CORONAL HOLE DIAGNOSTICS OUT TO 8 SOLAR RADIi

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ABSTRACT

Line width measurements (from SiVIII & OVI) and Nₑ estimates (from SiVIII and SiIX) based on SUMER and CDS observations are combined with LASCO and UVCS output to provide an overview of its variations with height above a polar coronal hole. From the combined dataset we find a radial dependence of the electron density, in the range 1 – 2 solar radii as r⁻⁴, from 2 to 4 solar radii as r⁻² and then as r⁻¹. Combining the SUMER OVI and SiVIII half width at 1/e of the peak intensity with the UVCS OVI half width, we find a small increase of the half width from 1 to 1.2 Rₛ, then a plateau until 1.3 Rₛ, followed by a small decrease to 1.5 Rₛ, thereafter a sharp increase until 2 Rₛ, finally a more gradual increase reaching 550 km s⁻¹ at 3.5 Rₛ. Our data suggests that the MHD waves responsible for the excess line broadening tends to become non-linear as it reaches 1.2 Rₛ. Our measured values of the half width at 1/e of the peak intensity is about 25% lower than that obtained with UVCS at 1.5 Rₛ.

Key words: coronal holes, line width, electron density.

1. INTRODUCTION

SKYLAB data have shown that the line width increases with height above the limb. These earlier observations were restricted to temperatures in or below the transition region and thus inferring details concerning coronal heating was not possible. With the launch of SOHO, and in particular the on-board SUMER and UVCS instruments, line width measurements of coronal lines as a function of position far above the limb can be obtained. The structure of the solar corona within holes at the base of the high-speed wind is still largely unknown. In order to construct proper models of the solar wind, one requires knowledge of the electron density and line width in this region as boundary conditions.

In this paper the widths of two lines from OVI and SiVIII as observed with SUMER are used to determine the thermal and turbulent speed associated with the solar coronal plasma. In addition, we used

<table>
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<th>Line</th>
<th>Date</th>
<th>Inst.</th>
<th>Exposure (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3 June '96</td>
<td>SUMER</td>
<td>16</td>
</tr>
<tr>
<td>O VI</td>
<td>3 June '96</td>
<td>SUMER</td>
<td>60</td>
</tr>
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<td>150</td>
</tr>
<tr>
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<td>4 Nov '96</td>
<td>SUMER</td>
<td>320</td>
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<td>10 Dec '96</td>
<td>SUMER</td>
<td>320</td>
</tr>
<tr>
<td>SiIX</td>
<td>17 Nov '96</td>
<td>CDS</td>
<td>120</td>
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line ratios from SiVIII and SiIX to determine the electron density over a similar distance off-limb.

2. OBSERVATIONS & DATA REDUCTION

2.1. SUMER

SUMER is a normal incidence spectrograph operating over the wavelength range ~500Å to 1600Å (Wilhelm et al. 1997). The off-axis parabola mirror is moveable in two dimensions around the focal point allowing pointing of the instrument independent of the spacecraft pointing. Four slits are available; 4″ x 300″, 1″ x 300″, 1″ x 120″ and 0.3″ x 120″. The telescope mirror can be scanned along two axes out to ±32 arc min from Sun center to provide point and raster images using one of the above slits.

The OVI observational sequence reported here consisted of three parts, the first part of the sequence extended onto the disk (towards low latitude) After each exposure, the slit was moved by 3 arcsec, accumulating an image covering an area of 300″ x 120″. In order to increase the S/N, we binned the data to a resolution of 6″ x 2″. The second and third part of the sequence was intended to obtain high signal to noise line profiles in the plume and inter plume regions above the limb out to 1.5 Rₛ. For both of these datasets, the 4″ x 300″ slit was used (see Table 1 for details). These had step sizes of 3.8 arcsec and 5.7 arcsec respectively, each producing a final image of 270″ x 300″. For the second dataset, we binned in groups of 15 pixels along the slit and in groups of 20 for the third dataset.

The two SiVIII datasets were taken a few months later using the 1″ x 300″ and 4″ x 300″ slits (see

The data reported were obtained above the south polar coronal hole on 21 November 1997 (Fludra et al. 1999a) using a 4'' × 240'' slit and a 120 second exposure to build a 2' × 4' raster. Twenty spectral bands in the normal incidence range were selected, three of which contained the lines of Si IX 342, 345 and 350 Å. The data were analysed as described in Fludra et al. (1999a,b) and discussed further by Doyle et al. (1999b). Briefly, the data were processed by removing cosmic ray strikes, and applying a standard intensity calibration. The spectra were then spatially averaged along concentric arcs at fixed heights above the limb in a position angle range of 10 degrees. Gaussian profiles were fitted to such averaged spectra to obtain a one-dimensional, radial dependence of line intensities. Statistical errors of intensities were determined by the fitting routine. The coronal hole area selected avoided any background or foreground emission other than polar plumes. Moreover, Fludra et al. (1999a) find that the electron density obtained from this dataset is the same as the electron density on four other days of coronal hole observations, spanning a period of seven months. Therefore, the CDS observation is representative of a typical coronal hole measurement.

