Mem. S.A.It. Vol. 74, 741

Memorie della

SOHO CDS observations of coronal hole plumes

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Abstract. Coronal Diagnostic Spectrometer (CDS) observations of a polar coronal hole plume are presented. Spectroscopic diagnostic techniques are applied to characterise the plume in terms of density, temperature, emission measure and elemental abundance. It is found that polar plume bases exhibit the same characteristics as the Elephant's Trunk equatorial plume, i.e. are nearly isothermal with temperatures $\simeq 8 \times 10^5$ K, have densities $N_\mathrm{e} \simeq 1.2 \times 10^9$ cm^{-3}, and do not have a significant FIP effect, contrary to what has long been thought.

Key words. Solar coronal holes – elemental abundances

1. Introduction

Plumes are an intrinsic feature of polar coronal holes. They appear in white-light coronagraph and eclipse images as ray-like structures, extending up to many solar radii above the limb of the Sun. In the EUV we see comet-like structures that are probably the bases of the rays seen in white-light as argued by DeForest et al. (2001). Plumes expand almost radially, and are thought to be tracing the open field lines emerging from the coronal holes, where the fast solar wind originates (Noci 1973).

The question that still needs an answer is how the fast wind is generated and the role of the plumes. Before the advent of the Solar and Heliospheric Observatory (SOHO), results were mostly based on coronagraph or Skylab data. The spatial-spectral resolution was such that it was not possible to distinguish clearly between the plasma characteristics of plumes and those of the surrounding coronal hole (interplume) regions. There was no concensus on the subject of plume temperatures and densities. Only one Skylab measurement of elemental abundances was available (Widing & Feldman 1992). Elemental abundances are an important diagnostic tool for our understanding of the sources of the fast wind. In fact, coronal abundances have been found to differ from photospheric values in a way which appears to be related to the first ionization potential (FIP) of the various elements (see the review of Raymond et al., 2001). A recent study (Von Steiger et al., 2000), based on a re-analysis of the Ulysses data finds that the fast solar wind approximately has photospheric abundances, but the slow wind has an average FIP effect of about 2-3. Widing & Feldman (1992) found a very large FIP factor of 10 for the Skylab plume. If all plumes have a large FIP effect, then they cannot be the major contributors to the fast solar wind. SOHO spectroscopic data

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(CDS, SUMER and UVCS) have indicated so far that the fast solar wind is accelerated in the interplume regions (see, e.g. Noci et al., 1997, Teriaca et al. 2003). Here, we present on-disc observations of a polar plume, to confirm the results of Del Zanna & Bromage (1999) on the low-latitude plume discovered in the Elephant's Trunk coronal hole of 1996.

2. Spectroscopic diagnostics

For a description of spectroscopic techniques see, e.g., Mason & Monsignori Fossi (1994) and Del Zanna et al. (2002). The observed intensity $I_{\rm ob}$ of an optically thin spectral line can be compared to the theoretical value:

$$I_{\rm ob} = \int A_b(X) C(T)\ DEM(T)\ dT \qquad (1)$$

where we have defined the differential emission measure $DEM(T) = N_{\rm e} N_{\rm H} \frac{dh}{dT}$, $A_b(X)$ is the element abundance, and $N_{\rm e}$ and $N_{\rm H}$ are the electron and hydrogen number densities. The *contribution function* $C(T)$ of each line contains all the atomic parameters, calculated with the CHIANTI atomic database (v. 4.0, Young et al. 2003).

The relative element abundances have been determined by normalising the DEM curves of the different elements, as described in Del Zanna & Bromage (1999). Note, however, that most authors still use an approximate approach, that neglects the DEM distribution (see Del Zanna et al. 2001). A major uncertainty in the derivation of the DEM and element abundances is due to the ionization balance calculations (those of Mazzotta et al. 1998 were used here). What is still largely neglected in the literature is the fact that a large number of ions exhibit anomalous behaviour (see the review of Del Zanna et al., 2002) and results obtained from them are normally incorrect.

