PROPERTIES OF PLASMA DYNAMICS IN THE POLAR CORONAL PLUMES

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ABSTRACT

We use spectral shapes of EUV line profiles to study the plasma dynamics, acceleration and heating in polar coronal plumes. We find that the observed profiles are reproduced fairly well when considering very low plume wind speeds and about four times lower velocity turbulence than in inter-plumes at low altitudes followed by a rapid acceleration and heating of the plasma to reach the properties of inter-plume regions by $\approx 3.0 - 4.0\ R_\odot$. We also find that plumes very close to the pole give narrow components at all heights that are not observed above $\approx 2.5\ R_\odot$. This suggests a tendency for plume footpoints to lie more than 10° away from the pole. EUV images and high resolution magnetograms from SOLIS support this hypothesis.

Key words: Sun: corona – Sun: magnetic fields – Sun: solar wind – Line: profiles – Turbulence.

1. INTRODUCTION

SOHO and UVCS in particular gave new insights into coronal physics and spectroscopy. In the coronal holes, heavy ions emit very broad components reflecting the plasma dynamics complexity in these regions. Raouafi & Solanki (2004, 2006 and in the present volume) give a simple interpretation of the broad line profiles based on assuming Maxwellian velocity distributions without anisotropy in the kinetic temperature of the different coronal species. In the following sections, inter-plumes regions will be treated in the same way as by Raouafi & Solanki (2006; hereafter referred to as RS06)

The contribution of polar plumes to the fast solar wind recently became a matter of debate and controversy. Several authors claim that polar plumes contributes significantly if not the main source of the fast solar wind (see Gabriel et al. 2003 and references therein). Others think otherwise (Wilhelm et al. 2000 and references therein). EUV coronal emissions provide an excellent diagnostics for the plasma dynamics in different coronal structures, in particular in polar plumes. We use primarily the profile shapes of coronal lines to select between models of polar plumes in order to constraint the height evolution of the plasma outflow speed (acceleration) and velocity turbulence (heating) in these fine coronal structures.

2. POLAR PLUME EMISSION PROPERTIES

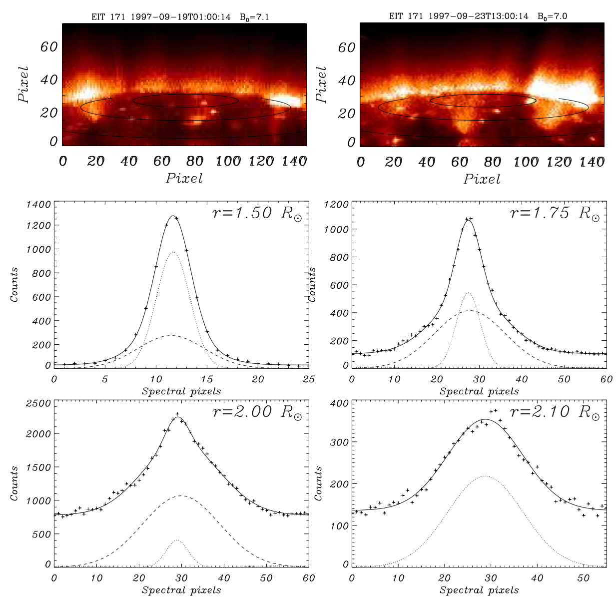

Figure 1. Top: EIT images of the north solar pole on September 19-23, 1997, showing polar plumes. Contours are placed every 5° from the pole. Middle and bottom: observed O VI *profiles at the same times (+ signs). The solid lines are two Gaussian fits and the dotted and dashed lines are the individual Gaussians used for the fits.*

The O VI profiles emitted in the polar coronal holes have a broad and a narrow component up to $\sim 2.0\ R_\odot$. The spectral behaviors of the two components as a function of height above the limb are quite different. The width of the broad component increases much faster than that of the narrow one, which remain almost constant in the range where it is observed (below $\sim 2.0\ R_\odot$; see Kohl et al. 1997). The plume's spectral contribution (narrow component) to UV lines as observed by UVCS are characterized as follows:

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- Dominates the profiles below $\sim 2.0\ R_\odot$ and decreases above;
- Not seen in the profiles beyond $\sim 2.5\ R_\odot$. Only the broad component remains above this altitude;
- Mostly located at the center of the broad component which is close to the rest wavelength of the spectral lines. Thus, no significant Doppler shifts are observed for the narrow component;
- The width of narrow component hardly changes as function of height in the range where it is observed (see Kohl et al. 1997).

In order to study the height dependence of the heating and acceleration of the plasma in plumes, we use the evolution of spectral profiles over altitude (namely the narrow component) as first criteria to constraint the dynamics of the plasma. We explore the parameter space of the plasma and select those that reproduce the observed profile shapes and also the other moments of the profiles.

