PLASMA DIAGNOSTICS OF THE LARGE-SCALE CORONA WITH SUMER

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ABSTRACT

In the present work we measure physical quantities such as electron temperature, emission measure, element abundances, line widths, non-thermal velocities, and photo-excitation effects over a wide quiet Sun region above the west solar limb. The dimensions of the field of view are 0.5 Rₚsun × 1.8 Rₚsun. Our aim is to provide a comprehensive, empirical picture of the off-limb solar corona that can provide experimental constraints to theoretical models of the large-scale coronal structure, coronal heating, and solar wind acceleration.

Key words: Solar Wind – Plasma Diagnostics.

1. INTRODUCTION

Models of coronal heating and solar wind acceleration need accurate knowledge of the plasma properties of the solar upper atmosphere close to the solar surface (1.0-1.5 Rₚsun). For this reason, a number of analyses of coronal hole spectra were aimed at measuring the acceleration of fast solar wind plasma, and similar attention has been paid to the quiet Sun corona and streamers, to investigate the acceleration of the slow solar wind. The importance of the physical properties and of the element abundances of the lower corona for the determination of the solar wind origin and acceleration mechanisms has been recently discussed by Woo et al. (2004), while a review of some of the most important coronal results obtained by CDS and SUMER was given by Feldman et al. (2005). However, all these studies suffered from the limited size of the field of view, since the latter was usually restricted to one or a few slit sizes: in this way, no comprehensive information on the large-scale corona and on the boundary between coronal holes and quiet Sun could be obtained. Only a few large-scale studies of the solar corona properties are available, and they have been carried out with UVCS at altitudes between 1.4 Rₚsun and 2.5 Rₚsun by Spadaro et al. (2005) and Ventura et al. (2005), in search of the interface between streamers and coronal holes; however, these studies were unable to provide the connection to lower-altitude coronal structures since they were below the UVCS field of view. Thus, a comprehensive study of the physical properties of the entire corona at low altitude is still missing. In the present work we will provide the measurements necessary to complement UVCS results with information on the solar corona at altitudes in the 1-1.5 Rₚsun range.

We analyze a large set of off-disk spectra with a field of view ranging from 1.02 to 1.5 Rₚsun in the E-W direction and from -0.9 to 0.9 Rₚsun in the N-S direction. The plasma in the field of view consists of quiet Sun corona, but small coronal hole areas were present at high latitudes, whose emission along the line of sight contaminates the quiet Sun spectral line intensities.

2. OBSERVATIONS

The spectra analyzed in the present work were observed on April 22-24, 1998. The center of the SUMER slit was placed at 36 different locations corresponding to a 6×6 grid shown in Fig. 1. The field of view includes mostly quiet Sun plasma, although some coronal hole plasma is present in the NW corner. At each of the 36 grid locations, six spectral windows were observed, each recording a 43 Å-wide section of the SUMER spectrum: these windows were centered near 880 Å, 955 Å, 1035 Å, 1090 Å, 1155 Å and 1235 Å. In addition, the complete SUMER spectrum was recorded at six positions inside the field of view of the 6×6 grid; these positions are also shown in Fig. 1.

Scattered Light From the Solar Disk: Scattered light usually contaminates significantly the SUMER spectra when they are recorded at limb heights greater than about 1.3 solar radii. Scattered light consists of a ghost spectrum recorded on the detector as if it was observed by an instrument with no spatial resolution, which viewed the Sun-as-a-star with no Doppler shift. This spectrum overlaps the true coronal spectrum and contaminates it. By knowing the Sun-as-a-star spectrum and the values of the in-
tensity of lines composed only of scattered light as a function of height, it is possible to evaluate the scattered light contribution to the measured intensities of true coronal lines using the Sun-as-a-star ratios of the former to the latter.

We measured the scattered light using chromospheric lines from C II, O IV, N IV and He I, determining an average scattered light intensity map normalized to its median value. We then determined the Sun-as-a-star intensity ratios between the coronal lines and the chromospheric lines used for scattered light measurement from available spectral atlases of the disk. These ratios, and the normalized scattered light map, were then used to calculate the contribution to the coronal line emission. For N V, O VI, Ne VIII, Mg X and Fe XII we have also subtracted the scattered light by considering the line profiles, since we are interested in the widths of these lines. The method we used is the same as the one described above, with the only difference that instead of subtracting scattered light line intensities, we have subtracted the scattered light spectrum pixel by pixel along the wavelength direction, assuming that the width of pure scattered light lines is the same as in the solar disk spectrum.

3. PLASMA DIAGNOSTICS

to carry out plasma diagnostics, we used CHIANTI emissivities (version 5.0, Landi et al. 2006), Mazzotta et al. (1998) ion fractions, and Feldman &

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<tr>
<td>1238.82</td>
<td>N V</td>
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<td>Si VIII</td>
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<td>1031.92</td>
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<tr>
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<tr>
<td>770.41</td>
<td>Ne VIII</td>
<td>580.92 b</td>
<td>Si XI</td>
</tr>
<tr>
<td>780.33</td>
<td>Ne VIII</td>
<td>1242.00</td>
<td>Fe XII</td>
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Table 1. Lines used in the present analysis. b The line is observed in second order.

Laming (2000) coronal abundances. We first built intensity maps of the field of view, using scattered light-corrected intensities of lines of low-FIP and high-FIP ions: examples are shown in Fig. 2.

