
Spectroscopic Diagnostics of Polar Coronal Plumes

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Summary. Polar coronal plumes seen during solar eclipses can now be studied with space-borne telescopes and spectrometers. We briefly discuss such observations from space with a view to understanding their plasma characteristics. Using these observations, especially from SUMER/*SOHO*, but also from EUVI/*STEREO*, we deduce densities, temperatures, and abundance anomalies in plumes and inter-plume regions, and discuss their implications for better understanding of these structures in the Sun's atmosphere.

1 Introduction

Polar coronal plumes are ray-like structures aligned along open magnetic field lines in polar coronal holes. A total eclipse of the Sun shows these rays in white light, depicting the magnetic configuration of the Sun in a coronal hole. Many studies have been carried out to relate these rays to the coronal magnetic field inferred by current-free photospheric magnetic field extrapolation. The coronal plumes and the inter-plume regions seem to play a rôle in the acceleration mechanism of the fast solar wind. They have been extensively observed from space across the electromagnetic spectrum. Investigations have been made to unravel the appearance and disappearance of these plumes. The fact remains that we know little about them, probably because we have no direct knowledge of the coronal magnetic field. The identification of the sources that produce coronal plumes and their contribution to the fast solar wind is still a matter of investigation (DeForest et al. 1997; Wang et al. 1997; Wilhelm et al. 1998; Gabriel et al. 2003; Teriaca et al. 2003; Antonucci et al. 2004; Curdt et al. 2008). To understand the processes of plume formation, we need to know the physical conditions in plumes and the surrounding inter-plume environment, such as electron densities, n_e , and electron temperatures, T_e , the effective ion temperatures and non-thermal motions, the plume cross-section relative to the size of the coronal hole, and the plasma bulk speeds.

In this paper, we briefly discuss the observations of polar coronal plumes from space with a view to understanding their plasma characteristics. Using

these measurements, especially from SUMER/*SOHO*, we deduce electron densities and temperatures as well as abundance anomalies in plumes. This will improve the understanding of these structures in the Sun's atmosphere, which are the subject of an International Team Study at ISSI, Bern¹.

2 Spectroscopic Observations of Coronal Plumes

In the framework of a *Hinode/STEREO/SOHO* cooperation, observations of coronal plumes in a coronal hole were performed in April 2007, using spectrographs and imagers (cf., EUVI/*STEREO*) aboard these spacecraft (cf., Curdt et al. 2008). SUMER performed a scan in the southern coronal hole of the Sun from 7 April 2007, 01:01 UTC to 8 April 2007, 12:19 UTC. Emission was observed from the O VI, Ne VIII, Mg VIII, Mg IX, Si VIII, Si IX, Al IX, and Na IX lines. The spectral lines were recorded almost simultaneously at each location. Contribution functions and the FIP (First Ionization Potential) values of the corresponding elements are shown in Fig. 1. Density-dependent Si VIII and temperature-dependent Mg IX line ratios were observed to produce n_e and T_e maps. Line-width studies allowed us to monitor the ion temperatures, which are much higher than the electron temperatures.

3 Results and Discussion

Figure 2 shows a large raster above the southern coronal hole, obtained in several VUV emission lines. All maps are noisy above a height of 150 Mm. The density and temperature maps are, therefore, averaged over larger height ranges along the line of sight. A detailed analysis of similar observations obtained in 2005 has shown that the plume density is about five times higher than that of the environment in this altitude range (Wilhelm 2006). The electron temperature, T_e , in plumes is lower than in interplume regions (cf., Wilhelm et al. 1998). This is confirmed by the Mg IX T_e -sensitive line pair in the present data. The insensitivity of the Si VIII ratio to scattered radiation is discussed by Wilhelm et al. (1998). It is caused by the lines being barely visible on the disk (Curdt et al. 2001) so that the stray-light is subtracted by the standard background correction for coronal observations.

Electron density and temperature maps are shown in Figs. 3a and 3b, respectively, in which gray represents cooler plasma conditions. All radiance maps (except for Al IX) show the plume structures. It is still to be investigated why the Al IX radiance map does not show plume structure. The line ratio Ne VIII/Mg VIII can monitor the abundance variations between high-FIP and low-FIP elements. However, the different temperatures in plume and interplume regions should be taken into account in view of the high-temperature

¹ <http://www.issibern.ch/teams/solarcoronal>

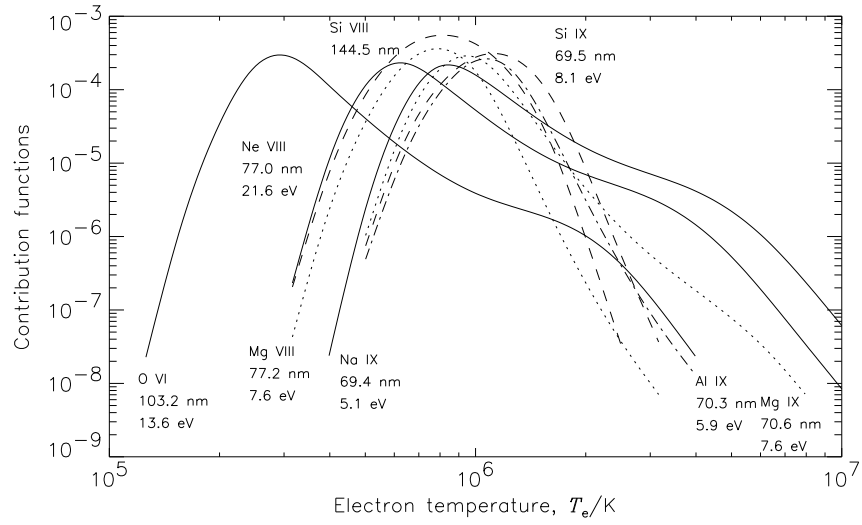


Fig. 1. Contribution functions of the observed lines and the FIP values of the corresponding elements, based on ionic fractions from Mazzotta et al. (1998). Neon and oxygen have high FIP values, whereas the other elements have low values < 10 eV.

