BRIGHT PLUMES AND DARK LANES AS OBSERVED IN Mg X 625 Å AND N V 1239 Å IN THE SOLAR POLAR CORONA

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ABSTRACT

We present an analysis of SUMER observations made in the north polar regions of the Sun for 6 hours on July 20, 1996. The intensities, positions and widths of the EUV emission lines of Mg x at 624.943 Å and N v at 1238.821 Å have been measured. Ray-like features in intensity have been observed as a function of height above the solar limb. These so-called polar plumes are analyzed and compared with the darker lanes of the ambient corona embedding the plumes. The intensity shows structures right from the visible limb out to 150" - 200", with a typical spatial width of about 2" - 3" in polar angle. The intensity ratio between these polar plumes and the darker rays of the ambient corona is about 1.3 to 2.5. The line width also shows small-scale variations along the limb, which tend to be anti-correlated with the intensity. The scale heights of the radial intensity profiles of the bright plumes and dark lanes are the same and about 60". The radial profiles of the Mg x line width and position have a similar shape. They stay constant or slightly increase at low altitudes, while they clearly increase at higher altitudes. From the radial profiles of the observed line width we find that the equivalent velocity is 40 - 50 km/s and increases with altitude, especially for heights above the limb greater than 110". Altitude profiles of the intensity and the Doppler shifts and widths of the N v line are also presented, which indicate no sizable outflow velocities in this line. A continuous increase of the mean Doppler widths of both Mg x and N v is found and seems indicative of an increasing level of unresolved turbulence or rise in kinetic temperature of these heavy ions with height in the transition region and corona. The physical and theoretical implications of our observations are briefly discussed.

Key words: Sun: corona, plumes, EUV emission lines

1. INTRODUCTION

The polar coronal holes of the Sun are regions of paramount interest in solar and heliospheric physics, because they are known to be the source of long-lived high-speed solar wind streams, as the Ulysses mission has clearly shown (see, e.g., Marsden et al., 1995). The SUMER instrument (Wilhelm et al., 1995) provides important plasma diagnostics of the lower layers of the solar atmosphere through Doppler spectroscopy of EUV emission lines, characteristic of the temperature range from some $10^4$ to $10^5$ K, i.e., for the upper chromosphere, transition region, and lower corona.

Recent coronagraph pictures of solar holes show thin ray-like structures of an angular extent of 2° to 3° (Guhathakurta & Fisher, 1995, 1996), which extend out to many solar radii and seem to delineate the magnetic field lines, which are increasingly bent away from the radial direction with decreasing latitude as measured from the pole. The footpoints of these rays are visible in the SUMER off-limb images. In particular the polar plumes have been imaged in detail (for first imaging results see the paper by Lemaire et al., 1997). Here we present 6 hours worth of data obtained from a scan of the north polar coronal hole on July 20, 1996, covering a range of about ±20° in latitude around the pole.

There are many studies on transition-region radiation, however only few studies on the lower-corona emission lines (see, e.g., Mariska, 1992). Hassler et al. (1990) analyzed the Mg x 625 Å and 609 Å lines observed off the solar limb and found the Gaussian width increases with height and reaches 55 km/s at 1.1 - 1.2 $R_\odot$. However, this study only represents a few seconds of coronal observations. Further long studies are certainly needed. Such continuous observations are presently provided by the SUMER extreme ultraviolet spectrometer on SOHO.

The SUMER instrument is described in detail by Wilhelm et al. (1995), a paper where the observational sequences and technical functions of the spectrometer are explained. SUMER covers the wavelength range from about 465 to 1610 Å in first and second order together, and has a spatial resolution of
2. OBSERVATIONS

The observations were made with the 1" x 300" slit. The central position of the slit in north-south direction was located at $y = 980^\circ$ in the solar x-y coordinate system. The photospheric radius as seen from SOHO was 953". The telescope scanned from -361" to +355", with a step size of 1", yielding an array of 480 x 300 spatial pixels, for each of which spectra of 50 pixels in wavelength around a selected line were taken. For our data set the exposure time was 45 s. The data were not processed concerning flat field corrections, straylight or geometric distortions of the detector, which was not a serious problem because we averaged over both the x and y directions, before we applied Gaussian fits to the line profiles. The spatial resolution thereby decreased to about 1" in the y direction and to 19" in the x direction.