2.1. The Skylab plume

The plume observations of Widing & Feldman (1992) have been re-analysed. The emission measure loci $I_{\rm ob}/(A_b * C(T))$ curves for the plume, calculated with photospheric abundances (Grevesse & Anders 1991), are displayed in Fig. 1. They clearly show that the plasma is nearly isothermal ($\log T = 5.9$), since all the curves are crossing at one point, and that no FIP effect is present.

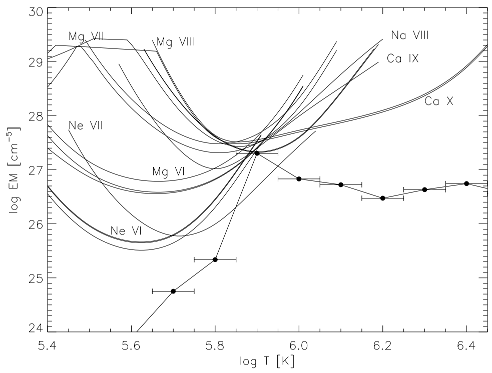

Fig. 1. The emission measure loci curves for the Skylab plume, together with the $EM(0.1)$ values (filled circles).

3. The polar plume observations of 10/11 October 1997

On 1997 October 10-11 CDS observed a plume in the north coronal hole, with both Normal Incidence (NIS) and Grazing Incidence Spectrometer (GIS). The plume was only visible in upper transition region temperatures (cf. Fig. 2) and had a density $N_{\rm e} = 1.2 \pm 0.2 \times 10^9$ cm^{-3} (as derived from Mg VII line ratios), a value higher than in the coronal hole regions, but similar to quiet sun values.

Ratios such as Mg VI/Ne VI, Mg VII/Ne VII are clearly enhanced in the plume area (Fig. 3). At first sight, this is

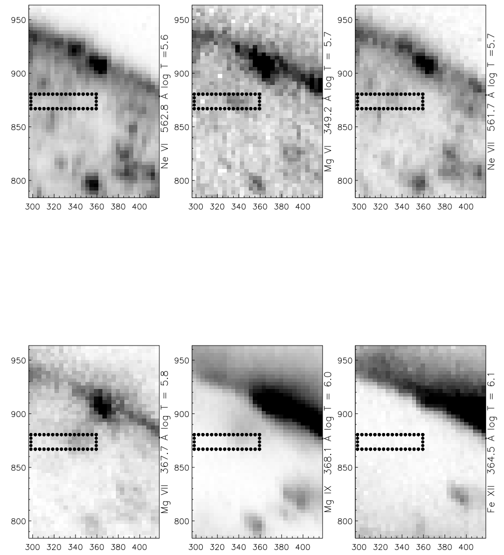

Fig. 2. Monochromatic images (negative) of the plume in a few NIS lines.

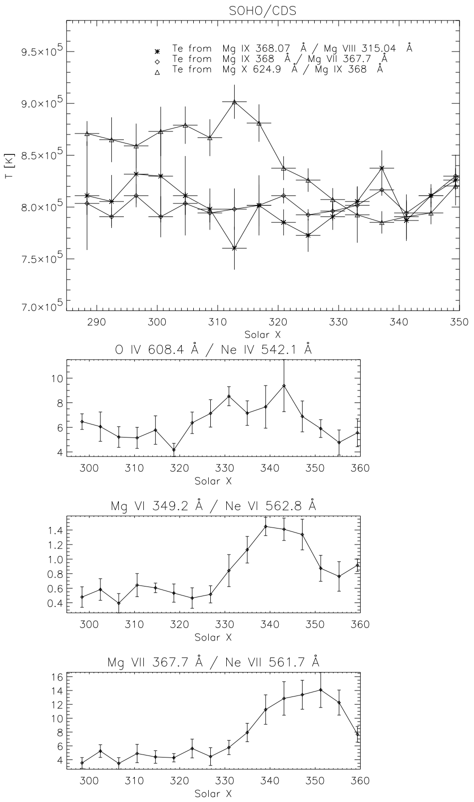

Fig. 3. Isothermal temperatures as derived from CDS line ratios indicate isothermality ($T_{\rm e} \simeq 8 \times 10^5$ K) in the plume region (Solar X=330-340″). Intensity ratios across the plume indicate a large increase in the low- vs. high-FIP ratios (e.g. Mg VI/Ne VI), and a variation of the Ne/O intensities.