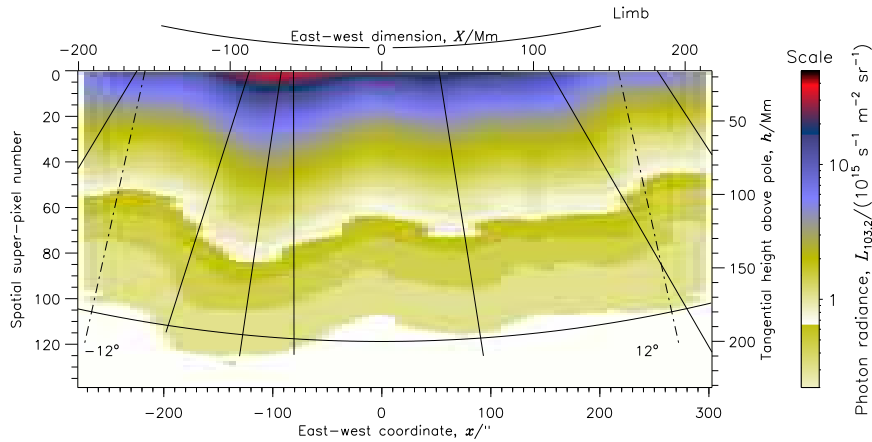


Fig. 2. A large raster above the southern coronal hole was obtained in several VUV emission lines. It took 36 h starting on 7 April 2007 at 01:01 UTC from West to East. The photon radiance of O VI λ 1032 is shown here. Radial dashed-dotted lines are shown at $\pm 12^\circ$ off the pole.

tail of the lithium-like Ne^{7+} . The contribution functions of Ne VIII and Mg VIII overlap considerably in the temperature range just below 1 MK. The contribution functions of Ne VIII and Mg IX are more similar at higher temperatures than that of Ne VIII and Mg VIII . And yet, the same signature is visible which indicates that a temperature effect hardly plays a rôle. In particular, the $\text{Ne VIII}/\text{Na IX}$ ratio shows that the abundance anomaly is real and not a temperature effect. The estimated FIP bias for Ne and Mg is 1.5 to 2. The search for Doppler shifts in the O VI line did not indicate any significant flows in plumes, although some of them were directed out of the plane of the sky (cf., Curdt et al. 2008). The super-radial expansion of plumes is evident in the O VI map.

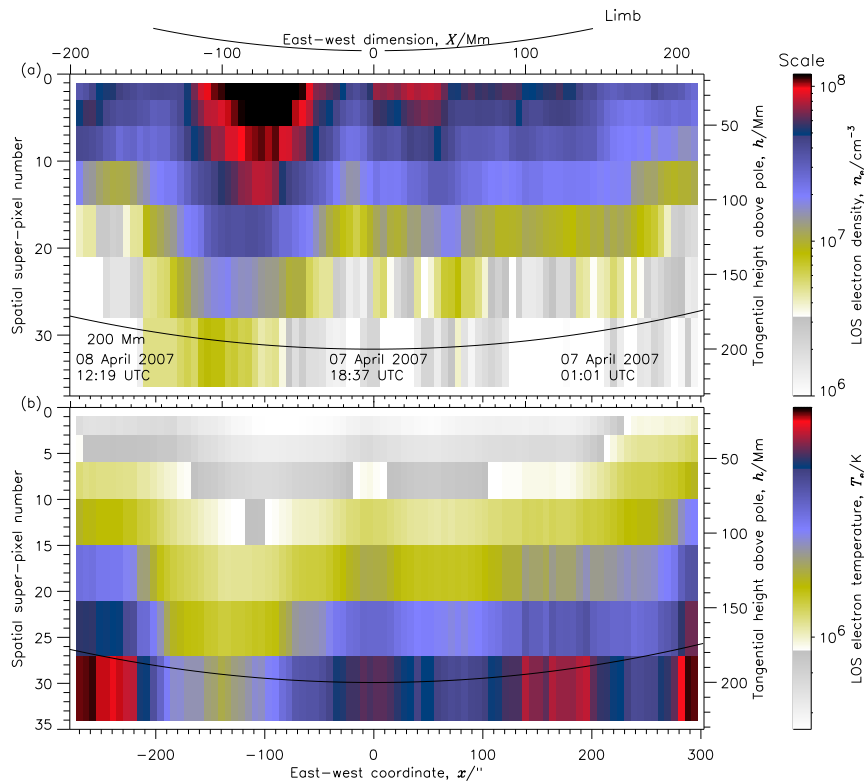


Fig. 3. (a) Electron density map; (b) Electron temperature map (gray represents cooler plasma conditions).

Investigating lines of high- and low-FIP elements in the SUMER data set, we find:

- a temperature effect hardly plays a rôle, reconfirming the existence of abundance anomalies in plumes;
- T_e is lower in plumes than in inter-plume regions in agreement with earlier findings;
- plumes have higher densities than their environment;
- no significant flows could be detected in coronal plumes below 150 Mm.

Implications of deducing physical parameters, such as ion and electron temperatures, densities, abundance anomalies, outflow velocities in plumes and inter-plume regions are crucial to develop theoretical models of these features and of high-speed solar wind. This will also help in understanding the plume footpoint (e.g., XBPs), the relationship between processes at the footpoint and the plume characteristics, and to explore whether there is a relationship between plumes and the fast solar wind. We plan to expand this work and to communicate it as an article to the *Astrophysical Journal*.

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