The two lines of interest here are N V 1239 Å and Mg X 825 Å, for which a wavelength calibration was obtained by comparison with the known position of the unshifted Si I 1250 Å emission line, which was measured simultaneously as a chromospheric reference line. Each pixel in the N V spectrum corresponds to 0.044 Å, or 10.5 km/s in equivalent Doppler shift. Since the count rates become very low off limb, we had to average over many spatial pixels, in order to get decent statistics in the spectral domain and better spectral resolution. While degrading the spatial resolution this way by more than a factor of ten we improved the mean spectral resolution to values of about 0.1 to 0.2 of a pixel, corresponding to a few kilometers per second in equivalent velocity.

Figure 1 shows an image of the intensity of the Mg X line over the north polar region of the Sun. We see very clear coronal rays in the image. The bright regions may be called Mg X plumes. There are three bright and adjacent dark regions, which may represent the ambient coronal hole. These dark structures and bright plumes do not all point in the radial direction. To describe the geometric position of these structures we use an angular coordinate system shifted with respect to the Sun’s center to the point (0", 494") in the x-y coordinate system. Lines with constant polar angle $\alpha$ in this shifted coordinate system describe the geometric extension of the rays-like structures very well. The reason seems to be that the other magnetic field lines are more strongly bent than for a dipole because of sizable quadrupole contributions (see, e.g., the inner corona imaged by LASCO, Schwenn et al., 1997). The solar latitudes of those points, where the lines of constant $\alpha$ cross the ‘limb’, are given by the numbers in brackets at the bottom of Figure 2.

3. RESULTS

Figure 2 shows the variation of the intensity, line width and line position as derived from the Gaussian fit to the measured Mg X 824.943 Å line as functions of the polar angle $\alpha$. The count rates of the bright plumes and the dark rays differ by about a factor of 1.3 to 2.5. The spatial size of these structures is about 2" to 4" in $\alpha$, corresponding to 1" to 2" in solar latitude. We show from the top panel to the bottom panel first the intensity, i.e., total counts in one spatial pixel obtained during the exposure time of 45 s and through integration over the wavelength range extending from the spectral pixels 16 to 41 (1 px \(\pm 0.02185 \) Å). Then we show the Gaussian-fit parameters, i.e., the standard deviation (\(\sigma\), one unit is \(\sqrt{2}\) px \(= 14.8\) km/s) and central wavelength (\(\lambda\)). The uncertainties of $\sigma$ and $\lambda$ have been estimated by the average differences between the Gaussian fit parameters and the moments of the line. This error corresponds to 0.1 pixels for the curves in both panels. The dark-shaded areas marked with p1, p2, and p3 show three plumes. The light-shaded areas marked with c1, c2 and c3 show three dark lanes of the ambient coronal hole. The data have been spatially averaged over 9 pixels along the y and 5 pixels along the x coordinate for the heights 23", 71" and 119", respectively. From Figure 2 we can infer as a general trend that the line widths increase with increasing distance from the limb, changing from about 45 km/s at 29" to about 55 km/s at 119", consistently with the earlier observations made by Hassler et al. (1990).

The bottom panel of Figure 2 shows the variation of the line position. If we assume that the Si I line at 1250.584 Å, which reaches its maximum in the line profile at pixel 13, since being a chromospheric

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Figure 2. The spatial variation of the line intensity, width $\sigma$ and position $\lambda$ of MgX 624.943 Å along three circles around the pole at different heights, 29$''$.7 (solid line), 71$''$.3 (dashed line), and 119$''$.2 (dotted line), respectively, above the solar 'limb' (as defined by the circle with radius r = 958$''$.8). The angular position of the structures is marked by $\alpha$ (see the text for its detailed definition). The solar polar angle of the cross points between lines of constant $\alpha$ and the limb are indicated by the numbers in brackets (degrees) at the bottom of the figure.

The MgX emission line does not have a Doppler shift, then the rest wavelength position of MgX 624.943 Å should be at pixel 28.9. From the figure we see a blue shift of this line for $\alpha$ greater than -20 and for the height 119$''$. Figure 3 shows the Gaussian-fit-parameter variations with distance from the solar limb for the three plumes (p1-solid, p2-dashed, p3-long dashes) and the three ambient coronal hole regions (c1-dotted, c2-dash dot, c3-dash dot dot dot dot). The top panel gives the resulting intensity variations. For comparison, we put also the intensity profiles of Sii on this figure; see the lines inside 40$''$. The region between the two maxima of the Sii and MgX lines represents the range over which the coronal heating takes place, and in which the coronal temperature (in terms of line formation temperature) jumps from $10^4$ to $10^6$ K. This jump occurs within a distance range of about 30$''$, corresponding to about 21000 km.

