THE FALL 2001 POLAR SOHO–ULYSSES QUADRATURE CAMPAIGN: PRELIMINARY RESULTS

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Abstract

We present here UVCS observations of a polar coronal hole, acquired during the October/November 2001 SOHO-Sun-Ulysses quadrature. SOHO-Ulysses quadratures occur when the SOHO-Sun-Ulysses included angle is 90° and offer the unique opportunity of comparing the properties of plasma parcels, observed by SOHO in the corona, with properties of the same parcels, measured *in situ*, in due time, by Ulysses. The October/November 2001 quadrature occurred at a time when Ulysses was at ≈ 2.2 A.U., at a northern heliographic latitude of $\approx 80°$, off the West limb of the Sun. Observations were taken from October 29 to November 12, 2001, with a ≈ 3 days data gap, after the eruption of CMEs and the emission of highly energetic particles, on 3-4 November. The UVCS slit was set normal to the solar **radius**, with the radial to Ulysses going through its zero position. At the time of the campaign, the radial to Ulysses crossed a polar coronal hole. Although its shape was changing, Ulysses was permanently located in a high speed region where CMEs signature can be recognized. Observations in Hydrogen Lyman-α and in the 1032 and 1037 Å O VI doublet lines have been made at 1.6 and 2 $R_{\odot}$. Line intensities are compared with intensities typically found, at the same altitudes, in polar coronal holes at minimum solar activity and in equatorial holes. The temporal profile of the O VI doublet line ratio and of the O VI line widths, at the position where the radial to Ulysses traverses the solar corona, are shown and a tentative interpretation of the data is outlined.

Key words: fast wind; corona; *in situ* data.

1. Introduction

SOHO-Ulysses quadratures occur when the SOHO-Sun-Ulysses included angle is 90°. They offer an opportunity to compare a plasma parcel, as seen in the corona by SOHO, with the same plasma parcel, as seen *in situ* by Ulysses. The fall 2001 quadrature was especially interesting, as it occurred at a time when Ulysses was at the West limb of the Sun, at a latitude of $\approx 80°$, with high chances of being immersed in a solar maximum high speed wind stream.

In situ observations have shown the fast wind to be fairly uniform, if compared with the slow wind variability. Occasional CMEs, however, disrupt the fast wind pattern, both at coronal and large heliocentric distances. In our case, and focussing only on the plasma parcel lying along the Ulysses direction, we may anticipate a further cause for variations in its physical parameters, whenever the radial to Ulysses crosses the edge of a coronal hole to enter an adjacent streamer region. Hence, a primary objective of this analysis is a study of the morphology of the regions traversed by the radial to Ulysses, over the quadrature campaign, and of the accompanying changes in the characteristics of the observed coronal spectra. These will then be compared with *in situ* data, appropriately scaled to account for the time it takes plasma to reach the Ulysses position.

As seen by *in situ* experiments, major differences between fast wind, emerging from polar regions, and slow wind, emerging from streamer areas, include a drop in the wind speed (see, e.g. McComas et al., 1998) and a sudden change in wind composition (see, e.g. Aellig et al., 1999). In this brief report we present results from a preliminary analysis of i) the morphology of the regions traversed by the radial to Ulysses, ii) the behavior of UVCS data iii) the behavior of Ulysses data. The analysis is, so far, at a semi-qualitative stage, but a future modeling effort is also outlined.

2. Morphology of polar regions

As we mentioned, Ulysses latitude was $\approx 80°$ at the time of the fall 2001 quadrature. More precisely, Ulysses polar angle changed from $\approx 10.7°$ on October 24, to $\approx 15.3°$ on November 18. At that time