Figure 2. Intensity maps of the Mg X 624 Å, Fe XII 1242 Å and Si XI 580 Å lines.

Photo-excitation and self-absorption of Li-like resonance lines: In regions where the electron density is low, photo-excitation by self-absorption or resonant scattering of the line emission from lower altitudes may compete with collisional excitation when the intensity of the line is strong. The 2s 2p 2S-2P doublets of N V, O VI, Ne VIII and Mg X might be affected by these two processes, and it is necessary to assess their importance on line intensities, in order to correct for them. Fig. 3 shows the doublet ratio for these ions as a function of height. The theoretical collisional ratio is also shown.

The signature of self-absorption is a decrease of the doublet ratio in proximity of the solar limb. Only Mg X shows some indication of self-absorption close to the limb, but this effect is within the ratio uncertainties. This process will be neglected in the rest of this work.
In the case of pure collisional excitation, the intensity ratio $R$ of the Li-like doublets correspond to the ratio of their collision strengths, i.e., $\approx 2:1$. In the case of pure photo-excitation the intensity ratio of purely photo-excited lines is $4:1$; from intermediate values we can measure the relative importance of the two excitation mechanisms. Figure 3 shows that the O\textsc{i} ratio is the most affected by photo-excitation, and photo-excitation provides 30\% to 83\% and 18\% to 70\% of the total emission in the 1031 Å and 1037 Å lines respectively. In Ne\textsc{viii}, the contribution of collisional excitation decreases down to 54\% and 70\% for the 770 Å and 780 Å lines respectively. Mg\textsc{x} is little affected by photo-excitation. The contribution from photo-excitation was subtracted from the measured intensities of each of these lines before applying the plasma diagnostic techniques used here.

**Electron Temperature:** We used the Mg\textsc{x} 624.94/Si\textsc{xi} 580.92 line ratio as a diagnostic tool to measure the electron temperature. The resulting temperature map shows that the plasma is slightly hotter (< 25\%) at higher altitudes. This can also be seen from Fig. 4, showing the temperature measurements as a function of distance from the solar limb as stars. The measured temperature is in the range 6.10$\leq$log T$\leq$6.20.

**Nonthermal Motions:** We have measured the line widths at all positions assuming Gaussian profiles, and from line widths we determined the non-thermal velocities assuming that ion and electron temperatures are equal.

The maps of non-thermal velocities, obtained using the measured electron temperatures, are shown in Fig. 5. The change of non thermal velocities is mostly concentrated in the NW portion of the field of view, where coronal hole plasma is present, and it ranges between 20 and 40 km s$^{-1}$, while in the other is around 10 km s$^{-1}$.

**Electron densities:** Electron densities were measured using the Si\textsc{viii} 1440/1445 line intensity ratio observed in the full spectrum dataset at the positions indicated in Fig. 1 by diamonds. Measured electron densities range between 4.0$\times$10$^6$ and 1.3$\times$10$^8$ cm$^{-3}$ and decrease rapidly with distance.

**Emission measure (EM) and temperature:** The measured EM values (in cm$^{-3}$) decrease with the distance from the limb and are in the 42.0$\leq$log EM$\leq$44.2 range. We have fitted the dependence of the EM from height with a parabola and determined the plasma temperature from the scale.
height of the electron density, calculated from the fitted EM using $EM = N_e^2 A L$ (where $A$ is the area of the field of view and $L$ is the path length) and the hydrostatic equilibrium assumption. The EM-based temperature is displayed in Fig. 4, where the discrepancy with the values obtained from line ratios is large, and seems to indicate that the plasma is not in hydrostatic equilibrium. These results, however, hold only if a number of assumptions are verified: 1) the plasma in the field of view lies along the same field lines; 2) the line-of-sight $L$ is constant, and 3) the plasma filling factor is unity.

**Elemental abundances** We have measured the Mg/Ne relative abundance from the EM values obtained from those ions, finding that the assumed Mg/Ne relative abundance needs to be increased, so that the FIP effect appears enhanced as height increases; the largest corrections to the FIP bias occur in regions of the field of view most affected by the coronal hole plasma.

### 3.1. Elemental settling

The Mg/Fe and Si/Fe ratio allow to measure the Fe gravitational settling, finding that Fe is strongly depleted with height, especially where coronal hole plasmas might be contaminating the emission. The depletion in Fe XII causes the EM values obtained from the Fe XII line intensity to be smaller than those obtained with Mg, implying in turn a smaller EM-based temperature, as shown in Fig. 4.

### 4. SUMMARY

In the present work we have measured the physical properties of a large area of the solar corona above the west limb. We have found that

1. Photoexcitation affects O VI and Ne VIII lines;
2. The temperature is constant with distance within uncertainties in all the field of view, and it is in 1.3-1.6×10⁶ K range.
3. Non-thermal velocities from Mg X and Si XI slowly increase with height, while those from N V, O VI and Ne VIII show a factor of two increase where coronal hole plasma is present;
4. The EM-based temperature is much higher than measured from line ratios, showing that the plasma is not in hydrostatic equilibrium;
5. The FIP bias increases with height;
6. Fe is affected by gravitational settling.

Due to their spatial variability, it appears that non-thermal velocities and element abundances are the most promising tracers of boundaries between coronal holes and the quiet Sun, while the electron temperature is more dependent on the lines and the ions chosen for line intensity ratios.

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