SOLAR WIND ACCELERATION IN THE SOLAR CORONA

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ABSTRACT

The ratio of O VI 1037/1032 lines observed with the Ultraviolet Coronagraph Spectrometer (UVCS) onboard SOHO can be used as a diagnostics to determine the solar wind outflow velocity in the extended corona. A study of the O VI ratio measured in the solar corona between 1.5 and 3.8 $R_\odot$, performed on the basis of observations obtained during the period August 19–September 1, 1996, shows that solar wind acceleration is much more rapid at the poles than in the mid-latitude and equatorial regions. At the poles the level corresponding to a velocity of about 100 km s^{-1} (line ratio 0.5) is reached at approximately 2.0 $R_\odot$. At lower latitudes the 100 km s^{-1} level is approximately tracing the separation between polar coronal holes, where the high-speed solar wind is expected to originate and flow, and the streamer belt. The 100 km s^{-1} level is running along the streamer borders; the acceleration of the solar wind is also high in regions between streamers. In the central part of streamers, the outflow velocity of the coronal plasma remains below 100 km s^{-1} at least within 3.8 $R_\odot$. The regions at the North and South poles, characterized by a more rapid acceleration of the solar wind, also correspond to regions where the UVCS observes enhanced O VI line broadenings, that is, an increase in the width of the line-of-sight velocity distribution, which is probably related to the mechanism of the solar wind acceleration.

Key words: solar physics; SOHO; solar wind.

1. OBSERVATIONS

In this paper we present an analysis of the intensity ratio of the O VI doublet (1032 Å, 1037 Å) in the extended corona. The O VI intensity data have been obtained with the Ultraviolet Coronagraph Spectrometer (UVCS) on SOHO in 12 days in the period from August 19 to September 1, 1996, during the SOHO campaign "Whole Sun Month". For the polar coronal data we also used the long-term observation above the North pole of the Sun performed during the first run of the SOHO Joint Observing Program JOP2 on May 21, 1996.

The capabilities and performance of the UVCS instrument are described by Kohl et al. 1995 and Kohl et al. 1997. In the observations performed during the Whole Sun Month the UVCS instantaneous field of view was selected to be 14" x 40'. For each spatial element along the instantaneous field of view, of 14" x 56" in the O VI channel, a high-resolution UV spectrum of the O VI 1032 and O VI 1037 lines was obtained. The spectral resolution used was 0.18 Å corresponding to a slit width of 14". Figure 1 shows an example of the spectral data obtained in the O VI channel by positioning the instantaneous field of view at 1.5 $R_\odot$ on an equatorial streamer observed on August 20, 1996.

Images at a given polar angle were build up by scanning the extended corona from 1.5 to 3.8 $R_\odot$, in steps of 0.1 $R_\odot$ up to 2.2 $R_\odot$, 0.2 $R_\odot$ up to 2.9 $R_\odot$; the last two steps to reach 3.8 $R_\odot$ were larger (0.4 and 0.5 $R_\odot$). Polar regions were scanned in a slightly different manner to account for a more rapid intensity decrease. A global map was obtained by combining the 12 individual scans obtained by rolling the instrument in steps of 30°. The scan position angles, considered counterclockwise with origin at the North pole, were chosen to be: 15°, 45°, 75°, 105°, 135°, 165°, 195°, 225°, 255°, 285°, 315°, 345°. At a given position angle a complete observation from 1.5 to 3.8 $R_\odot$ was performed in approximately 10 hours to obtain high statistics. The O VI 1032 map of the full corona is given in Figure 2. The quantity plotted in the false color images is the total intensity of the line integrated over wavelength and averaged over each spatial element (14" x 56"). Brighter regions correspond to regions characterized by higher line intensity. Continuity in the maps is obtained by interpolating between instantaneous field of views. The East limb is characterized by two mid-latitude streamers and the West limb by one streamer with a large latitudinal extent.

In the observation of the coronal region above the North pole performed during the JOP2 the polar region was scanned from 1.5 to 3.5 $R_\odot$, by moving the mirror with a variable step and positioning it at 11 different altitudes. In this case the width of the spectrometer slit of the O VI channel was selected equal

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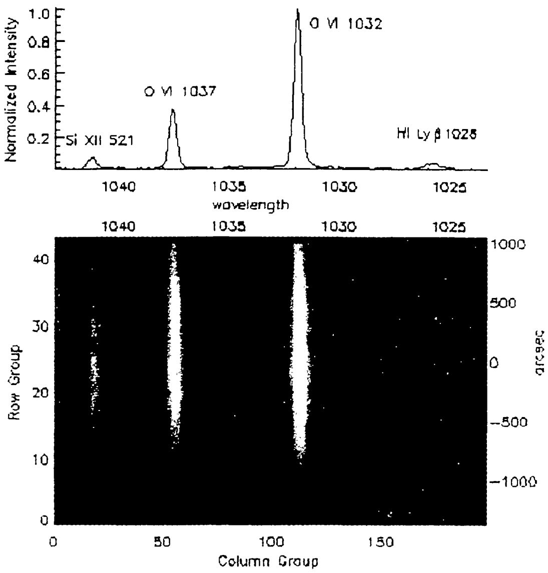

