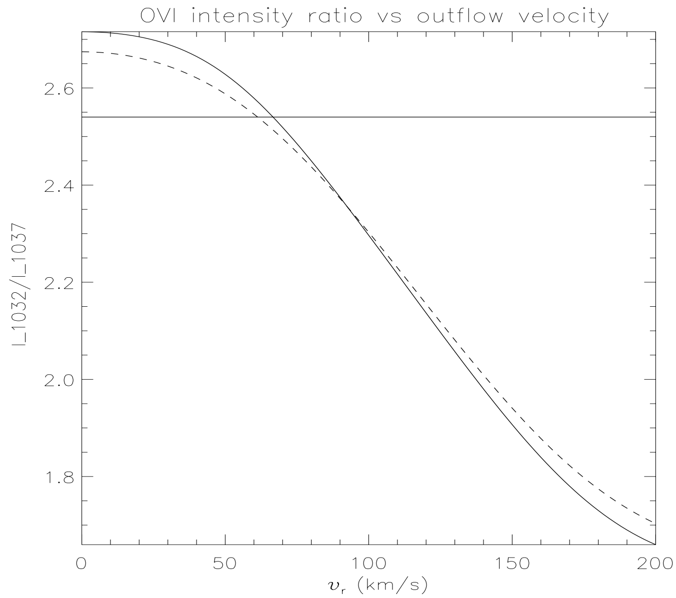

Fig. 2. Doppler dimming curves for the O VI doublet intensity ratio (C II pumping has been included). The continuous and dashed lines correspond to the minimum and the maximum $T_{\rm ion}$ of Table 1 respectively. The horizontal line represents the observed intensity ratio.

and (2) typical uncertainties of 10 % in each one of the physical parameters of Table 1 used for our calculations.

4. Discussion

Combination of the radial and the LOS velocity gives a value of about 67 km s^{-1} for the total outflow velocity. The above outflow velocity of the oxygen ions is also the outflow velocity of the solar wind bulk (e.g., protons) since they are very tightly coupled in the inner corona (e.g., Esser et al. 1999).

This is the first time, to our knowledge, that the full wind outflow velocity has been derived at the coronal base. The measured velocity is substantially larger than the bulk velocities in polar plumes estimated by Wilhelm et al. (1998). By using the measured LOS velocities and a typical inclination angle of polar plumes, these authors found that the plasma bulk velocity is not larger than about 18 km s^{-1}. We note here that, since we do not know the geometry of interplumes, in order to define their inclination angles similar estimations as above are not possible. Our result is consistent with the large oxygen ion outflow velocities of 115–175 km s^{-1} observed in interplume regions in the inner corona (1.7 $R_\odot$) by UVCS (Giordano et al. 2000). Moreover, the fact that plumes occupy a very small portion ($\approx 4\%$) of the total surface of the observed Coronal Hole (as estimated from EIT images) along with their small flow speeds and their not particularly large (a factor 2–4) electron densities with respect to the background corona, indicate that they are not significant global mass contributors to the ambient solar wind. Thus, the significant velocity that the outflowing plasma attains in interplumes, already at a heliocentric distance of 1.05 $R_\odot$ along with the smaller plume velocities and their small mass contribution provides *new and strong* evidence that interplumes are the major source of the fast solar wind.

The solar wind mass flux density for the observed interplume region is $4.8\,10^{-10}\,\mathrm{g\,cm^{-2}s^{-1}}$ (we assumed a plasma with 10 $\%$ helium) which compares well with the solar wind mass flux density tabulated by Withbroe $\&$ Noyes (1977) at coronal levels (2.0 $10^{-10}\,\mathrm{g\,cm^{-2}s^{-1}}$). The super-radial expansion factor of a flux tube linking the coronal base with the heliosphere at 1 AU is about 11. For its calculation we used the $n_e v_r$ measured by us at 1.05 $\mathrm{R_\odot}$ and by Goldstein et al. (1996) at 1 AU ($2.0\,10^8\,\mathrm{cm^{-2}s^{-1}}$) along with conservation of mass flux.

Since interplumes and the network seem to be the main sources of the fast solar wind when viewing off-limb and on the disk respectively, it is of interest to find out if they can fit within a common model. For this we calculated what fraction (ϕ) of the total solar surface produces solar wind with the $n_\mathrm{e} v_\mathrm{r}$ of the observed interplume to yield mass flux conservation at 1 AU. We found a ϕ of about 6.9 $\%$ of the total surface. We estimate from EIT images that PCH cover about 10 $\%$ of the solar surface. This means that 69 $\%$ of their surface - if it emits solar wind with the characteristics mentioned above - is sufficient to satisfy the solar wind mass flux conservation. This is in a good agreement with the Hassler et al. (1999) Ne VIII and Si II observations of the network-originating outflows, since the network occupies a comparable portion of PCH. From the above we can conclude that a solar wind outflow starting from the network and then continuing in the interplumes is a reasonable conceptual description.

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