Plumes as seen in the Ultraviolet

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Introduction

- Plumes have been observed and studied since long time in white light during total eclipses (Abbot 1900, Saito 1965, Koutchmy 1977).

- They appear as linear structures rooted in coronal holes and extending towards the interplanetary space.

- More recently, plumes have been also observed in other regions of the electromagnetic spectrum: VUV (e.g., Ahmad & Withbroe 1977), Soft-X (e.g., Ahmad & Webb 1978), and radio (e.g., Woo & Habbal 1997).
VUV spectroscopy

- Plasma with temperature of the order of 1 MK emits strongly at VUV wavelengths (from 16 to 200 nm: EUV 16 – 120 nm + FUV 120 – 200 nm).
- The VUV spectrum is dominated by thousands of emission lines arising from atoms of different elements and in different ionization states.
- In general, for lines formed in the solar corona we have:
  \[ L = \frac{A_{el}}{4\pi} \int G(T_e, N_e) N_e^2 \, dh \]

Gain information on \( N_e \), \( T_e \), \( ed \), \( A_{el} \)
Plumes & Coronal Holes

• VUV lines formed around 1 MK allow the study of the plumes roots on the disk where their intensity is enhanced with respect to the background CH emission.

• Plumes are a prominent feature of the Polar Coronal Holes (PCHs) characterizing the Sun around its minimum of activity.

EIT $\lambda$17.1 – $T=0.9$ MK
However, there are reports of plumes being detected within Equatorial Coronal Holes (ECHs) from observations in the EUV (Wang & Sheeley 1995, Del Zanna & Bromage 1999) and radio (Woo 1996).

Del Zanna et al. (2003): plumes within ECHs have similar characteristics (i.e., abundance, temperature and density) of polar plumes.
Plumes & Fast Wind

By comparing the Soft X-ray flux and the in-situ wind speed Krieger et al. (1973) find coronal holes to be the source region of the fast wind. Confirmed by Ulysses.

Krieger et al. 1973
Plumes & Fast Wind

• Being the most prominent feature within CHs, plumes have been and are considered as a strong candidate for the source regions of the fast wind.
• Theoretical models give opposite indications. Del Zanna et al. (1997) and Casalbuoni et al. (1999) show that the outflow speed in plumes can be larger or smaller than in the ambient depending on the temperature and Alfvén wave flux assumed in the two regions.
• Can VUV observations help us in understanding the relevance of plumes on the fast wind?
VUV data permit studying off-limb plumes below 1.2 \( R/R_{\text{Sun}} \), a region accessible in WL only at eclipses.

Teriaca et al. 2003
Morphology

- De Forest et al. (1997) find plumes to be rooted on (2"-5" wide) unipolar magnetic flux concentrations.
- By combining images in EUV and WL they show that plumes can be traced from their roots up to 15 \( R/R_{\text{Sun}} \).
- Super-radial expansion between 1.2 and 4 – 5 \( R/R_{\text{Sun}} \) (DeForest et al. 1997, 2001).

DeForest et al. 1997
Morphology

- LASCO C1, C2 and EUV data confirm that the structures seen at the base of the corona are preserved in the observed 1.1 – 3 R/R_{Sun} range (De Forest et al. 2001).
Lifetime

- Llebaria et al. (1998): plumes are recurrent structures (lifetime of a few days) in rigid rotation with the Sun, transiently active.
- Young et al. (1999): lifetime of 2-3 days.
- De Forest et al. (2001): plumes are episodic in nature, lasting perhaps 24 hours, but recurring for up to weeks at a time.
Time evolution over two months
Time evolution over one day
Electron density

• Reliable measurements are provided by density-sensitive line ratios (e.g., Si VIII $\lambda 144.0/\lambda 144.5$, Si IX $\lambda 34.2/\lambda 34.5/\lambda 35.0$).

• Electron densities $\approx 2$ higher than in the surrounding dark areas (Wilhelm et al. 1998, Young et al. 1999, Del Zanna et al. 2003).