The MgX intensity decreases with height. The six lines in Figure 3 are rather straight and run parallel to each other from 50$''$ to 150$''$, whereby the p1 profile coincides with the profile of c2. That means the ratio of the intensity between the structures does not change and the structures extend to at least 150$''$. The corresponding scale height is about 60$''$.

The middle panel shows the profiles of the line width. The general trend revealed by these data is that the line width increases radially starting from 42 km/s at 20$''$; it stays at about 50 km/s (or slightly increases) out to 110$''$ distance off limb, and then increases again to about 57 km/s at 160$''$. This second increase does not appear in the data of Hassler et al. (1990). The bottom panel shows the profiles of line position. If we identify the unshifted MgX line position to be at pixel 28.9, then we see red shifts at lower heights, while some blue shifts occur at high altitudes in each curve, except for the p1 profile, which has only red shifts. However, on the limb we find the MgX maximum at the 28th pixel (not shown here). If we assume this is the unshifted position of the line, then most of the lines observed off limb would be blue shifted. Here a 1-pixel shift corresponds to 10.5 km/s in flow speed.

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Figure 4. Radial profiles of the three Gaussian-fit parameters of the $\text{N} \nu$ 1239 Å line. From top to bottom the line intensity, width ($\sigma$, 1 unit is $\sqrt{2}$ px = 14.8 km/s), and wavelength ($\lambda$, 1 px = 10.5 km/s), are displayed along the plumes (p1) and ambient coronal hole (c1) dark lane as marked in Figure 2, where the legend is solid for p1, dotted for c1, and dashed-dotted for p1 background, and dashed for c1 background. The height is here defined as the difference between the distance of the radiating parcel (in a 2-D plot) and the arbitrary reference distance of 953°, which is near the visible limb of the MgX emission line.

In Figure 4 we show the radial profiles of the three Gaussian-fit parameters of $\text{N} \nu$ 1239 Å. From top to bottom the line intensity, the width ($\sigma$), and wavelength ($\lambda$), are displayed along the plumes and ambient coronal hole dark lane as marked in Figure 2, where the legend is solid for p1, dotted for c1, and dashed-dotted for p1 background, and dashed for c1 background. The altitude is here defined as the difference between the distance of the radiating plasma parcel (in a 2-D plot) and the reference distance of $r = 953°$, which is near the visible limb as seen in the MgX emission line. The spectra have been averaged over 19 spatial pixels along the x coordinate and over the whole shaded range in y, over which the plume or dark lane in the ambient coronal hole extends laterally (see Figure 2).

Note that the intensity increases from the disk (spatial pixel -30°) to a maximum value off limb, which is located near -6° and roughly twice as large as the on-disk value. This is expected for the line of sight being tangent to the limb, in which case the plasma column sampled simply doubles in length. The intensity then steeply declines to 10 count/px/4s at 20° and levels off to a linear decline somewhat above the background. Note that the $\sigma$ and $\lambda$ curves become somewhat ragged between 20° and 70°, which is due to the low number of counts in the line and thus poor statistics. There are no systematic differences between the brighter plume and darker lane. The line width increases from about 2.5 pixels at -30° to 3 pixels at 20°, thus indicating either an increasing intrinsic temperature of the $\text{N} \nu$ ions or a sizable turbulent velocity. The equivalent line width increases from 37 km/s to 44 km/s, which is less pronounced than for the MgX line. The $\text{N} \nu$ line shift tends to decline relatively, but only by about half a pixel or even less, corresponding to an increasing relative red shift with altitude.

Figure 5 shows some examples of the averaged line profiles (triangles for plumes and crosses for the ambient dark corona) and the corresponding Gaussian-fit profiles of the MgX 625 Å line. Clearly visible are the increases in line width and shift with increasing height. Similar examples of the averaged spectral line of $\text{N} \nu$ at 1239 Å are shown in Figure 6, which gives in the top panel the line shape at an altitude of 70° along the plume p1 and dark lane c1. The middle panel and bottom panel show the averaged lines as obtained closer to the limb at the altitudes 30° and 10°. The increasing line width with distance off limb is clearly visible in the sequence of line shapes from the bottom to the top, whereas no clear line shift is discernable.