3. MODEL POLAR PLUME AND INTER-PLUME PLASMA PARAMETERS

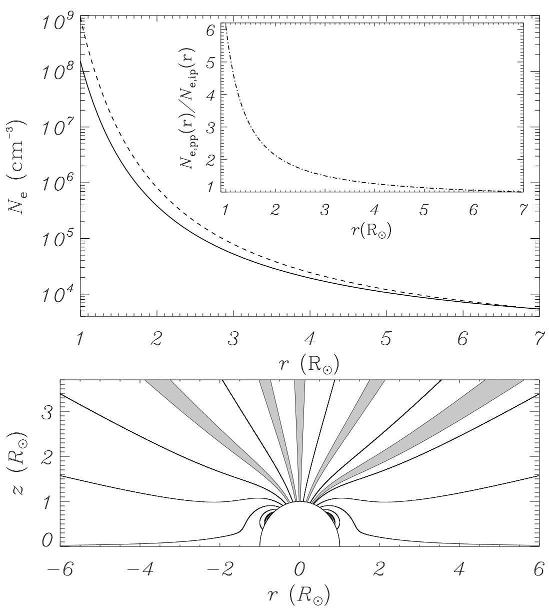

Figure 2. Top: plume (dashed line) and inter-plume (solid line) electron densities. The dot-dashed line gives the ratio of densities in the two media as a function of height. Bottom: polar plume distribution used for the calculations of the coronal line profiles. Plume footpoints are $\approx 15 - 20$ Mm *wide.*

Here are some of the characteristics of plumes and inter-plumes that are taken into account in the model. In particular, we assume simple Maxwellian velocity distributions for both regions but different velocity turbulence. Electron densities are given by the solid (Doyle et al. 1999; SOHO data) and dashed curves in the top panel of Figure 2 for inter-plume and plume regions, respectively. At low altitudes, a density ratio of 3-6 is assumed, which is in agreement with the observation by Wilhelm (2006). We assume also that plumes expand in line with the rest of the corona where the magnetic field is given by the model of Banaszkievic et al. (1998). The electron density and magnetic field models are used to compute the outflow speed in inter-plume plasma using the mass-flux conservation equation (for details see RS06). The plasma outflow speed in plumes is assumed to be proportional to inter-plume outflows with the proportionality coefficient depending only on the distance to Sun center.

4. PLUME PLASMA DYNAMICS: BEST FIT CASE

Figure 3 displays the best profiles (top-right and six-middle panels) obtained when considering one plume along the LOS whose footpoint is placed 15° away from the pole (very left plume in the bottom panel of Figure 2). This is comparable to where the plume footpoints are based in EIT images in Figure 1. The computed profiles show lots of similarity with the observed ones. In particular, the plume contribution (narrow component) obeys the qualitative properties presented in section 2: dominance of the profiles and no significant Doppler shifts at low altitudes and disappearance above $\approx 2.5\ R_\odot$.

These profile shapes are obtained only when considering plume plasma that remains much cooler and much slower than inter-plume material up to $\approx 2.0\ R_\odot$. Then, both the plume outflow speed and velocity turbulence increase rapidly to reach the inter-plume properties by $\approx 3.0\ R_\odot$ as shown by the top-left and top-middle panels of Figure 3. This rapid evolution with height could be the result of interaction with the fast and hot surroundings (inter-plume medium).

The bottom panels of Figure 3 display the different moments of the profile widths, total intensities and the intensity ratios of the O VI doublet. The measured values are also displayed for comparison. The line widths, total intensities and intensity ratios are in fairly good agreement with the measurements. In particular, the computed width of the narrow component hardly changes with height in excellent agreement with the observed value obtained by Kohl et al. (1997). Intensity ratios at very low altitudes (below $1.3\ R_\odot$) are smaller when plumes are taken into account along the line of sight (full circles in bottom-right panel of Figure 3) than otherwise (empty circles). This is due to the enhanced electron densities in plumes. This is in disagreement with the interpretation of Gabriel et al. (2003) who invoked Doppler dimming effects due higher outflow speeds in plumes than in inter-plumes at these altitudes.

