On the network structures in solar equatorial coronal holes

Observations of SUMER and MDI on SOHO*

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Abstract. By combining observations of the Sun made by SUMER and MDI aboard SOHO, the network structures in equatorial coronal holes have been studied, in particular the relationship between the ultraviolet emission-line parameters (line radiance, Doppler shift and line width) and the underlying magnetic field. The bases of coronal holes seen in chromospheric spectral lines with relatively low formation temperatures generally have similar properties as normal quiet-Sun regions, i.e., small bright patches with a size of about 2'' to 10'' are the dominant features in the network as well as in cell interiors. With the increase of the formation temperature, these features become more diffuse, and have an enlarged size. Loop-like structures are the most prominent features in the transition region. In coronal holes, we found that many of such structures seem to have one footpoint rooted in the intra-network and to extend into the cell interiors. Some of them appear as star-shape clusters. In Dopplergrams of the O VI line at 1032 Å, there are also fine structures with apparent blue shifts, although, on average, they are red shifted. Structures with blue shifts have usually also broader line widths. They seem to represent plasma above large concentrations of unipolar magnetic field, without obvious bipolar photospheric magnetic features nearby.

Key words. Sun: chromosphere – Sun: transition region – Sun: corona – Sun: solar wind – Sun: UV radiation – Sun: magnetic fields

1. Introduction

Coronal holes (CHs) of the Sun are known as the sources of the fast solar wind. They appear as dark regions if seen in coronal emission lines with high formation temperatures. However, the plasma properties at the base of coronal holes, where the nascent fast solar wind starts, have not been clearly understood. For a review of the constraints placed by remote-sensing observations on the solar wind models see Marsch (1999) and references therein. Spectroscopic measurements are the most important means to probe these source regions. With the high spectral resolution of space-based instruments (for a recent review see Wilhelm 2003), the profile of an ultraviolet line can be analysed in detail, from which line parameters such as radiance, Doppler shift and width can be deduced. These parameters provide useful information about the plasma properties at the base of CHs and are crucial for a good understanding of the physical processes occurring there, as well as for the modelling work.

The morphology of CHs has been intensively studied since the Skylab era (see, e.g., Zirker 1977, and references therein). During the SOHO (Solar and Heliospheric Observatory)

mission, SUMER (Solar Ultraviolet Measurements of Emitted Radiation) and CDS (Coronal Diagnostic Spectrometer) have been used to investigate both polar and equatorial holes on the disk (see, e.g., Peter 1999; Peter & Judge 1999; Del Zanna & Bromage 1999; Hassler et al. 1999; Lemaire et al. 1999; Wilhelm et al. 2000, 2002a; Feldman et al. 2000; Stucki et al. 2000b, 2002; Xia et al. 2003; Popescu et al. 2004). These studies showed that the temperature-dependent variation of the average radiance between holes and quiet-Sun (QS) regions is generally in agreement with a previous analysis by Huber et al. (1974). For the equatorial CHs, Wilhelm et al. (2002a) reported that their characteristics are very similar to those of polar CHs observed during the sunspot minimum. The radiance ratios decrease with the formation temperature from one in the continuum to about 0.3 for Mg IX. All CHs studied show no differences in the brightness and the structure of the chromospheric network seen in the continua and the Si II and O II lines.

Measurements of the Doppler shift and line broadening have been made by various authors. One of the most interesting discoveries is that in the QS the emission lines of the transition region are systematically red shifted (Doschek et al. 1976; see also Brekke et al. 1997, and references therein). The reason is not yet fully understood. These persistent downflows are still lacking explanation. If they represent steady flows, moreover,

* Table 1 is only available in electronic form at
<http://www.edpsciences.org>

a physical mechanism should be found for how this mass flux is injected into the transition region in the first place. One hypothesis that has been proposed explains the red shift by the return of spicular material (see, e.g., Pneuman & Kopp 1978; Athay & Holzer 1982; Athay 1984; Cheng 1992). Although similar measurements have not yet been studied systematically in CHs, average red shifts of the transition-region lines were also reported, but the velocities tend to have smaller values in CHs than in QS regions (Doschek et al. 1976; Rottman et al. 1981, 1982; Dere et al. 1989; Warren et al. 1997; Stucki et al. 2000b, 2002; Popescu et al. 2004). Warren et al. (1997) reported that the C II (1037 Å), N IV (765 Å) and O VI (1038 Å) lines observed by SUMER are predominantly red shifted in CHs. For N IV and O VI, however, there are more blue-shifted profiles in the hole than in the QS. This latter tendency was also confirmed by Stucki et al. (2000b, 2002), who analyzed 26 spectral lines observed by SUMER and 14 lines by CDS, and found that all lines formed above 10^5 K, as well as the He I and He II lines formed below 10^5 K, are blue shifted inside the CH compared to the QS. Moreover, the difference tends to increase with the temperature. However, in the work by Stucki et al. (2000b, 2002), all Doppler shifts in the hole were compared to the quiet-Sun shifts, without absolute wavelength calibration.