• Interplume densities are $\approx 2$ lower than in the quiet corona (Banerjee et al. 1998, Doscheck et al. 1998).
Electron temperature

- Ratios of Fe IX-X $\lambda 17.1$/Fe XII $\lambda 19.5$ images indicate interplume to be a 30% hotter than plumes (DeForest et al. 1997).
- Reliable measurements are provided by the temperature-sensitive line ratio Mg IX $\lambda 70.6$/\lambda 75.0.
- Electron temperature lower than in the surrounding dark areas. In interplumes $T_e$ goes from $7.8 \times 10^5$ K at 1.03 $R/R_{Sun}$ to $8.8 \times 10^5$ K at 1.30 $R/R_{Sun}$. In plumes it goes from $7.3 \times 10^5$ K to $5.8 \times 10^5$ K over the same range (Wilhelm et al. 1998).
- A temperature of $8 \times 10^5$ K is given by Del Zanna et al. (2003) at the root of a plume.
Abundances

- From Skylab data Widing and Feldman (1992) find the ratio of Magnesium over Neon in plumes to be around 10 times higher than in the photosphere.
- An enhancement of 1.7 – 3.5 was found by Wilhelm & Bodmer (1998).
- Young et al. (1999) report the ratio of Magnesium over Neon to be enhanced by ≈1.5.
Abundances

• Del Zanna et al. (2003) claim no FIP effect to be present in plumes but neon is depleted with respect to Oxygen by ≈0.2 dex.

• In interplumes the Mg/Ne ratio has photospheric values, while the Si/Ne ratio is enhanced of a factor of 2±1, similarly as they find in the quiet corona (Doschek et al. 1998).

• Observations seem converging towards small or no FIP effects in plumes. No relevant difference with interplumes.
Line Width

• The widths of coronal lines largely exceed their thermal values pointing to unresolved motions due to wave activity and heating.


• Wilhelm et al. (1998): Doppler widths of O VI lunes are broader in interplumes ($\approx 19$ pm, $\approx 55$ km s$^{-1}$) than in plumes ($\approx 15$ pm, $\approx 43$ km s$^{-1}$).
Line Width

O VI \( \lambda 103.2 \)

Banerjee et al. 2000

Tuesday October 04
MPS Solar Group Seminar
Line Width

• Spectral lines appear to be broader in Interplumes also in UVCS data between 1.5 and 2.5 \( \frac{R}{R_{\text{Sun}}} \) (Giordano et al. 1998, 2000; Teriaca et al. 2003).

• These findings are confirmed also by spectra of the Fe X red line at 637.4 nm (Raju et al. 2000).

• Preferential heating in Interplumes?
Doppler Shifts

• Measure Doppler shift along the LOS.
• It does not rely upon assumptions on the local plasma parameters (density and temperature).
• It depends on the observing geometry.
• Correct for the angle between the LOS and the direction of the magnetic field lines.
• More weight to lower, denser (brighter?) layers.
• Wilhelm et al. (2000) measure speeds of $-3 \text{ km s}^{-1}$ in He I and Ne VIII on a Polar Coronal Hole.
Doppler Shifts: PCH

They obtain an average radial speed of $-14 \text{ km s}^{-1}$ after correcting for the angle between the LOS and the direction of the magnetic field lines (using the magnetic field model of Banaszkiewicz et al. 1998).

Large outflows from the darker regions.

Wilhelm et al. 2000
Doppler Shifts: PCH

• Tu et al. (2005) find an outflow speed of $-10 \, \text{km s}^{-1}$ in Ne VIII that they establish to form at an altitude of about 20 Mm ($1.28 R/R_{\text{Sun}}$).

• Wilhelm et al. (1998) find bulk outflows $\leq 18 \, \text{km s}^{-1}$ in plumes (O VI) and $\leq 34 \, \text{km s}^{-1}$ in interplumes (Mg IX) below 1.2 $R/R_{\text{Sun}}$. 

Doppler Shifts: ECH

• In ECHs the observing geometry is much more favorable.
• Xia et al. (2003) find an average upward velocity of $-7.5 \text{ km s}^{-1}$ in Ne VIII.
• The upflow is mostly coming from the darker regions.

Xia et al. (2003)
Doppler Dimming

- Electron impact excitation (collisional component).
- $I_{\text{coll}} = 0.85 (\Delta E_{\text{gu}}/4\pi) A_{\text{O/H}} \langle q(T_e) R(T_e) N_e^2 \rangle$
- Resonant absorption of disk radiation (radiative component).
- $I_{\text{rad}} = 0.85 (\Delta E_{\text{gu}}/4\pi) A_{\text{O/H}} B_{\text{gu}} I_{\text{Sun}} \langle D(W,T_0) R(T_e) N_e \rangle$
- $D(W,T_0)$ accounts for Doppler dimming and geometrical dilution factors.
- It is function of the ion temperature (consisting of the components perpendicular $T_\perp$ and parallel $T_\parallel$ to the magnetic field).
Doppler Dimming: O VI 103.2/O VI 103.7