Figure 1. Example of the spectral data obtained in the O VI channel with the instantaneous field of view positioned at 1.5 $R_\odot$ and at position angle 105° (counterclockwise from the North pole), on an equatorial streamer observed on August 20, 1996. The plot shows the spectral line profiles integrated along the slit. The bottom image shows the variation of the line spectrum along the slit (the axis of ordinates indicates the position along the slit, that is along the direction parallel to the tangential to the limb and the abscissae indicate wavelength).

to 300 μm (84"), to obtain an improved statistics at the expenses of a reduction in spectral resolution (1.1 Å). The spatial resolution along the instantaneous field of view (84" x 40'), that is along the slit, is 28". Therefore this observation is optimized for the study of the line intensities ratio, at the expenses of spectral resolution.

2. OVI DOUBLET RATIO DIAGNOSTICS

The ratio of the intensities of the O VI 1037 and O VI 1032 lines can be used as a diagnostic technique to determine the radial velocity of the coronal plasma, that is, the solar wind velocity in the extended corona (Noci et al. 1987). Due to the nearby presence of the C II 1037.0 line, the intensity of the O VI 1037.6 transition region photons resonantly scattered by the coronal ions is affected by Doppler dimming quite differently than the O VI 1032 intensity, when the coronal plasma outflow velocity is above 100 km s^{-1}. The pumping of O VI 1037.6 by C II is efficient for solar wind velocities between 100 and 250–300 km s^{-1}. This diagnostics allows us to set constraints for solar wind velocities. A ratio below 0.5 implies either stationary conditions or plasma moving at velocities below 100 km s^{-1}, the value 0.5 of the ratio indicates that the outflow velocity reaches a value close to 100 km s^{-1}. The curves of the emissivity ratio for the OVI 1037, 1032 studied by Noci et al. 1987 show that a value of about 100 km s^{-1} for the outflow velocity can be determined in good approximation independently of other physical parameters.

3. SOLAR WIND OUTFLOW VELOCITIES

The image in Figure 3 is a map of the O VI 1037/1032 ratio. A continuous line, corresponding to the altitude of the 0.5–ratio point, separates regions where the outward velocity of the coronal plasma is less than 100 km s^{-1} (green regions) from those with velocities above 100 km s^{-1} (orange regions). As expected solar wind acceleration is much more rapid at the poles than in the mid–latitude equatorial regions. In polar regions the acceleration of the solar wind to about 100 km s^{-1} occurs over a distance of 1 $R_\odot$. Along the open field lines running close to the borders of streamers the 100 km s^{-1} point is reached farther out in the corona. Between mid–latitude and equatorial streamers the outflow velocity also increases indicating the existence, as in the polar regions, of open field lines where solar wind acceleration is more effective. The 100 km s^{-1} line which outlines, except near the poles, the borders of polar coronal holes, well describes the divergence of the open magnetic field lines over the poles.

A quantitative evaluation of the acceleration of the solar wind in different regions is given in Table 1, where position angle are considered counterclockwise with origin at the North pole.

Table 1. Altitude of 100 km s^{-1} Point.

Position Angle (degrees)	100 km s^{-1} Point $R_\odot$
0°	2.0
45°	2.8
90°	3.5
135°	2.0
180°	2.0
225°	2.5
270°	$>$ 3.8
315°	1.9

Comparing this analysis with a study of line broadening performed for the same set of data (Antonucci et al. 1997), we can see that the orange regions at the North and South poles, where solar wind accelerates more rapidly, correspond very closely to the regions where OVI line broadenings are enhanced. The green region of stationary or low velocity plasma instead corresponds to the central elongated region, including mid–latitude and equatorial streamers, where line broadening is minimum. We suggest that the 100 km s^{-1} line, which outlines the separation between coronal holes and streamers also corresponds to the transition between narrow and wide lines. The correlation between regions where higher acceleration of the solar wind occurs and regions characterized by O VI spectral lines with enhanced broadening is a