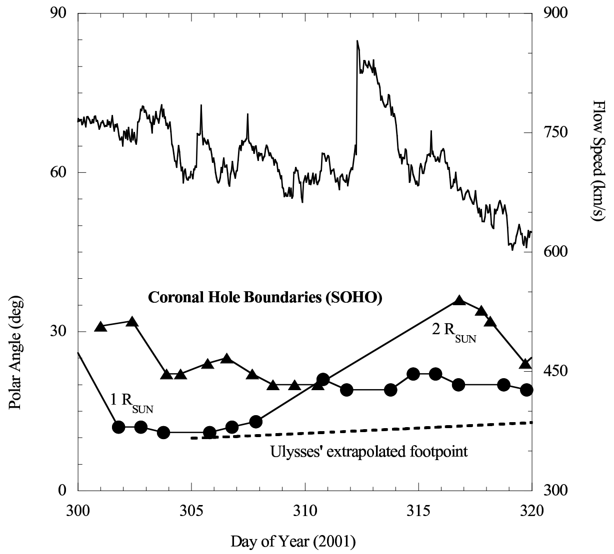

Figure 1. Top: plot of the wind speed (km/s) as observed by the SWOOPS experiment on Ulysses over a time interval which includes the SOHO-Ulysses quadrature campaign (Day of Year 300 corresponds to October 27). Bottom: the two plots represent the polar angle of the southernmost edge of the North coronal hole measured at the western limb via, respectively, at 1 $R_\odot$, the EIT 195 Å images (filled circles) and, at 2 $R_\odot$, the LASCO C2 images (filled triangles). The position of the Ulysses footpoint is also shown (dashed line).

an irregularly shaped polar coronal hole circled the North Pole, with a southward extension which, at times, was reaching down to a latitude of $40-50°$.

Even before analysing coronal or *in situ* data, we can check whether the radial to Ulysses is lying inside the coronal hole boundary, as seen at coronal levels, throughout the observing campaign: there are no chances to observe a coronal hole/streamer crossing if the radial to Ulysses is permanently located inside (or outside) the coronal hole area. To this end, we estimated the polar angle of the southernmost edge of the coronal hole,at the West limb, from EIT 195 Å and LASCO C2 images. Results from this analysis are shown in Figure 1 (bottom), together with the wind speed (top), as observed by the SWOOPS experiment onboard Ulysses.

Figure 1 shows that the only opportunity we might have to observe a transition from the coronal hole to the streamer regime, occurs early in the campaign. However, such a possibility is only marginal, because the Ulysses footpoint seems to be rooted inside the coronal hole even in this case. Moreover, the coronal hole area expands superradially with altitude, its edge at 2 $R_\odot$ extending to larger polar angles than the boundary at 1 $R_\odot$. Hence there is indirect evidence that the radial to Ulysses is immersed in the coronal hole throughout the quadrature campaign. We resort now to UVCS data to see whether this preliminary result can be confirmed.

3. UVCS quadrature observations

Observations have been taken by SOHO UVCS, at altitudes of 1.6 and/or 2 solar radii, with two grating positions that cover the Hydrogen Ly-α and Ly-β lines, the 1032 and 1037 O VI doublet lines, and a few more lines from Si XII and Mg X ions. The UVCS slit was set normal to the solar radius with its zero position lying along the radial to Ulysses: in the following we refer only to physical quantities measured at this central pixel of the UVCS slit. Data have been acquired with a spatial binning of $\approx 70''$ and a 2 pixel spectral binning (1 pixel = 9.25 mÅ). Typical observing times were on the order of 9-10 hours per day; spectra were taken alternating in between the two grating positions.

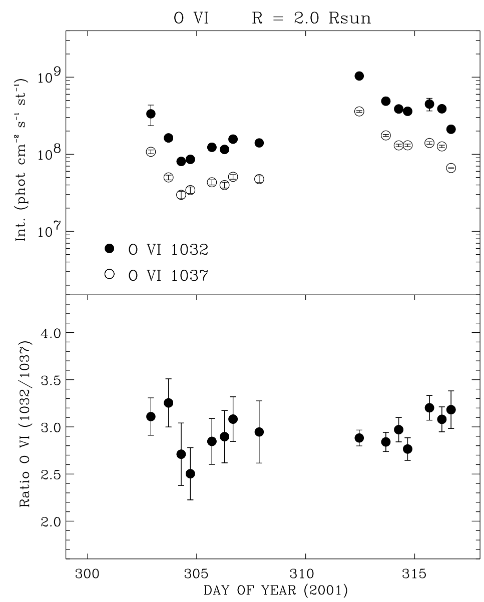

Figure 2. Top: total line-integrated intensities (ph $cm^{-2}s^{-1}st^{-1}$) for the 1032 (filled circles) and 1037 (open circles) Å lines of the O VI ion, vs. time, at 2 $R_\odot$, from UVCS observations. Bottom: ratio between the O VI λ1032 and O VI λ1037 line intensity, vs. time, at 2 $R_\odot$. Both panels give the 1σ error bars.

