PLUME AND INTERPLUME REGIONS AND SOLAR WIND ACCELERATION IN POLAR CORONAL HOLES BETWEEN 1.5 AND 3.5 R\_S

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ABSTRACT

The first observations of polar coronal hole regions obtained with the Ultraviolet Coronagraph Spectrometer (UVCS) on SOHO in the O \textsc{vi} 1032 line have revealed differences in the physical characteristics of plumes and interplume regions (Antonucci et al. 1997, Noci et al. 1997). In particular O \textsc{vi} line profiles were found to be narrower within plumes than in the interplume regions and the difference in line width was observed to increase with distance from Sun center. Furthermore line broadening was increasing with distance from Sun center. In this paper we present an analysis of both the O \textsc{vi} 1032 and H I Ly \alpha 1216 line profiles, and the O \textsc{vi} 1032, 1037 doublet intensity ratio obtained during two observations at the North pole: the April 6–9, 1996 observation and the first run of the SOHO Joint Observing Program JOP2, performed on May 21, 1996 with the aim of determining the temperature structure and outflow velocity in polar regions. The analysis has confirmed that the O \textsc{vi} line width is enhanced in interplume regions, and increases with altitude both in plume and interplume regions. Furthermore, we find that also the H I Ly \alpha profiles are wider in the interplume regions. From the O \textsc{vi} doublet intensity ratio we infer that during the minimum of the solar cycle the acceleration of the solar wind in polar regions, that is, in polar coronal holes, is such that the outflow velocity of the coronal plasma reaches approximately 300 km s\(^{-1}\) at 3.5 R\(_{\odot}\).

Key words: solar physics; SOHO; coronal holes; plumes.

1. INTRODUCTION

The Ultraviolet Coronagraph Spectrometer (UVCS) onboard SOHO is the first instrument capable of detecting UV images and UV spectra of the extended solar corona within 1.5 and 12 solar radii (R\(_{\odot}\)). The UVCS measures profiles and intensities of the H I Ly \alpha (1216 Å), the O \textsc{vi} doublet (1032, 1037 Å) and several minor lines (Kohl et al. 1995, Gardner et al. 1996). The most intense coronal ultraviolet emission is the H I Ly \alpha line, emitted predominantly by resonance scattering of the chromospheric radiation by the few neutral hydrogen atoms remaining in the extended corona (Gabriel et al. 1971). The O \textsc{vi} lines are emitted both by collisional excitation and resonant scattering. Resonant scattering becomes predominant in the extended corona. Profiles and intensities of the resonantly scattered UV lines allow a measure of both the velocity distribution along the line-of-sight (l.o.s.) of the neutral hydrogen atoms and the oxygen ions, and the radial outflow velocities of the solar wind by means of Doppler dimming (Beckers & Chipman 1974, Noci et al. 1987).

Figure 1. Image of plumes in the coronal hole at the North pole in the O\textsc{vi} 1032 Å line intensity, observed on April 6-9, 1996.
2. POLAR CORONAL HOLE OBSERVATIONS

In this paper we present preliminary results concerning polar coronal hole observations.

In the first detailed observation of the coronal region above the North pole of the Sun performed with UVCS, the polar hole was scanned for 72 hours during the period April 6–9, 1996 from 1.45 to 2.48 Rs. The UVCS instantaneous field of view of the O VI channel (14' x 30') was centered on the North pole. The width of the spectrometer slit was selected equal to 50 μm (14'). The detector pixel binning along the direction parallel to the UVCS slit was selected to be 2 in order to maintain high spatial resolution (14'). For each spatial element (14' x 14'), profiles of the O VI 1032 Å and 1037 Å lines were observed with high spectral resolution (0.20 Å). The H I Ly α line analyzed in this study is that observed in the O VI channel with spectral resolution 0.18 Å. The polar region was scanned by moving the mirror by steps equal to the slit width (14'), so that no interpolation was needed to reconstruct the image of the polar coronal region.

The second long-term observation of the coronal region above the North pole was performed during the first run of JOP2 on May 21, 1996. In this case the polar region was scanned from 1.5 to 3.5 Rs, by moving the mirror with a variable step and positioning it at 11 different altitudes. The image of the polar region was reconstructed by interpolation. The width of the spectrometer slit of the O VI channel was selected equal to 300 μm (84'). To obtain an improved statistics but reduced spectral resolution (1.1 Å spectral pixel), the spatial resolution along the instantaneous field of view of (84' x 40'), that is along the slit, is 28'. Therefore this observation is best suited to study the intensity ratio of the O VI doublet. High spectral resolution is retained in the UVCS Ly α channel, used to study the profiles of H I Ly α line. In this channel a spectral resolution of 0.28 Å is obtained with a slit width equal to 50 μm (14'). The spatial resolution along the slit is the same as in the O VI channel (28').

Images of the North polar coronal hole, constructed by computing the total intensity of the O VI 1032 Å line, are given in Figure 1 and Figure 2. Both images show that the coronal plasma in polar holes is far from uniform even in the extended corona above 1.5 Rs, and plumes can be clearly identified at least up to 2 Rs. In the analysis of April 6–9, 1996 observation (see Figure 1) groups of data obtained at nearby mirror positions have been combined to improve statistics.