suggestive of a large FIP effect (Mg has a low FIP and Ne a high one). However, a *DEM* analysis (Fig. 4) of the CDS line intensities has shown that the observations are consistent with photospheric abundances (with the exception of Ne, lowered by 0.2 dex), and a quasi-isothermal distribution peaked at $T = 7.9 \times 10^5$ K.

CDS/GIS spectra have been compared to SOHO EIT (EUV Imaging Telescope) broad-band images, to show that temperatures derived from the EIT ratio technique are largely overestimated, for plumes and coronal holes. This is partly due to the fact that the so called 'Fe XII 195 Å' and 'Fe XV 284 Å' filters are not isothermal, and in coronal holes and plumes lower-temperature lines dominate the EIT signal. As a result, these filters cannot be reliably used for temperature estimates without an in-depth analysis.

4. Summary and conclusions

Polar plumes exhibit the same characteristic signatures as the low-latitude plume, namely, enhancement of the cool, upper transition region lines such as Mg VII, no emission in the hotter coronal lines (formed above 1.2×10^6 K), and an order-of-magnitude increase in ratios of high-FIP to low-FIP lines (e.g. Mg VII/Ne VII).

Both line ratio techniques and *DEM* analysis have shown plume plasma to be close to isothermal, with a temperature $T \simeq 7 - 8 \times 10^5$ K, a little cooler than the surrounding coronal hole region. The large enhancement of some intensity ratios (such as Mg VII / Ne VII) seen at

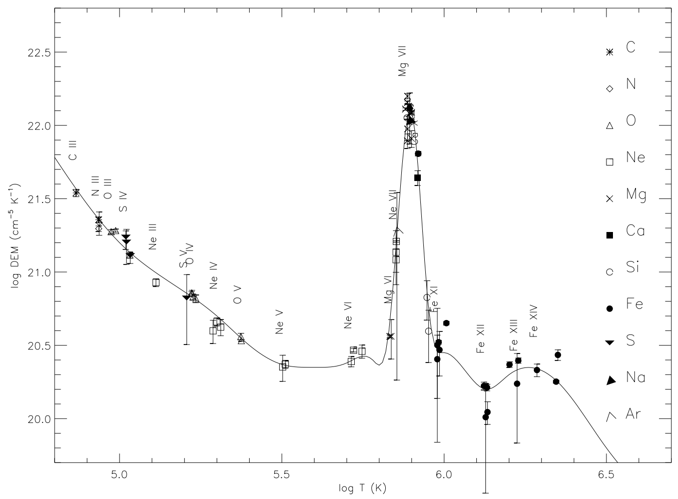

Fig. 4. The DEM distribution of the plume base area (solid line) with the observed points.

the bases of plumes can be explained by their quasi-isothermal temperature structure, rather than imply large FIP effects, still within the framework of ionization equilibrium. More refined studies will only be possible when more accurate ion fraction calculations will be available. The Skylab plume observations can similarly be explained by the plume's temperature characteristics. Approximate methods such as that one used by Widing & Feldman (1992) are still widely used, but can lead to inaccurate results in terms of element abundances. The result that plumes do not after all exhibit any significant FIP effect means that the previous deduction that plumes could not be the source of the fast solar wind is no longer valid.

Acknowledgements. Support from MIUR (Italy) and PPARC (UK) is acknowledged. SOHO is a project of international collaboration between ESA and NASA.

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