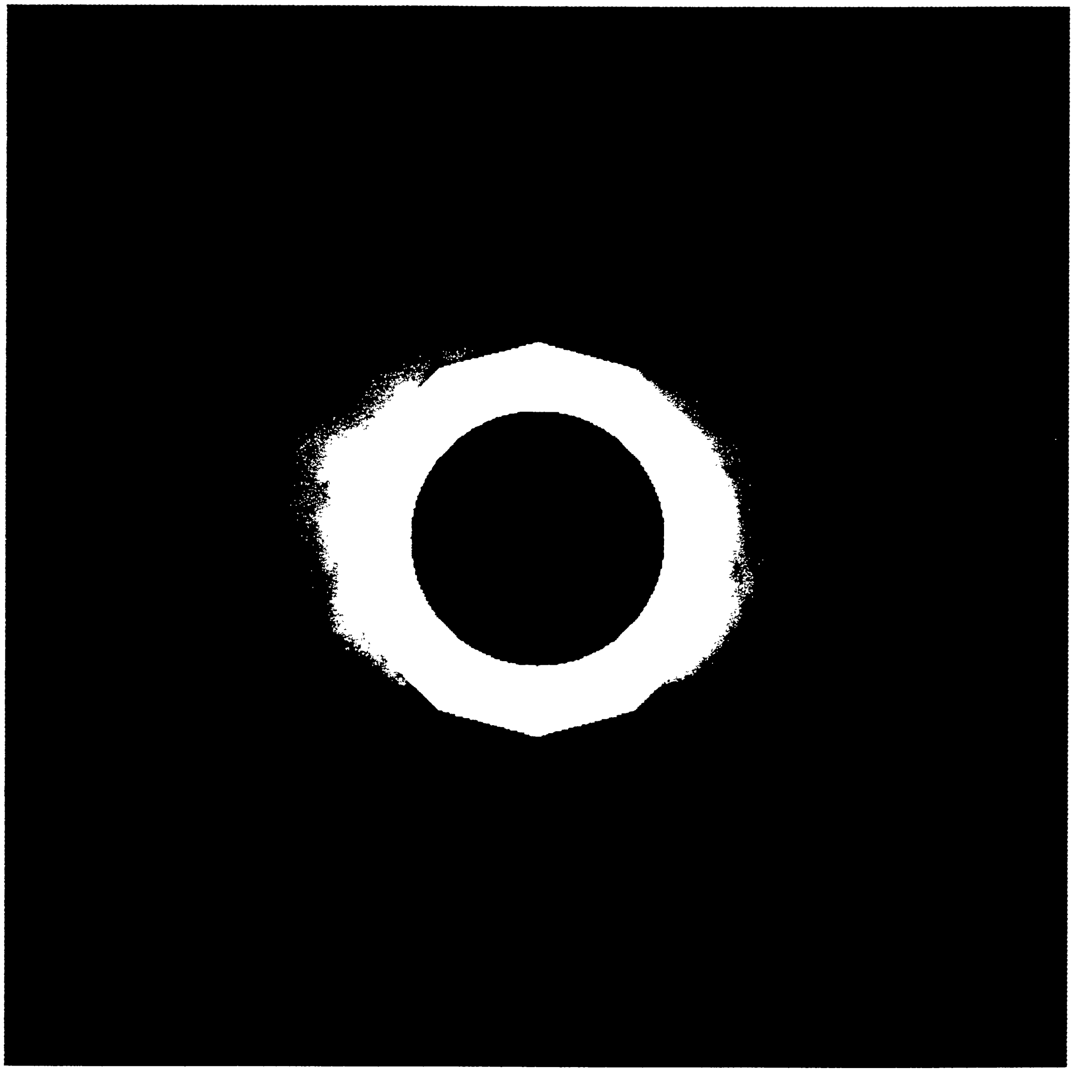

Figure 2. O VI 1032 intensity map of the full corona obtained in the period August 19–September 1, 1996. The UV corona is imaged between 1.5 and 3.8 $R_\odot$. The quantity plotted in the false color image is the total intensity of the line integrated over wavelength.

clear indication that the acceleration process is related to the width of the velocity distributions along the line of sight.

The general behaviour of the O VI ratio in the polar coronal regions is consistent with the result deduced from the observations obtained on May 21, 1996, which have higher statistics. In this case we can determine the ratio of the O VI doublet well beyond the 0.5 point. This ratio continues to increase to a peak value, reached at about 2.4 $R_\odot$ and then it decreases again to 0.5 approaching 3.5 $R_\odot$, (Giordano et al. 1997). The peak at approximately 2.4 $R_\odot$ is indicative of velocities of about 170 km s^{-1} and the subsequent decrease of this ratio indicates a decreased efficiency of the C II line pumping which becomes negligible for an outflow velocity of 250–300 km s^{-1}. Therefore we conclude that the outflow velocity of the solar wind approaches 300 km s^{-1} over a distance of about 2.5 $R_\odot$, that is the average acceleration of the solar wind in the polar coronal hole from the limb out to 3.5 $R_\odot$ is about 0.026 km s^{-2}. If we consider that the level of 100 km s^{-1} is reached over a distance of 1 $R_\odot$ above the limb, it turns out that the average initial acceleration is 0.007 km s^{-2}. That is acceleration is rapidly increasing with altitude over the pole within the first 2.5 $R_\odot$ above the limb.