The data in the previous figures were smoothed considerably by spatial averaging. We show the less-averaged data (only averaged over two pixels along y, no averaging along x) together with data of other lines again in Figure 7, in which the intensity profiles of $\text{N} \nu$ 1239 Å (solid lines), $\text{Si} \Pi$ 1250 Å (dashed lines), MgX 625 Å (dashed-dotted lines), and the background for $\text{N} \nu$ 1239 Å (dotted) are displayed. Here the intensity was calculated by summing up the total number of counts in the spectral window around the line.

In Figure 7 the maxima of the $\text{Si} \Pi$ and $\text{N} \nu$ emission coincide and are located to the left of the minimum of the MgX emission, which dominates in the corona for distances larger than 10°. The transition region line of $\text{N} \nu$ dominates the intensity in the distance range between 0° and 10°, whereas the upper chromospheric emission line of $\text{Si} \Pi$ dominates from -20° to 0°. The continuation of the MgX line in this range corresponds to the continuum emission around 1250 Å seen in first order by the SUMER spectrometer. We may use the difference between the lower edge of the MgX intensity at 5° and the maximum of $\text{N} \nu$ at -6° in the top panel of the plume to estimate the average temperature gradient, giving $\Delta \log T/\Delta r = (6.1 - 5.3)/11 = 0.073$, which corresponds to a log $T$ of 0.073 per arcsec. Here the formation temperatures 1.26 x 10^5 K for MgX and 2 x 10^5 K for N+ ions have been used. Note that S+ has a formation temperature of 2 x 10^4 K only. The temperature run through the transition region estimated by these three point is rather steep and amounts to about 10^5 K per arcsec. Note that the MgX intensity in the range from pixel 10 to 30 is rather constant, perhaps indicating a steady contribution originating from hot loops extending above the visible solar limb (Dowdy et al., 1986).
4. DISCUSSION

We have studied the radiation of Mg X 625 Å in the north polar regions of the Sun. The ray-like structures have the angular size of $2^\circ$ to $3^\circ$ in solar latitude and may be related with the supergranular cells in the chromosphere, which have a similar size. However, since the radiation of the Mg X line is very weak on the solar disk, we cannot directly trace these ray-like structures to the supergranular cells. The decreasing intensity may be explained by a static atmospheric model with thermal pressure balancing solar gravity. However, the observations for line width and line position seem to suggest that at lower heights, the radiation may come from hotter network loops, while at greater altitudes the radiation may come from coronal funnels and the expanding solar wind, supporting the picture drawn by Dowdy et al. (1988). We do not know whether hot dilute loops crossed the plumes and ambient coronal hole regions, thus smoothing the gradients of the intensity. But we did not see any clear loop-like structures in the image of Figure 1.

Since Mg $^{+9}$ has the atomic mass number 24, the thermal speed at the formation temperature ($T_{Mg} = 1.26 \times 10^{5}$ K) is about 21 km/s. The line widths derived from Figure 3 are much broader in equivalent velocities. The Doppler width is calculated as $c \delta \lambda / \lambda$, where $\delta \lambda$ is $\sqrt{2} \times \sigma$, and equals $(2k_B T_{Mg}/m_{Mg} + \delta v^2)^{1/2}$, under the assumption that the ion formation temperature equals the ion temperature and that there is turbulent wave broadening of the line. For a total Doppler width of 50 km/s, the associated wave amplitude $\delta v$ would be 40 km/s. Our observations of the size of the wave amplitude and about their radial gradients, and the notion that wave amplitudes are higher in the dark lanes than in the plumes, all these features support the model ideas presented recently by Tu & Marsch (1997), and Marsch & Tu (1997a,b). The intensity variation we saw in Figure 3 may be the result of a superposition of many differently oriented coronal structures intergrated along the line of sight of SUMER in the x direction. For a consistent understanding of these observations one needs three-dimensional images and models, which do not exist at the present time.

We have also studied the radiation of N v 1239 Å in
50 km/sec, the associated wave amplitude \( \delta v \) should be 48 km/s. Our observations of the size of the wave amplitude and about their radial gradients are somewhat larger than earlier estimates (Mariska et al., 1992) and support the assumptions made about wave amplitudes in recent model calculations by Marsch & Tu (1997a) on wave-driven flows in the magnetically open coronal funnels.

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