SOHO/CDS OBSERVATIONS OF PLUMES IN CORONAL HOLES

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ABSTRACT

SOHO/Coronal Diagnostic Spectrometer (CDS) observations of plumes in coronal holes are presented and discussed. Spectroscopic diagnostic techniques are applied to the observations, characterising plumes in terms of density, temperature and element abundance, in order to understand their contribution to the high-speed solar wind streaming out of the coronal holes. The observed plumes exhibit a quasi-isothermal distribution that peaks at upper transition region temperatures, with a slightly higher density, and different element abundances, compared to the surrounding coronal hole regions, thus suggesting that plumes are not the source of the high-speed solar wind.

Key words: solar corona; coronal holes; plumes; spectroscopic diagnostics.

1. INTRODUCTION

Solar coronal plumes are common stable features of coronal holes during solar minimum. Most of what was known about plumes before SOHO, was derived from Skylab observations, and was limited, in terms of a spectral characterisation. Moreover, these observations were not able to clearly distinguish the characteristics of plumes and coronal hole (inter-plume) regions. Many open questions were then waiting for an answer, a possible outcome of the new SOHO observations. For example, it was not clear if plumes were cooler or hotter. Another open question is if plumes are the source of the high speed solar wind or not.

Only a few studies have been published on plumes. For example, one study (Widing and Feldman, 1992) analysed a polar plume observed by the Skylab S082A spectroheliograph on the 11th of December 1973, and derived a large first ionization potential (FIP) bias. It is well known that different solar structures show different element abundances that appear to be related to the FIP of the various elements. Low-FIP (≤ 10 eV) elements tend to be more abundant (relative to those with a high FIP) by about a factor of 4 in the corona and slow solar wind, while coronal holes and the fast solar wind have abundances closer to the photospheric values.

Special observing sequences have been designed to observe coronal hole plumes, and carried out in August 1996 and October 1997, using the Coronal Diagnostic Spectrometer (CDS) grazing incidence spectrograph (GIS) and normal incidence spectrograph (NIS) on SOHO (Harrison et al. 1995). Many plumes have been observed. Del Zanna and Bromage (1999a) report the first detection by SOHO of a low latitude plume visible on the disc. Del Zanna and Bromage (1999b) have already shown that for this plume a large Mg VI/Ne VI intensity ratio was observed, compared to the nearby coronal hole region. Note that also Widing and Feldman (1992) reported a large Mg VI/Ne VI ratio, from which a large FIP bias was derived. However, it was shown, with a differential emission measure analysis, that this was mostly due to a temperature effect, and that this plume had only a small FIP effect, in contrast with the Widing and Feldman (1992) finding.

Here, observations of a polar plume are presented and compared to nearby coronal hole regions and to the observations of the low-latitude plume, to show that polar plumes have the same characteristics as the low-latitude plume. More observations and results based also on the analysis of other plumes can be found in Del Zanna (1999) and Del Zanna and Bromage (2000).

2. SPECTROSCOPIC DIAGNOSTICS

The intensity \( I(\lambda_{ij}) \), of an optically thin spectral line of wavelength \( \lambda_{ij} \) can be written (see, e.g., Mason and Monsignori Fossi, 1994):

\[
I(\lambda_{ij}) = A_b(X) \int C(T, \lambda_{ij}, N_e) \, DEM(T) \, dT
\]  

(1)

where \( DEM(T) = N_e N_H (dh/dT) \) is the differential emission measure, \( C(T, \lambda_{ij}, N_e) \) is the contribution function, \( A_b(X) \) is the element X abundance (assumed constant over the emitting region), \( N_e, N_H \) are the electron and hydrogen number densities, and \( h \) is the line-of-sight coordinate. Given two elements \( X_1 \) and \( X_2 \), the relative element abundance \( A_b(X_1)/A_b(X_2) \) can be deduced from the observed intensity ratio \( I_{ab}(1)/I_{ab}(2) \), once the DEM distribution is known.


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The reduced FIP effect derived by Del Zanna and Bromage (1999b) can be explained because the FIP effect was mainly derived with the use of Mg VI and Ne VI lines, as commonly done by previous authors. Since the Mg VI contribution functions are slightly skewed toward higher temperatures (compared to the Ne VI ones), at temperatures where plumes have their maximum emission measure, the DEM distribution has a strong effect in the derivation of the relative Mg/Ne abundance, as shown in Del Zanna and Bromage (1999c).

3. OBSERVATIONS AND RESULTS

Here we report CDS observations of one polar plume, seen on the 23rd August 1996. This plume lasted for several days in the north polar coronal hole, and represents one of the many 'typical' faint plumes observed by CDS during the minimum phase of the solar cycle (1996 and 1997).