4. CONCLUSIONS

The analysis of the O VI 1037/1032 intensity ratio, based on the observations of the full corona performed during the Whole Sun Month campaign, from August 19 to September 1, 1996, shows that open

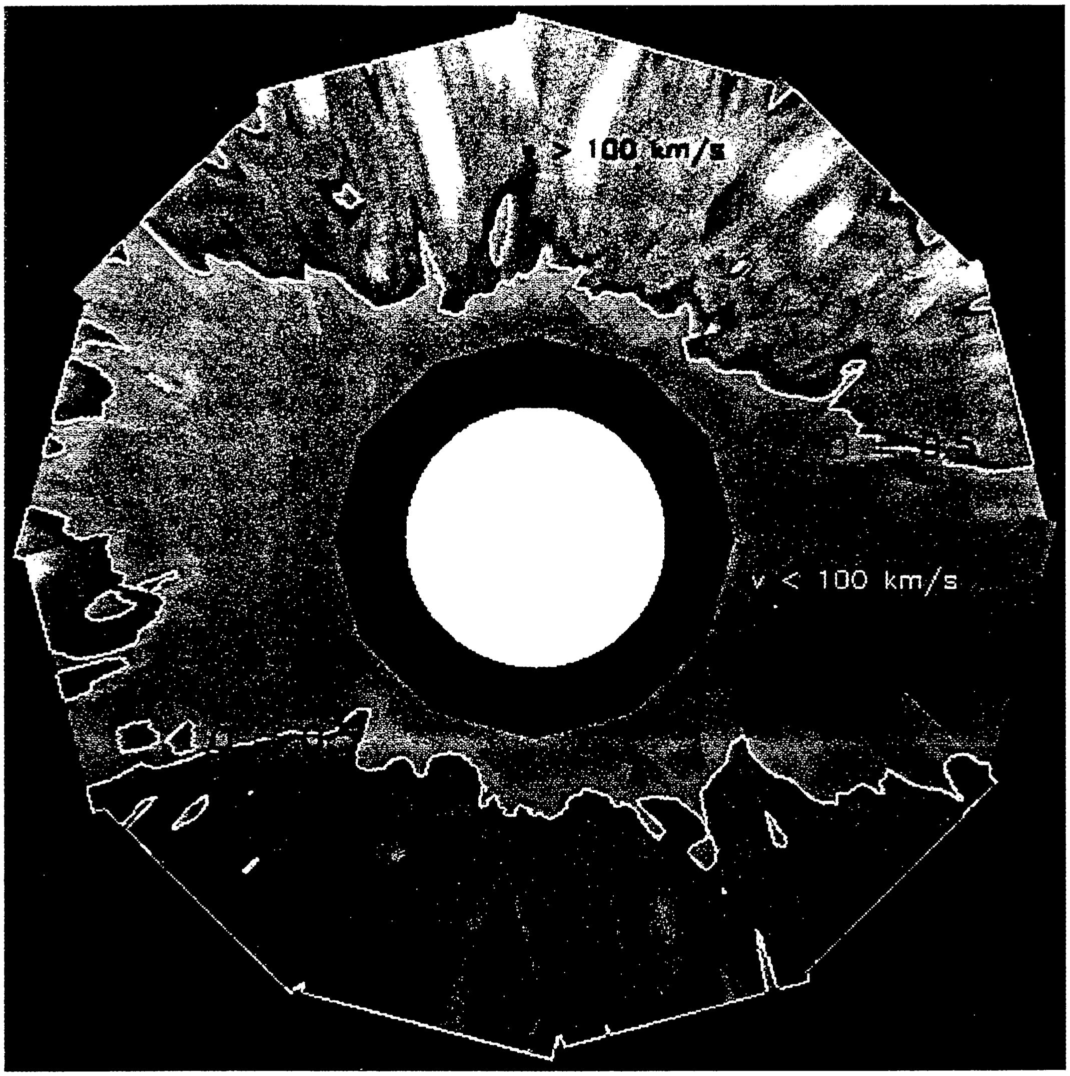

Figure 3. Map of the O VI 1037/1032 intensity ratio. A continuous line separates regions where the solar wind outflow velocity is less than about 100 km s^{-1} (green) from regions where the wind velocity exceeds 100 km s^{-1} (orange).

field line regions are characterized by a more rapid acceleration of the solar wind, both in the polar regions and in the regions between mid-latitude/equatorial streamers. The 100 km s^{-1} contour runs near the borders of streamers, that is near the transition between closed and open field lines. The O VI ratio diagnostics indicates that in polar coronal holes the outflow 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 $R_\odot$. This corresponds to an average acceleration of 0.026 km s^{-2}.

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