3. RESULTS

For the SUMER data, we first approximate the line shapes (averaged over 10 to 20 pixels, depending on height above the limb) by Gaussian fits in order to determine the most probable speed along the line of sight. The instrument line width correction was then applied to obtain the Doppler width \( \Delta \lambda_D = \text{FWHM}/(2\sqrt{\ln 2}) \), where FWHM is the full width at half maximum of the line after instrumental effects have been taken out.

The measured line profiles will also depend on the instrumental characteristics, in particular the slit width. The magnitude of this correction is small, although it does result in a correction in the derived non-thermal velocity of \(~2.5 \text{ km s}^{-1}\) for the 4'' × 300'' slit. The most probable speed, \( v_{\perp e} \), is then calculated via \( \Delta \lambda_D = \lambda v_{\perp e}/c \). The line of sight speed \( (v_{\perp e}) \) distribution includes two distinct contributions, namely the thermal motions and the small scale unresolved turbulent motions. If the corresponding velocity distributions are both assumed to be Gaussian, we can superpose these distributions and simply add their variances such that,

\[
v_{\perp e}^2 = \frac{2k_BTeff}{M} = \frac{2k_BT_i}{M} + \xi^2
\]

where \( \xi \) is the non-thermal speed, related to the wave amplitude by \( \xi^2 = \frac{1}{2} \langle \delta v^2 \rangle \), where the factor of 2 accounts for the polarization and direction of propagation of a wave relative to the line of sight (for an Alfvén wave). \( T_i \) the ion temperature, and \( M \) the ion mass. One has to discriminate between the two terms on the right hand side of the equation in order to get a physical insight to the heating mechanisms in the corona.
Figure 2. Variation of most probable speed \( v_{1/e} \) and intensity with height in a north polar coronal hole along a polar plume (dashed line) and inter plume regions (solid line) for a region inside the limb. The diamonds represents inter-plume and the squares represents plume.

Figure 1 shows the contrast enhanced total line intensity of the O\( \text{vi} \) 1032Å line over a north polar coronal hole. One should note that we have not estimated the stray light contribution to the total line intensity as previously done by Hassler et al. (1997). Their assumption of no coronal contribution at 1.6 \( R_\odot \) to the O\( \text{vi} \) profile and also a Gaussian profile shape for stray light contribution seems unrealistic. Thus our estimates will provide an upper limit of the most probable speeds at coronal heights. An anti-correlation between the line intensity and the most probable speed is clearly evident as will be discussed further by Banerjee et al. (1999). The network structures, as visible on the disk, seem to continue as the plume regions outside the disk (see Fig. 1).

Warren et al. (1997) have shown in their scatter plot of non-thermal velocity versus intensity for the O\( \text{vi} \) 1038 Å line at disk center, that there is a tendency for brighter regions to have a higher average non-thermal velocity than faint regions. As we go off the limb, we find clear evidence of an anti-correlation between the intensity and \( v_{1/e} \). However, far off-limb, e.g. at 1.22 \( R_\odot \), the anti-correlation is rather weak. Also, at this height above the limb the plume structures have expanded slightly non-radially. This observed anti-correlation between intensity and width in polar plumes have been reported by Noci et al. (1997) with the UVOI instrument and also by Hassler et al. (1997) with SUMER.

As drawn in Fig. 1, we trace out a typical plume and inter plume (see Figs. 2 & 3), showing the variation of \( v_{1/e} \) (upper panel) and intensity (lower panel) with height for both inside and outside the limb. The solid line represents polar inter plume and the dashed line represents plume. One can clearly see an additional line width in the inter plume region which tends to disappear at 1.35 \( R_\odot \). Probably the plumes have expanded so much above these heights that it almost merges with the inter-plume regions.