A series of standard corrections was applied to the raw NIS data. These include de-biasing, flat-fielding, corrections for the burn-in of a few lines, non-linear corrections, cosmic ray removal and correction for the tilt of the spectra (details may be found in Del Zanna, 1999). Line intensities were obtained by using multiple gaussian line-fitting routines (see Haugan, 1997) on the corrected spectra, removing the 'background' intensity, which is mostly detector-dependent, and is due to scattered light in the NIS. A new CDS intensity calibration (Del Zanna, 1999) has been used here. This differs from the previous CDS calibrations, in particular in terms of the relative calibration between the NIS 1 and NIS 2 channels. Note that a different calibration affects the derivation of the FIP effect, since the Mg VI and Ne VI lines are observed in different detectors.

Fig. 1 shows monochromatic images of the region rastered by the NIS on 1996 August 23. This plume presents the typical spectral characteristics of plumes as observed by CDS. The plume is seen best in the upper transition region lines Mg VII, and Mg IX, with its base near the centres of the images. The plume is not visible in the high-FIP Ne lines, nor in the high-temperature (e.g. Fe XII) lines. The cooler lines (He II, Ne IV) show the cell centre - network pattern.

Intensity ratios of lines can give some indications of variations of density, temperature and abundances across the plume. Figure 2 shows some intensity ratio images, which indicate that the plume area has lower temperature, and at the base has increased Mg/Ne and O/Ne intensities, compared to the nearby coronal hole region. In order to increase the S/N, averaged spectra of three regions, shown in Figure 2, have been extracted: a profile along the plume, in the N-S direction; a region at the base of the plume; and a coronal hole region to the SW of the plume.

Figure 3 shows the profiles of the intensities of some selected lines from the N-S scan, from which it appears clear that the base of the plume (situated around Solar Y=850) is close to a network junction (where SOHO/MDI magnetograms show a concentration of unipolar flux). Note that since the plume

![Figure 1. Monochromatic images of the NIS observation – 23rd August 1996. The plume is seen best in Mg VII and Mg IX, with its base near the centre of the raster and the 'plume' extending up to the limb (and above). The north limb is visible in the chromospheric (He II) and transition region lines (e.g., Ne IV-VI).](image1)

![Figure 2. Ratio images of the NIS observation – 23rd August 1996, showing density ratios (Si IX); temperature ratio (Mg X/Mg IX); and O/Ne, Mg/Ne line ratios, indicating relative abundances. Selected areas are over-plotted. The plume area is a small region (within the long thin area indicated by four ‘+’ characters).](image2)
was aligned at an angle to the line of sight, the peak of the emission appears at different spatial locations, when lines emitted at different temperatures are examined. Strictly speaking, only the emission of lines of similar temperatures comes from the same region along the line of sight.

Figure 4 shows the profiles of some intensity ratios along the plume, in the N-S direction. The O/Ne and Mg/Ne ratios clearly show the presence of the plume base at Solar Y=850, and also indicate a possible second plume in the line of sight at Solar Y=890. These ratios have values similar to those of the low-latitude plume, discussed in Del Zanna and Bromage (1999a), once the same intensity calibration is applied to the data. Moreover, these ratios also indicate that it is probably the Ne abundance that is varying, relative to both Mg and oxygen. Indeed, a DEM analysis of this plume region has confirmed that the Ne/O abundance has a value lower than photospheric, by a 0.2 dex, and that this plume had a small enhancement in the Mg/Ne abundance ratio (by a factor of 1.6).

Figure 5 shows 'isothermal' temperatures derived from a few line ratios. Note that the three different ratios produce different temperatures in the coronal hole region, while in the plume region they are in close agreement, a strong indication that this plume was quasi-isothermal.

Table 1 shows the values of the parameters deduced from the averaged spectra of the plume base and the nearby coronal hole region. Although the results have relatively large errors, the indication is that the coronal density in the plume area was $N_e \simeq 1 \times 10^{10}$ cm$^{-3}$, about a factor of two higher than the nearby coronal hole region, which had a very low density. The
Table 1. Table of parameters deduced from the 23rd August 1998 averaged spectra of the selected regions. Electron densities ($N_e$) are in cm$^{-3}$, while ‘isothermal’ electron temperatures ($T_e$) are in K. The intensity ratios are calculated after the intensity calibration is applied to the data.