So far, we considered only the contribution from one polar plume at mid-altitudes (left-hand plume in the bottom panel of Figure 2). In the next section we study the effect

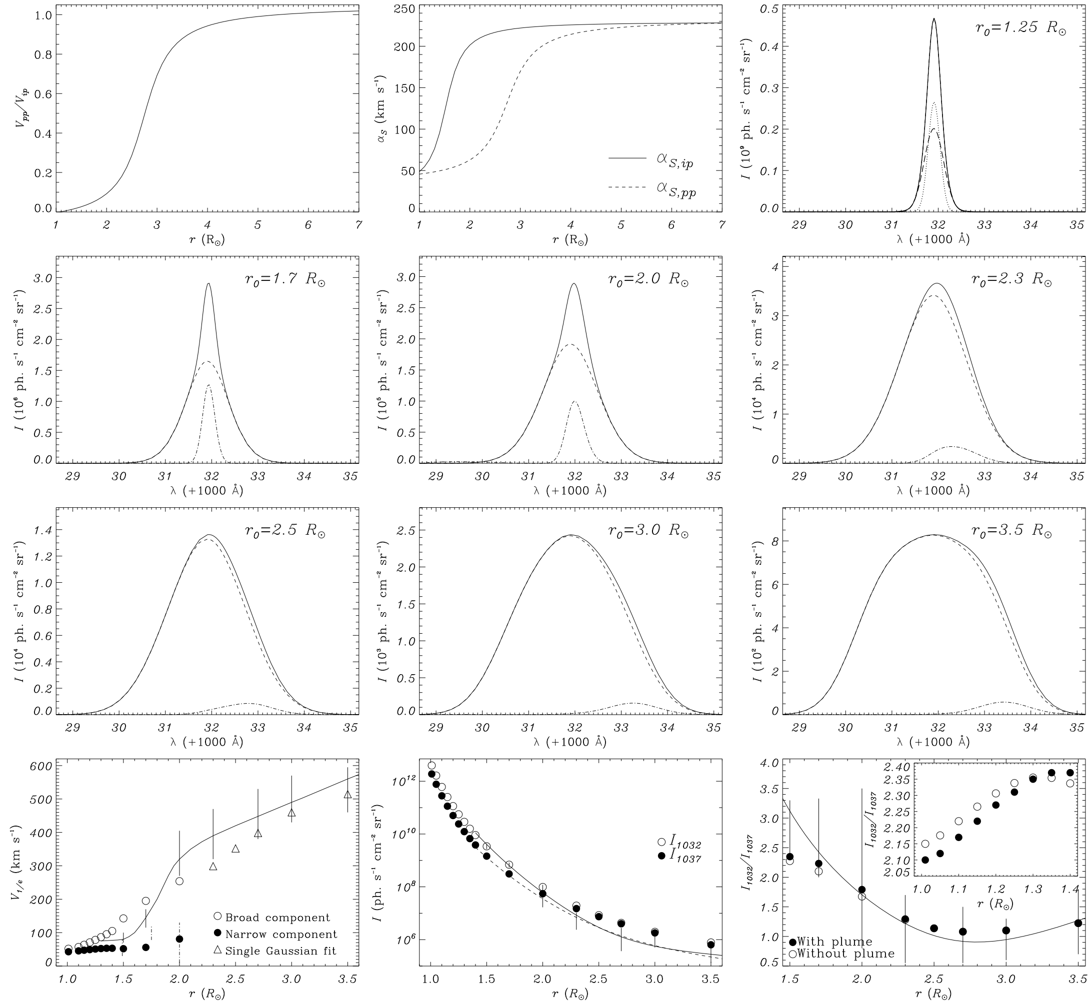

Figure 3. Top-left: V_{pp} non-linear-height dependent fraction of V_{ip}. Top-middle: velocity turbulence in both plume and inter-plume regions. Top-right and middle: O VI *1032 Å synthetic line profiles using the plasma parameters shown above. Bottom: Widths, total intensities and intensity ratios of the O* VI *doublet as functions of height.*

of polar plumes based closer to the solar pole.

5. ON THE PLUME FOOTPOINTS

The top-four panels of Figure 4 display the line-of-sight integrated profiles of the O VI 103.2 nm line with contributions from the four right-hand plumes in Figure 2 taken into account separately. Contrary to the observations, narrow components from plumes close to the pole are present at most heights. This suggests that polar plumes preferentially originate away from the pole. This last statement is a good test to show how realistic the present model is. If not confirmed observationally, the other results of the model would also be doubtful. However, if confirmed, it means the model is realistic enough not only to reproduce the observed profiles but also to make a definite prediction, namely that polar plumes cannot be based close to the solar pole.