These line width measurements can be combined with UVOI output to provide an overview of its variations with height out to 3.5 \( R_\odot \). Cramer et al. (1999) have presented a comprehensive and self consistent empirical model of several plasma parameters in the extended corona above a polar coronal hole. The model is derived from observations with UVOI. Their model calculations show that the velocities, which are valid between 1.5 and 3.5 \( R_\odot \), can be approximated by the best-fit function of the form,

\[
v_{1/e} = 74.3 + 200 \left[ 0.23 \left( \frac{R_\odot}{\varphi} \right)^{0.0337} + 4.69 \left( \frac{R_\odot}{\varphi} \right)^{2.36} + 1.58 \times 10^5 \left( \frac{R_\odot}{\varphi} \right)^{22.91} \right]^{-1}
\]

The first term on the right hand side is based on UVOI observations. This we feel is slightly over-estimated as our observations suggest the constant should be 55. The combined SUMER and UVOI results for the variation of \( v_{1/e} \) out to 3.5 \( R_\odot \) is shown in Fig. 4. The diamonds represents our observations with O\( \text{vi} \). The dashed line is the best fit to the observed results from O\( \text{vi} \) profiles of UVOI (Kohl et al. 1998). The solid line represents the polynomial equation (2) with the first term on the r.h.s as equal to 55 (based on our observation at 1.5 \( R_\odot \)). As an inset the Si\( \text{viii} \) results from Doyle et al. (1999a) have also been over-plotted (represented by triangles).

We now turn our attention to the electron density. In Fig. 3 we show the electron densities as derived from Si\( \text{viii} \) data (see Doyle et al. 1999a) compared to those derived from Si\( \text{ix} \) using SUMER data (Doyle et al., 1999b). As can be clearly seen there is excellent agreement, despite the fact that Si\( \text{viii} \) was observed in a northern coronal hole, while the Si\( \text{ix} \) data are from a southern coronal hole. This is consistent with
Figure 4. Variation of most probable speed $v_{1/4}$ with height in a north polar coronal hole. The diamonds represents results from O VI and the triangles from Si VIII (Doyle et al. 1999a). The dashed line is the best fit of the UVCS results and the solid line is the polynomial equation given by Eq. (2).

Figure 5. The electron density in a coronal hole as determined from Si VIII (diamonds) and Si IX (circles). The insert shows the electron density fall-off with $R_\odot$ from UVCS and LASCO data, the line fit is that obtained using Eq. (3) for $T_{eff} = 1.2 \times 10^6$ K. A similar line is obtained via the polynomial fit of Eq. (4).

the work of Fludra et al. (1999a,b) in their analysis of Si IX data, who showed that there was no noticeable time variability in the estimated $N_e$ as measured from several polar coronal holes over a 7 month period.

Doyle et al. (1999a) have coupled the electron density as obtained from the Si VIII SUMER data with measurements obtained from LASCO (Lamy et al. 1997) and UVCS (Kohl et al. 1998). The solid line fit given in Fig. 5 (see inset) is that resulting from the analytic prescription of the density profile from

\[ N(r) = \exp \left[ \frac{\mu m_p g_0 R_\odot}{k_B T_{eff}} \left( 1 - \frac{R_\odot}{r} \right) \right] \]  

where $N$ is the number density ($= N_e + N_p$), $\mu$ is mean atomic weight (= 0.62), $m_p$ is the proton mass, $k_B$ is the Boltzmann constant, $g_0$ is the solar gravity and the effective temperature $T_{eff} = (T_e + T_p)/2$, where $T_e$ and $T_p$ are the electron and proton temperature, respectively. The line fit as a function of $(1 - R_\odot/r)$ was for $T_{eff} = 1.2 \times 10^6$ K. This formula predicts an electron density of $4.5 \times 10^3$ cm$^{-3}$ at $8R_\odot$ in excellent agreement with observations. Although, as noted by Doyle et al., a polynomial fit where $N_e$ has a radial dependence in the range 1–2 $R_\odot$ as $r^{-8}$ from 2 to 4 $R_\odot$ as $r^{-4}$ and then as $r^{-2}$ further out also provides an excellent fit, i.e.

\[ N_e = \frac{1 \times 10^8}{r^8} + \frac{2.5 \times 10^3}{r^4} + \frac{2.9 \times 10^5}{r^2} \]  

The above estimate for $T_{eff}$ is lower than that given by Fludra et al. (1999a), who based their fit on only the CDS data close to the limb. The error on the derived temperature is very small; for example, if we adopted $T_{eff} = 1.3 \times 10^6$ K, the predicted density at $8R_\odot$ would be a factor of two larger than the observed value. Such a small value for $T_{eff}$ implies that the proton temperature is $T_p = 1.4 \times 10^6$ K compared to the electron temperature of $T_e = 1.1 \times 10^6$ K close to the limb. Further out, this may not be the case. David et al. (1998) have used two O VI lines and deduced $T_e = 10^6$ K peaking at $1.5R_\odot$ and decreasing to $T_e \sim 7 - 8 \times 10^5$ K at $1.3R_\odot$. This would imply proton temperatures a factor of two higher than the electron temperature, i.e. $T_p = 1.6 \times 10^6$ K. In our line ratio calculations we assumed $T_e = T_p$, but adopting the above proton temperature of $1.6 \times 10^6$ K and $T_e = 8 \times 10^5$ K only leads to a 7% increase in the theoretical ratio, well within the estimated uncertainties in the line ratio calculations of about 10–15%.