In contrast to previous results (Dere et al. 1989; Warren et al. 1997), Peter (1999) and Peter & Judge (1999) reported that in polar CHs a net outflow was found in C IV and O VI lines. They suggested that this difference in Dopplergrams of blue shifts may result from the difference in the filling factor between the equatorial and polar CH, because they found 67% of the area in polar CH was filled by blue shifts. Net blue shifts were also measured in polar holes with a radial outflow velocity of about 8 km s^{-1} for the He I absorption line (10830 Å) (Dupree et al. 1996), and with a line-of-sight velocity of about 3 km s^{-1} for the He I emission line (584 Å) (Wilhelm et al. 2000). For lines with formation temperatures above 6×10^5 K (e.g., Ne VIII and Mg X), the average QS Doppler shifts measured during the early phase of the SOHO mission were red (Brekke et al. 1997; Chae et al. 1998), which seems to be in contradiction to later measurements. This difference was mainly due to the use of new rest wavelengths of these lines determined from solar observations (Peter & Judge 1999; Dammasch et al. 1999). Measurements of the averaged line widths showed that the non-thermal broadening was only marginally greater in CHs than in QS regions (Dere et al. 1989; Lemaire et al. 1999; Stucki et al. 2000b; Wilhelm et al. 2002a).

The chromospheric network is the most prominent common feature of both CH and QS regions. Such structures can be distinguished by emission brightness or magnetic flux. One important question to be answered is what rôle they play in the origin of the fast solar wind from CHs. During the SOHO mission, studies of the relationship between Doppler shifts and line radiances have been used to probe the nature of the source regions of the fast solar wind. In polar CHs, the relationship between the Doppler shift of the Ne VIII line (770 Å) and chromospheric network was studied by Hassler et al. (1999). They found that the largest outflow velocities are closely associated with the underlying chromospheric network, where the Si II (1533 Å) brightenings in the radiance image were

used as an indication of the chromospheric magnetic network. Extending this work, Stucki et al. (2000a) did a statistical analysis and obtained a positive correlation between the blue shift of the Ne VIII line and the radiance of the N IV line (765 Å) (used also as an indicator of the network) in polar CHs, and thus corroborated the results of Hassler et al. (1999). Moreover, the largest blue shifts of the Ne VIII line was found to coincide spatially with very dark regions in the radiance image of a polar CH when seen in the same line (Wilhelm et al. 2000). Bright points and polar plumes seen in Ne VIII, however, did not show signatures of outflow.

With the high spectral and spatial resolution of the SUMER (Solar Ultraviolet Measurements of Emitted Radiation) instrument, the profile of an EUV line can be analysed in every spatial pixel. Its wide wavelength range allows different lines formed at different temperatures to be recorded in the same spectral window. Thus it is possible to study several layers of the solar atmosphere simultaneously. In our previous work (Xia et al. 2003), a direct comparison of the velocity field, which was deduced from the Ne VIII line formed at a temperature of about 6.3×10^5 K, with the measured photospheric magnetic field in an equatorial CH was made. It was found that larger blue shifts of the Ne VIII line are mainly associated with network regions with strong magnetic flux of a single polarity. Conversely, smaller blue shifts are mainly encountered in brighter regions with an underlying mixed-polarity magnetic structure nearby.

In this contribution, we will extend this work to lines formed at lower temperatures in the chromosphere and transition region. By combining observations made by SUMER and MDI (Michelson Doppler Imager) aboard SOHO, the relationship between the ultraviolet emission line parameters and the underlying magnetic field will be studied. Our attention will be focused on the small structures, because of their importance for understanding the physical processes leading to coronal heating and solar wind acceleration.