Figure 2 (top) shows the temporal behavior of the line-integrated intensities of the 1032 and 1037 Å O VI doublet, at 2 solar radii, over the quadrature campaign. There is a data gap of 3-4 days, when all SOHO experiments had been switched off, because of the eruption of CMEs and the emission of highly energetic particles. The O VI line intensities do not show any change, around DOY 305, when we anticipated a slight chance for crossing a coronal hole / streamer interface. However, rather unexpectedly, the O VI line intensities are not constant over the data set, but increase by a factor 2-3 in the second half of the campaign. Initially, the O VI intensities are typical of polar coronal holes (Cranmer et al., 1999), but become even higher than typical equatorial hole values at the end of the campaign (Miralles et al., 2001). There is no way, though, for the plasma parcel we are analysing to be outside the coronal hole area (see the position of the Ulysses' extrapolated footpoint in Figure 1, bottom).

This behavior might result in a drop of the plasma outflow speed, for which there is some evidence in the SWOOPS data (although the wind speed never reaches values typical of the slow wind emanating from equatorial holes, see the top panel of Figure 1). In an attempt to understand this behavior, we evaluated the ratio of the 1032 to 1037 O VI line intensities. It is well known (see, e.g. Noci et al., 1987) that this ratio is a proxy for the coronal plasma outflow speed, which, with some assumptions, can be quantitatively evaluated (see, e.g. Li et al., 1998).

The bottom panel of Figure 2 gives the temporal behavior of the ratio R between the O VI λ1032 and O VI λ1037 line intensity. Apart from a drop in the value of R around Day of Year 305, there is no evidence for a higher ratio (i.e., lower outflow speed) at the end of the campaign. An average value of $R = 3 \pm 0.1$ is representative of all but the 304.8 data points. This high R value is unexpected, being more adequate for an equatorial, than for a polar hole. Possibly, because we are dealing with a polar hole near the maximum of the solar activity cycle, a comparison with ratios given in the literature, which refer to solar minimum polar holes, is not correct. However, the $R = 2.5$ ratio on Day of Year 304.8, although on the high side, may be consistent with the polar hole R values given in Figure 6 of Cranmer et al., 1999.

A further parameter that may give us interesting information, is the line width. Observations have shown (Kohl et al., 1997) that the width of the O VI doublet lines (as well as of lines from other ions) is in polar coronal holes much larger than in streamers. At an heliocentric distance of 2 $R_\odot$, typical full widths at half maximum (FWHM) of the O VI lines are $\approx$ 1.7 Å in polar holes, and $\approx$ 0.5 Å in streamers. These values have been obtained by fitting the line profiles with single **G**aussians, after stray light removal.

We then analogously fitted the observed O VI line profiles using single Gaussians. Stray light profiles were computed during the Gaussian fitting procedure for a given disk intensity, and observing altitude, and subtracted to obtain the corrected line intensities. Line intensities were reproduced with errors $\leq$ 15% in all cases but on Day of Year 304-305, when a single Gaussian fit was inadequate to reproduce the line profile and lead to errors on the order of 20-30%. The FWHM we obtained with this procedure are given in Figure 3. Reported values represent upper limits to the FWHM of the lines, since we do not correct for the instrumental profile.

Figure 3 shows once more a different behavior in the widths of lines measured before and after the data gap. However, the line widths are much lower than usually found in coronal holes and approximate those measured in streamers. The only time when they may be close to those typically found in coronal holes is around Day of Year 304-305, when a fit with a two Gaussians plus a constant background (see, e.g. Miralles et al. 2001) may give us more precise information on the real line width.

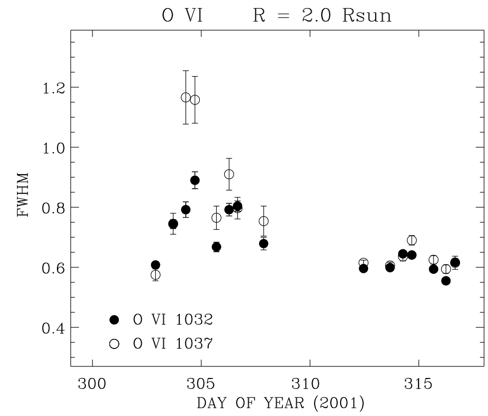

Figure 3. Full width at half maximum (FWHM, Å) for the 1032 (filled circles) and 1037 (open circles) Å lines of the O VI *ion, vs. time, at 2 $R_\odot$, from UVCS observations. The values are for single Gaussian fits to the line profile. See text for more details.*

4. Discussion and future work

The data analysis that we described in the previous section lead to controversial results: while SWOOPS wind data and EIT images suggest that we are immersed in a polar coronal hole, UVCS data yield O VI intensities, ratios and line widths only occasionally similar to those observed in polar coronal holes. If *in situ* data along the radial joining the central pixel of the UVCS slit to Ulysses were not available, we might hypothesize that the physical parameters of polar holes at maximum of the activity cycle are different from those of polar coronal holes at minimum activity. We remind the reader that polar low speed wind has been observed in 1990, i.e. at the past maximum of solar activity, by IPS observations (Ohmi et al., 2001). Not much information is available on the behavior of low-speed wind at solar maximum, see e.g. (Kojima and Kakinuma , 1987), (Watanabe et al., 1996), (Wang, 1994). Hence, we might conclude that UVCS observations provide evidence for the coronal origin of maximum low speed wind. Quadrature data, however, unequivocally dismiss this interpretation, as the wind speed associated with the region we examine is always $\geq$ 600 km s^{-1}. Hence, we need alternative explanations.