4. Discussion

SUMER line shape observations of O VI have been published by Wilhelm et al. (1998) and Hassler et al. (1997). We reconfirm their main result that the line profiles are slightly wider in inter-plume lanes than in plumes. The effect is significant in determining the structure of these two regions and the possible role of magnetohydrodynamic waves in heating and accelerating of the solar wind.

The anti-correlation between the intensity and velocity could be attributed to a lower ion temperature of the plumes as compared to the inter-plume lanes. The relation of ion temperature off-limb is unclear, several studies have shown that the assumption of collisionless ionization equilibrium and the common notion that $T_e = T_i$ in the coronal hole plasma can not be made any more (Wilhelm et al 1998; Doyle et al. 1999a). Most recent results from UVCS (Cranmer
et al. 1999) also shows that the electrons are much cooler than the ions. But the electron temperature estimates does not provide us the definitive clue on the ion temperature estimates. A closer inspection of the inset of Figure 4 reveals that $v_{1/s}$ for OVI is higher than Si VIII up to $\sim 1.3 R_\odot$. Since the turbulent line broadening should be the same for different ions, the difference at a particular height should be due to thermal contribution. Thus we reconfirm the inference of Tu et al. (1998), that the ion thermal speed decreases with increasing mass per charge.

The other (and perhaps more likely) possibility is that the non-thermal component of Equation (1) is responsible for the anti-correlation. If the thermal contribution in the plume and inter-plume lanes proves the existence of additional waves or turbulence. recent studies (Koutchmy et al. 1997; Wilhelm et al. 1998; Wang et al. 1997) have suggested that the source of the fast solar wind lies in the low density inter-plume lanes and not in the plumes. Our excess broadening and anti-correlation of intensity and velocity can be explained in the terms of the presence of Alfvén waves in the inter-plume lanes, which are believed to be the acceleration site of the fast solar wind.

From the combined $N_e$ dataset we find a radial dependence of the electron density, in the range 1–2 $R_\odot$ as $r^{-4}$, from 2 to 4 $R_\odot$ as $r^{-3}$ and then as $r^{-2}$. Combining the Si VIII half width at 1/e of the peak intensity with the UVCS O VI half width, we find a small increase of the half width from 1 to 1.2 $R_\odot$, then a plateau until 1.3 $R_\odot$, followed by a slight decrease to 1.5 $R_\odot$, thereafter a sharp increase until 2 $R_\odot$, followed by a more gradual increase reaching 550 km s$^{-1}$ at 3.5 $R_\odot$. Our data suggests that the MHD waves responsible for the excess line broadening tends to become non-linear as it reaches 1.2 $R_\odot$.

Note from Fig. 4 the relatively sharp variations occur around 1.5 $R_\odot$. This may be the location where the thermalization and the isotropization times of various species begins to exceed the local coronal expansion time. Esser et al. (1999) from a study of Mg x and O VI lines (observed with UVCS) found a transition from collisional to collisionless plasma between 1.75 to 2.1 $R_\odot$ in a polar coronal hole. Cramer et al. (1999) have presented an empirical model of H I and O VI distributions, which also indicates the presence of this transition. In their model they found a sharp variation between 1.8 $R_\odot$ - 2.1 $R_\odot$. It is also interesting to note that the electron density variation at 2 $R_\odot$ has changed to $r^{-3}$ from its earlier $r^{-4}$ fall-off. For line width measurements, UVCS data are not available below 1.5 $R_\odot$, so we feel that the combined SUMER and UVCS datasets allows us to locate this transition point with better precision suggesting that the physics of the plasma transport and wave dissipation diverges from classical Coulomb theory at heights beyond 1.5 $R_\odot$. At larger distances, e.g. above 2 $R_\odot$, the large $v_{1/s}$ can also be due in part to the ion-cyclotron resonant acceleration by high frequency MHD waves (McKenzie et al. 1995). We hope that our results will provide more precise input parameters at the base of the coronal hole for future solar wind models.

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