2. Observations and data analysis

The SUMER instrument has been described in detail elsewhere (Wilhelm et al. 1995; Lemaire et al. 1997). In this study, we selected two equatorial CHs (see Table 1). The observations of CH 1 comprise five spectral windows and provide a relatively complete spectral coverage, although this coronal hole was a small one. We should bear in mind that the SUMER images were obtained by a raster scan of the slit along the X direction (east-west) of the Sun, therefore they are not normal “pictures” that are taken simultaneously. The step size and the slit width determine the spatial resolution along the X direction, while the resolution element along the slit in Y direction (north-south; positive towards north) is approximately $1''$ and is given by the pixel size of the detector. With the help of this high spatial resolution, small structures in the CHs can be investigated in detail. It should be mentioned that SUMER rastered either in the east-west direction or west-east direction. Depending on whether the scan is in the sense of the Sun’s rotation, the effective field of view (FOV) becomes either smaller or larger.

One important objective of this study is to compare the morphology of CHs with that of the QS. The data observed

in the QS on 8 and 9 March 1999 were selected for a reference. During these observations, SUMER was operated under the same conditions as when observing the coronal hole (CH 1) on 11 to 13 March 1999. In previous studies, CHs have usually been compared with their surrounding areas considered as QS regions. However, the formation of CHs is in many cases closely associated with active regions, so that the areas surrounding the hole often contain signatures originating from such active regions. The net magnetic flux density (signed) averaged across the FOV of SUMER is about $-60 \mu\text{T}$ (-0.6 G), which is very small and indicates that this region has a nearly balanced flux of the magnetic field.

In the data analysis, we first applied the standard procedures for correcting and calibrating the raw data of SUMER. The procedures included decompression, reversion, as well as flat-field, dead-time, local-gain and geometrical corrections. Two methods were then applied to get the line parameters (radiance, central position of the spectral line and width). First, we fitted the average profile to a single Gaussian or multi-Gaussians, thereby using the PIKAIA software (Charbonneau 1995). Second, in order to deduce the Dopplergrams we calculated the central position for every pixel, by integrating the line radiance across a certain spectral window and determining subsequently the location of the 50% level with sub-pixel accuracy. This procedure was frequently used to obtain SUMER Dopplergrams (see details in Dammasch et al. 1999) and dramatically reduced the computing time for a large number of data. We found that the results deduced by these two methods were statistically consistent with each other (Xia 2003).

Furthermore, it should be mentioned that in addition a line-position correction was applied, to remove spurious spectral line shifts caused by thermal deformations of the instrument, and to eliminate residual errors (systematically varying along the slit) after the geometric correction using the standard software (Dammasch et al. 1999; Xia 2003).

The photospheric magnetograms were obtained by the MDI instrument (Scherrer et al. 1995) during the observations of SUMER. The full-disk magnetograms (calibrated, sampled at a rate of 15 per day) were used. We co-aligned a MDI magnetogram and a SUMER radiance map by computing the cross correlation between the two images.

3. Morphology of equatorial CHs

3.1. Line and continuum radiances

The CH morphology has been studied in detail by various authors (see introduction). In order to give a general impression on the CH appearance seen in different ultraviolet emission lines, we first present radiance maps obtained with a high spatial resolution ($\approx 1''$ per pixel). The spectra include the Si II, C IV and Ne VIII lines, and the continuum around $1539 \text{ \AA}$. The formation temperatures of these lines and the continuum span from about 10^4 K to $6.3 \times 10^5 \text{ K}$. They are emitted in the chromosphere, transition region and lower corona, respectively, and obtained by SUMER simultaneously so that they can represent temperature-dependent changes of the network structure. Their radiance maps are shown in Fig. 1 for the CH 1, and, for a

comparison, the corresponding spectroheliograms obtained in QS. The same scale of intensities is used to plot spectroheliograms for a given line. The regions inside and outside coronal holes are separated by dotted lines, which are determined by the CH boundaries as inferred from the images obtained in the Fe XII channel of EIT on SOHO. A logarithmic scale is used for all such maps to improve the image contrast.

3.1.1. Chromospheric lines and continua

The formation temperatures of the Si II line and the continuum shown here are $\approx 1.8 \times 10^4 \text{ K}$ and $\leq 1 \times 10^4 \text{ K}$, respectively. In Fig. 1, one finds that the chromospheric network is well defined in the Si II line and the continuum emitted by this layer, and has similar properties both inside and outside the CH. The radiance ratio between the CH and QS regions is found to be unity for the continuum and about 1.1 for the Si II line.