- Mainly a function of $N_e$ and $W$.
- $= 2$ for collisionally excited lines.
- $= 4$ for radiatively excited lines.
Doppler Dimming

- Allows to determine the radial component of the plasma outflow velocity from the analysis of off-limb spectra.
- The observing conditions are favorable although some assumption on the geometry of the coronal structures is necessary.
- It is strongly dependent on the ambient electron density.
Doppler Dimming

- Patsourakos & Vial (2000): outflows of \( \approx -67 \text{ km s}^{-1} \) in interplumes (1.05 \( R_{\text{sun}} \)).
- Giordano et al. (2000): interplume outflows between \(-105 \text{ km s}^{-1}\) and \(-150 \text{ km s}^{-1}\), plume outflows between 0 km s\(^{-1}\) and \(-65 \text{ km s}^{-1}\) (1.7 \( R/R_{\text{sun}} \)).
Doppler Dimming

• Using electron densities, temperatures and values of $T_\perp$ derived from a SUMER + UVCS + LASCO-C2 dataset and integrated with values from the literature, Teriaca et al. (2003) derived the outflow vs. altitude profile in interplumes required to reproduce the observed intensities.

• Then, assuming a static plume to be imbedded in the interplume ambient, they were able to reproduce the measured values of plume line intensities over the four orders of magnitude variation occurring over their data set.
Doppler Dimming

• From a SUMER data set, Gabriel et al. (2003) built a coronal outflow profile in interplumes that is consistent with the Teriaca et al. profile.

• However, Gabriel et al. predict outflows to be larger in plumes than in interplumes by a factor ≥ 2, with a velocity ≥ 70 km s\(^{-1}\) around 1.05 solar radii.

• If plasma is accelerated in plumes, can this process be variable in time?
Polar Coronal Jets

- Polar jets were discovered in EIT images (Gurman et al. 1996; Moses et al. 1997).
- They appear as bright jet-like structures originating near EUV bright points.
- They have been identified in LASCO-C2 images (Wang et al. 1998) as collimated (2°–4° wide) structures.
Polar Coronal Jets

- Their leading edges reach speeds up to 1000 km s\(^{-1}\) and bulk flows of about 250 km s\(^{-1}\) around 3.3 R/R\(_{\odot}\) (Wang et al. 1998, Wood et al. 1999).
- They have also been observed by UVCS (Dobrzycka et al. 2002) who report enhancements of a factor 2 in the electron density and of a factor 3 in velocity (to 200 km s\(^{-1}\)).
- Lites et al. (1999) report of a jet embedded in a plume structure.
- Transient outflows can be present in plumes.
Waves

- EIT observations indicate that coherent quasi-periodic perturbations with periods of 10 – 15 minutes are present in polar plumes (DeForest & Gurman 1998).
- These perturbations propagate outward with speeds of 75 – 150 km s$^{-1}$.
- However, Ofman et al. (2000) detected 7 – 10 minutes quasi-periodic fluctuations in pB at 1.9 in both plumes and interplumes.
- Periods of $\approx 20$ min are found by Banerjee et al. (2002) in both plumes and interplumes with CDS.
- Waves appear to be present in both structures.
Conclusions

- **Plumes** are outwardly directed structures that expand superradially between $1$ and $4 - 5 \, R/R_{\text{Sun}}$ and can be traced out up to $15 - 30 \, R/R_{\text{Sun}}$.
- They are cooler and denser than the surroundings.
- **Line widths and Doppler shift** are both smaller in plumes with respect to interplumes and seem to indicate interplumes as the sources of the fast wind.
Conclusions

• Doppler Dimming analysis at $1.7 \, R/R_{\text{Sun}}$ shows small or zero outflow in plumes.

• Below $1.25 \, R/R_{\text{Sun}}$ opposite results were found from two different works using the Doppler Dimming technique. However, they find a similar outflow profile in interplume.
Conclusions

• Transient jets are sometimes observed within plumes.

• Recently is emerging that no larger FIP effect seems to be present in plumes. The relevance of plumes to the fast wind cannot be excluded on abundance considerations.
Conclusions

- Waves are observed in both structures.
- A step forward in our observing techniques appear necessary to understand the relevance of plumes to the fast wind.
- Solar Probe, if confirmed and launched, will provide \textit{in-situ} measurements of ion speeds within different structures at distances as close as 3 $\text{R}/\text{R}_{\odot}$.
- Solar Orbiter will observe the Sun from an out-of-ecliptic point providing Doppler shift measurements of PCHs with a much less severe LOS effect.
Thank you