Ulysses data do not show evidence for a difference between the first vs. the second half of the campaign, because on DOY (Day of year) 312 (November 8), a

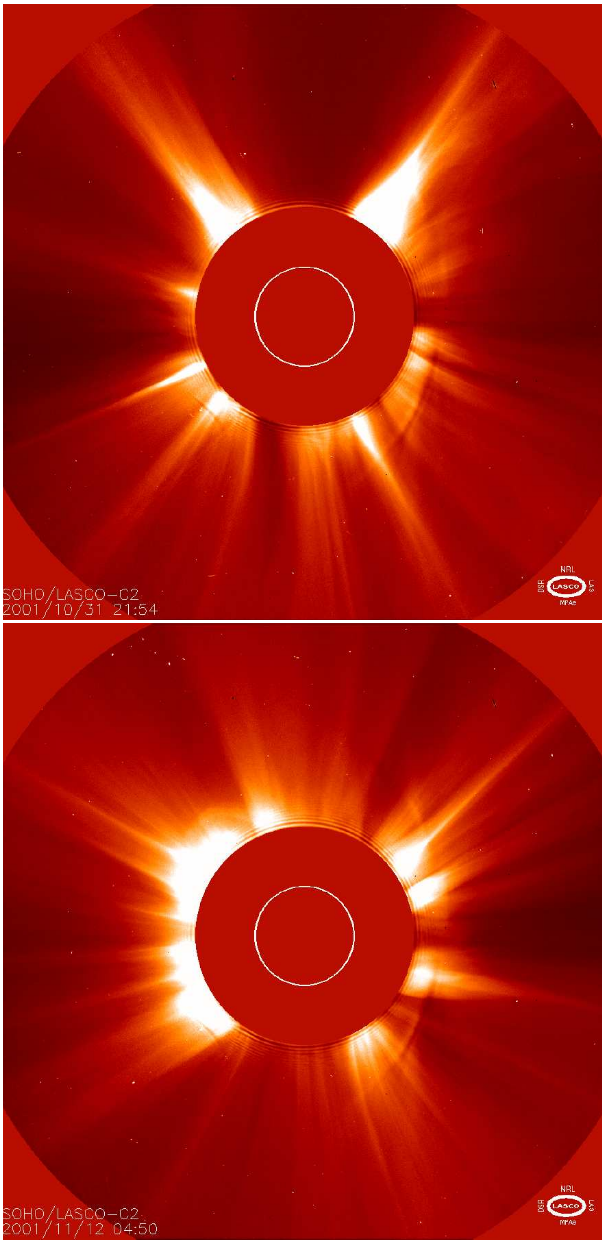

Figure 4. LASCO C2 images for October 31 (top) and November 11 (bottom), 2001.

quite unusual transient, apparently generated by a CME on November 4, developed a forward shock, followed by a long decrease in speed, which makes the data interpretation more complicated. We then resorted to LASCO data which showed a marked difference between images in the first vs. the second half of the campaign. Figure 4 shows that at 2 $R_\odot$ there may be quite a lot of intervening material, along the line of sight, made up of streamer material, which masks the hole plasma. This is particularly evident at the end of the campaign. Possibly the southward extension of the coronal hole, no longer visible by November 6, created an area free from closed structure, that made projection effects less severe over the first days of observations.

We plan to model this scenario, by reproducing the observed O VI line intensities and ratios, on two days representative of conditions in the first and second half of the campaign. The polar hole physical parameters are identifiable from data of Day of Year 304.8: assuming a different amount of streamer-like material along the line of sight at different times over the campaign we expect to be able to mimic observations. The physical characteristics of the streamer plasma will be evaluated from UVCS data off the slit center. This modeling effort is in its initial stage: preliminary values of streamer densities are comparable to those given by (Allen , 1955) for the equatorial maximum corona and higher by a factor ≈ 1.5 than those given by (Gibson et al., 1999) for streamers at minimum solar activity.

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