The continuum emission shown here is a mix of the Si I (in the first order) and the H I Lyman (in the second order) continua. The Si I continuum is formed in the lower chromosphere (near the temperature minimum), while the H I Lyman continuum is in the upper chromosphere (Vernazza et al. 1981). The latter contributes approximately 0.2 of the counting rate under QS conditions (Wilhelm et al. 1997, 2002b). In the continuum radiation, the most prominent features seen are small bright patches with enhanced emission in the network as well as in cell interiors. These features have spatial sizes of about $2''$ to $10''$, are larger and brighter in the network, and usually elongated in the slit direction if observed with SUMER. Similar results were also found in QS regions by other authors (see, e.g., Cook et al. 1983; Landi et al. 2000; Feldman et al. 2001). The phenomenon that the patterns are longer in the slit direction has been interpreted as being caused by the fact that the lifetimes of these bright points are shorter than the sampling time at a certain scan position. For instance, if a bright point has a size of $5''$ in diameter, the total time for the slit crossing of this feature with our scan parameters is about 10 min, so that we can only get a size of about $2''$ along the raster direction if the lifetime is less than 5 min. The small bright patches in the cell interiors become less pronounced if seen in the Si II line, and the bright structures in network appear more diffuse.

The temperature-dependent variations of the chromospheric network can also be seen in other lines and continua (Wilhelm et al. 2002a; Xia 2003). An obvious change of the network morphology appears in equatorial CHs when seen in the He I line ($584 \text{ \AA}$), the H I Lyman lines and the continuum near $710 \text{ \AA}$, in which loop-like structures similar to those in transition-region lines are often found. The formation processes of these lines are very complicated, and a discussion is beyond the scope of this paper.

3.1.2. Transition-region lines

The formation temperatures of the C IV and Ne VIII lines are $1 \times 10^5 \text{ K}$ and $6.3 \times 10^5 \text{ K}$, respectively. The emitting ions are Li-like, and have extended contribution functions versus the electron temperature. In Fig. 1, it can be found that the network

Fig. 1. Radiance maps (logarithmic scale) obtained in the spectral window 1532 Å to 1552 Å. From left to right: continuum (around 1539 Å); Si II (1533 Å); C IV (1548 Å); and Ne VIII (770 Å in the second order). *Upper panel:* CH 1 observed on 11 March 1999 between 8:05 and 12:05 UTC; *bottom panel:* QS observed on 8 March 1999 between 15:20 and 19:21 UTC. The dotted lines represent the border of the CH. The observations of the lines and the continuum in each interval were made simultaneously.

structure is still well defined in the C IV line. The locations of enhanced emission in these lines coincide with those in chromospheric lines, but appear more extended into the cell interiors if seen in high-contrast images (Patsourakos et al. 1999). The network is highly structured and its width tends to be broader in the CH than in the QS.

The appearance of the network is very different if seen in the Ne VIII line, which is in our data sets obtained in the second order. On the disk, emissions in this line stem mainly from the upper transition region and lower corona. The majority of loop-like structures, which can be seen in the C IV line, are invisible in the CH except for some large ones. The network is almost absent and only vague remnants still exist. In the QS region, the chromospheric network is still distinguishable in Ne VIII, but appears more diffuse than in other transition-region lines.

The radiance ratio between the CH and QS regions is found to be 0.85 for the C IV line and about 0.3 for the Ne VIII line.

Although we give here only one example, it turns out that all transition-region lines formed below 5×10^5 K essentially have similar characteristics. These results are in agreement with those obtained by Wilhelm et al. (2002a). In the following, we will discuss more details of the fine structures in the CH network.

3.2. Fine structures seen in the O VI line

The CH images of the radiances of the C I continuum, H I Ly β (1025 Å, $\approx 2 \times 10^4$ K), C II (1037 Å, $\approx 5 \times 10^4$ K) and O VI (1032 Å, $\approx 3 \times 10^5$ K) lines are plotted in Fig. 2. In Fig. 3 the MDI magnetograms and Doppler shifts of all CH observations are presented. All figures are overlaid by contours of the continuum emission observed simultaneously in order to outline the network region ($\approx 33\%$ of the CH area is occupied by the network). The spectroheliograms shown have been processed with an increased contrast of the radiance in order to display the loops more clearly. The Doppler shifts of the C II and O VI lines are measured relative to the chromospheric lines of O I, while the Ly β line is referenced to its average position due to the lack of reliable reference lines in its spectral neighbourhood. In addition, due to its non-Gaussian shape with an obvious self-absorption reversal, the Doppler shift of this line is deduced from the line wings by simply using Gaussian fits. In the fitting procedure, we set a weight of zero to the central part of the line profile (reversal part), so that the parameters of the line profiles are essentially determined by the wings outside the reversal.