To make this test we looked at EIT images from solar minimum (1996-1997) at times when one of the poles is well seen which corresponds to months around March and September. We find very few bright structures (probably plume footpoints) at less than 10° from the pole and much fewer based at less than 5°. Most of the polar plumes are based further away. This problem could also be looked at using photospheric magnetograms. High resolution magnetograms from SOLIS are the best to date for this purpose due the high sensitivity of the instrument which provides excellent signal at high latitudes. The bottom panel of Figure 4 is an example of an average of a month worth of SOLIS magnetograms for September 2005 showing the magnetic flux concentrations at the north polar region. It shows a trend for the flux to be concentrated in a latitude ring between roughly 10° and the edge of the polar hole. The very polar region is cleaner although we are not at the solar minimum yet. This supports the fact that polar plumes that emerge from magnetic flux concentrations originate preferentially far away from the pole.

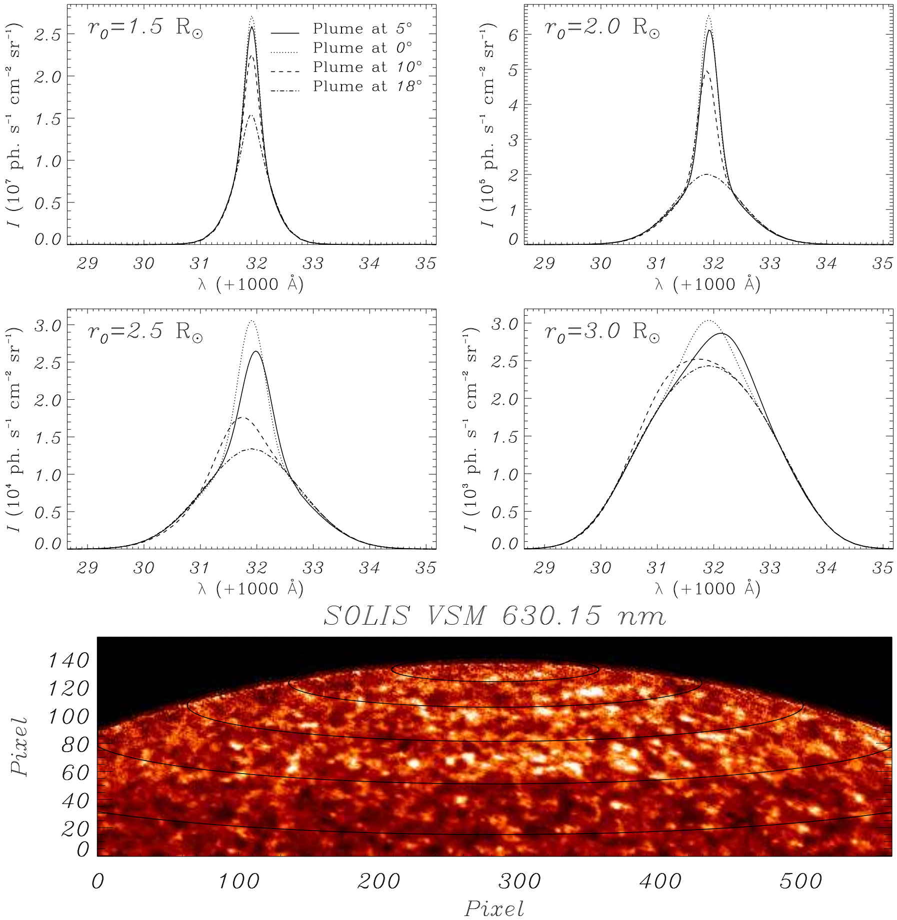

Figure 4. Top and middle: profiles with contributions from the 4-right-hand plumes in Figure 2 taken into account separately. Bottom: SOLIS magnetograms displaying the magnetic flux distribution around the north pole for September 2005.

6. CONCLUSIONS

We used the EUV coronal line profiles (namely those of O VI) to study the height dependence of the plasma dynamics (heating and acceleration) in polar coronal plumes. The profile shapes are used as first criteria to constrain the parameter space. Line widths, total intensities and intensity ratios are then used to confirm the obtained results. We find:

- Strongly height-dependent plasma velocity broadening and outflow speeds in plumes are needed to reproduce the observed profile shapes, in particular the characteristics of the narrow component;
- Plumes have low plasma temperature and outflow speeds up to $\approx 2\ R_\odot$ that rapidly increase to reach inter-plume values by $\approx 3\ R_\odot$. This could be the result of interaction with the inter-plume plasma;
- Contributions from plumes based close to the solar pole yield narrow component at all altitudes in contrast to the observations where the narrow component disappear above $2.5\ R_\odot$. This suggests a trend for polar plume to be based more than $10^\circ - 15^\circ$ away from the pole. SOLIS high resolution magnetograms shows greater magnetic flux concentration toward the edge of the polar hole and less near the very polar area. SOHO/EIT images from the solar minimum show also very few bright features close to the pole which suggests also very few plumes originating closely to the pole. These observations tend to support the hypothesis of plumes based away from the pole.

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