<table>
<thead>
<tr>
<th></th>
<th>plume base</th>
<th>Coronal hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_e$ (O IV 625.8/608.4 Å)</td>
<td>7.5±10$^9$</td>
<td>7.1±10$^9$</td>
</tr>
<tr>
<td>$N_e$ (Mg VIII 315.0/317.0 Å)</td>
<td>1.2±0.8 10$^8$</td>
<td>0.6±0.4 10$^8$</td>
</tr>
<tr>
<td>$N_e$ (Mg VIII 315.0/313.7 Å)</td>
<td>0.8±0.5 10$^8$</td>
<td>0.7±0.4 10$^8$</td>
</tr>
<tr>
<td>$N_e$ (Si IX 349.9/341.5 Å)</td>
<td>1.3±0.8 10$^8$</td>
<td>0.5±0.5 10$^8$</td>
</tr>
<tr>
<td>$N_e$ (Si IX 349.9/345.1 Å)</td>
<td>0.9±0.8 10$^8$</td>
<td>0.2±0.2 10$^8$</td>
</tr>
<tr>
<td>$T_e$ (Mg X 624.0 Å/ Mg IX 368 Å)</td>
<td>8.1±0.2 10$^5$</td>
<td>8.0±0.3 10$^5$</td>
</tr>
<tr>
<td>$T_e$ (Mg IX 368 Å/ Mg VIII 315.0 Å)</td>
<td>8.3±0.1 10$^5$</td>
<td>8.3±0.3 10$^5$</td>
</tr>
<tr>
<td>$T_e$ (Mg IX 368 Å/ Mg VII 367.7 Å)</td>
<td>7.8±0.1 10$^5$</td>
<td>7.8±0.8 10$^5$</td>
</tr>
<tr>
<td>I[(O IV 608.4 Å/ Ne IV 542.1 Å)]</td>
<td>7.4±0.9</td>
<td>4.5±0.2</td>
</tr>
<tr>
<td>I[(Mg VI 349.17 Å/ Ne VI 562.8 Å)]</td>
<td>1.1±0.1</td>
<td>0.4±0.1</td>
</tr>
<tr>
<td>I[(Mg VII 367.67 Å/ Ne VII 561.7 Å)]</td>
<td>7.1±1</td>
<td>4.1±3</td>
</tr>
</tbody>
</table>

For the first time, a low-latitude plume in a coronal hole (the Elephant’s Trunk) was identified by Del Zanna and Bromage (1999a) from its spectroscopic characteristics, rather than from its morphology. Here, it has been shown that a polar plume also presents the same spectral and physical characteristics.

The typical plume analysed shows a lower temperature than the ambient coronal hole regions. No emission in high-temperature lines, formed above 1.2x10$^6$ K, was observed. Moreover, this plume has almost isothermal plasma distribution at coronal heights, with a peak at $T \approx 8 x 10^5$ K. The surrounding coronal hole regions are less isothermal, at least at the low heights examined.

In terms of densities, measurements at lower-corona heights ($T \approx 8 - 9x10^5$ K; e.g., Mg VIII, Si IX) have rarely shown significative differences between plume and inter-plume regions ($N_e \approx 2x10^8$ cm$^{-3}$). However, due to low signal, the uncertainties are large. The measurements are consistent with plumes having slightly higher densities.

At lower temperatures ($T \sim 2x10^5$ K), in the lower transition region (O IV), plumes are not visible. Indeed, they appear to have the same densities as in the nearby coronal hole network regions ($N_e \approx 7x10^8$ cm$^{-3}$).

In terms of element abundances, the observed plumes exhibited the well-known large increase in the Mg/Ne intensity ratios, but also showed an enhancement in the O IV/Ne IV intensity ratios, suggesting that most of the variations are to be attributed to Ne abundance variations.

Spectroscopic analyses of on-disc EUV observations of coronal hole plumes have been performed. This allowed a spectroscopic characterisation of plumes to be obtained for the first time. As for many other coronal structures, plumes have also shown a wide range of characteristics. Here, only one typical faint plume as observed by CDS during the minimum of the solar cycle has been considered. More details and results based on the analysis of other observations, can be found in Del Zanna (1999) and Del Zanna and Bromage (2000).

4. SUMMARY AND CONCLUSIONS

Spectroscopic analyses of on-disc EUV observations of coronal hole plumes have been performed. This allowed a spectroscopic characterisation of plumes to be obtained for the first time. As for many other coronal structures, plumes have also shown a wide range of characteristics. Here, only one typical faint plume as observed by CDS during the minimum of the solar cycle has been considered. More details and results based on the analysis of other observations, can be found in Del Zanna (1999) and Del Zanna and Bromage (2000).
thus confirming the Phillips (1997a) suggestion that the previously reported high-FIP in plumes could be due to a temperature effect. However, after taking into account the DEM distribution of the plume, a small FIP effect (less than a factor of 2) does appear to be present.

The small FIP effect found in plumes, together with their lower temperature, compared to the ambient coronal hole regions, suggests that plumes are not the source of the fast solar wind. Indeed, considering the element abundances, since the high-speed solar wind does not have a significant FIP effect, and the plumes have, the major contribution to this wind should be coming from the inter-plume regions. This is in agreement with other recent studies based on SUMER and UVCS observations (Wilhelm et al., 1998, and Noci et al., 1997), that found plumes to be cooler than the ambient region. Note, however, that there are relatively large uncertainties in the FIP effect determination, some due to the method employed, and some due to the uncertainties related to the paucity of the lines used, the atomic physics, and in the intensity calibration. Uncertainties in the photospheric values of many elements should also be taken into account (see, e.g. Grevesse and Sauval (1998), where the C,N,O photospheric values obtained are lower by 25%, compared to the previously known “standard” values).

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