3. LINE-OF-SIGHT VELOCITY IN POLAR PLUMES AND INTERPLUME REGIONS

From the analysis of the H I Ly α and O VI 1032 line profiles, obtained with a spectral resolution of 0.18 Å (H I Ly α) and 0.20 Å (O VI) during the April 6–9, 1996 observation, the root mean square value of the velocity distribution along the l.o.s. of the neutral hydrogen atoms and the oxygen ions is derived according to the formula:

\[ v_{\text{r.m.s.}} = \frac{c}{\lambda_o} \sigma. \] (1)

where \( \sigma \) is the standard deviation of the gaussian curve which best fits the line profile and \( \lambda_o \) the wavelength of the spectral line. Line profiles are first corrected for instrumental effects and then fitted with a single gaussian curve. The observed l.o.s. velocity distribution is due to different kinds of motion: thermal motions and bulk motions of different origin (wave motion, turbulence, etc.), which cannot be separated when considering line profiles of a single ion.

A comparison of line emission and r.m.s. velocity in the polar region shows very clearly that the velocity is systematically reduced where emission is enhanced, as shown by a comparison of the O VI intensity map (Figure 1) and that of the r.m.s. velocity of the oxygen ions along the line-of-sight (Figure 3). That is the spread of the velocity distribution is larger in the interplume regions where the intensity is reduced. This is well described in Figure 4, where the intensity of the O VI line (continuous line) is compared with the velocity of the oxygen ions (points with error bars). Outside the central region where plumes are more evident, the velocity increases to 140 km s\(^{-1}\), effect which is partially due to an increase in altitude when approaching the edges of the slit. In the interplume regions velocities are about 10 km s\(^{-1}\) larger than in plumes. Minimum velocities of 100
km s$^{-1}$ are found in the brightest plume at polar angle $-10^\circ$ (counterclockwise, with origin at the North pole), at 1.5 R$_{\odot}$. A study of the O VI line width versus distance from Sun center shows that the r.m.s. velocity increases with altitude. For instance, the interplume velocity increases from about 80 km s$^{-1}$ at 1.5 R$_{\odot}$ to 180 km s$^{-1}$ at 2.0 R$_{\odot}$, confirming the analysis of Antonucci et al. 1997 performed on data corrected by using preliminary calibration. It is also confirmed that the plume/interplume velocity difference increases with distance from Sun center.

We have searched for the modulation of the line-of-sight velocity distribution in the polar region, evident for the O VI data, in the H I Ly $\alpha$ line profiles. Although the effect is reduced, also H I Ly $\alpha$ line profiles are modulated as shown in Figure 5, where line intensity (continuous line) is compared with the velocity of the neutral hydrogen atoms (point with error bars). The modulation can be traced at least up to 1.9–2 R$_{\odot}$. Plume/interplume velocity differences in this case are of about 5 km s$^{-1}$ and the large increase outside the plume region observed for the O VI ions is not noticed. In the H I Ly $\alpha$ line width the thermal contribution is expected to be large due to the small mass of the emitting atom.

4. OUTFLOW VELOCITY IN A POLAR CORONAL HOLE

The ratio of the intensities of the O VI 1037 and O VI 1032 lines is a function of the outflow velocity of the coronal plasma, because of Doppler dimming of the resonantly scattered radiation (Noci et al. 1987). When the outflow velocity exceeds 100 km s$^{-1}$, the ratio of the O VI 1037 to the O VI 1032 intensity exceeds the value 0.5, because of the pumping effect of C II 1037.0 Å which is efficient for solar wind velocities between 100 and 250–300 km s$^{-1}$. A ratio below 0.5 implies either stationary conditions or plasma moving at velocities below 100 km s$^{-1}$.

We do not observe in the May 21, 1996 data significant variations of the value of the O VI doublet intensity ratio in plumes and interplume regions, as found for the l.o.s. velocity. The ratio instead is changing dramatically with distance from Sun center as shown in Figure 6.

The O VI lines intensity ratio exceeds the 0.5 value at about 1.9 R$_{\odot}$. That is, along the open field lines of the polar coronal hole the acceleration of solar wind to velocities above 100 km s$^{-1}$ occurs within the first 2 R$_{\odot}$. This is consistent with the result deduced from the observations on April 6–9, 1996, which reached an altitude of only 2.4 R$_{\odot}$. In the observations on May 21, 1996, which extends farther out in the corona, we can follow the ratio of the O VI lines well beyond the 0.5 point. The ratio continues to increase to a
5. CONCLUSIONS

The observations of the coronal hole at the North pole performed on April 1996 and during JOP2 on May 21, 1996 show that the coronal hole plasma is characterized by large random velocity of the oxygen ions along the line-of-sight. In addition velocities are enhanced in the interplumes regions. These observations are also confirming that line-of-sight r.m.s velocities are increasing with distance from Sun center in agreement with the results of Antonucci et al. 1997 (this issue). These effects, although much reduced, are also observed for the neutral hydrogen atoms. The O VI ratio diagnostics indicates that in polar coronal holes the outflow velocity, that is the solar wind velocity, is progressively increasing with distance from Sun center; it exceeds 100 km s$^{-1}$ near 2 R$_\odot$, reaches 170 km s$^{-1}$ at 2.4 R$_\odot$, approximately and 250–300 km s$^{-1}$ at 3.5 R$_\odot$.

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