Fig. 2. CH images in radiance (logarithmic scale) in the spectral window around 1030 Å. From left to right: continuum, H I Ly β , C II and O VI. The equatorial CHs were observed on 11 March 1999 between 12:09 and 13:09 UTC (*upper panel*) and on 8 November 1999 between 02:10 and 02:51 UTC (*bottom panel*). The contours repeat the network lanes as seen in the continuum. The dotted lines represent the border of the CH.

From Fig. 2, we can confirm again that the CH network is dominated by loop-like structures when seen in transition-region lines. However, they can also be identified in the hydrogen Ly β line, but not in the continuum, which appears as small bright patches outlining the cell boundaries.

Comparing the network structures outlined by the continuum contours with the magnetograms in Fig. 3, one can readily find that the network in CHs is dominated by the positive polarity (red colour) of the magnetic field, while some mixed-polarity features are also present. As found by Xia et al. (2003), mixed-polarity magnetic features usually correspond to locations with bright points seen in transition-region and coronal lines. In these figures, they indeed appear as brighter cores seen in the O VI line. Moreover, the locations of these bright cores spatially coincide with those seen in the continuum and the H I Ly β and C II lines. This implies that such an enhanced

network emission is very likely caused by the interaction of the closed magnetic loops with the unipolar fields in the coronal hole.

For other bright network structures in CHs, however, one finds that there is generally no visible stronger magnetic flux with the opposite polarity nearby. By inspection of the spectroheliograms, many loop-like structures seem to have a footpoint rooted in the intra-network and extend into the cell interiors, and some of them appear as clusters with a star-like shape. Moreover, their visible footpoints apparently correspond to the bright patches seen in chromospheric emissions (see Fig. 2).

From the Dopplergrams shown in Fig. 3, we find that CHs are on average red shifted in the transition-region lines. Red shifts come from both the cell regions and the network. However, one finds that fine structures with large blue shifts are also present (more obvious in the CH 2). Some of these

Fig. 3. CH images in magnetogram and line shift. From left to right: MDI magnetogram (units: Gauss), H I $\text{Ly}\beta$, C II and O VI (units: kilometer per second). The equatorial CHs were observed on 11 March 1999 between 12:09 and 13:09 UTC (*upper panel*) and on 8 November 1999 between 02:10 and 02:51 UTC (*bottom panel*). The contours repeat the network lanes as seen in the continuum in Fig. 2. The positive magnetic field is plotted in red colour, while the negative in blue. The dotted lines represent the border of the CH. Note that the Doppler shifts of the C II and O VI lines are measured relative to the chromospheric lines of O I, while the $\text{Ly}\beta$ line is referenced to its average position.

structures appear as loop-like and spatially coincide with the locations of the loop-like ones seen in the radiance image, while some appear as blue points with less extension and the locations corresponding to the footpoints of the radiance loop-like structures.

Moreover, by inspection of the Dopplergrams of the $\text{Ly}\beta$, C II and O VI lines, one finds that at the locations where blue shifts are seen in the O VI line usually blue shifts are also seen in the $\text{Ly}\beta$ line. For the C II line, the shifts often appear in Dopplergrams as small blue points with smaller magnitude of shifts and spatial size.

In Fig. 4, we show segments of the full images obtained from observations of both CH and QS in order to study the relationship between the Doppler shift and other line parameters in some individual structures. The MDI magnetograms and the Doppler shift of the O VI line are plotted with the same

colour scale as before. In CHs, the blue structures usually have a broader line width. Like the Ne VIII line discussed by Xia et al. (2003), they tend to be present above the concentration of a large unipolar magnetic field without obvious bipolar magnetic features nearby. Red-shifted structures usually have a low radiance and small line widths if coming from the cell interiors, and have intermediate line widths if coming from the network.

Finally, the Dopplergrams observed in the QS region reveal very different properties from those of the CH regions (see bottom panel in Fig. 4). It seems that no apparent blue shifts are found in the O VI line. However, the line width shows a positive correlation with the radiance, i.e., the large line widths are mainly found in the network.

Hence, it can be concluded that in CHs blue shifts can be also found in transition-region lines, although they are on average red shifted, and tend to occur in the network where a large

Fig. 4. Fine structures seen in the O VI line. *Upper panel:* equatorial CH on 11 March 1999 between 12:09 and 13:09 UTC; *middle panel:* equatorial CH on 8 November 1999 between 02:10 and 02:51 UTC; and *bottom panel:* QS on 8 March 1999 between 01:25 and 02:25 UTC. From left to right: MDI magnetogram, line width, Doppler shift and radiance. For the line widths, the red colour represents larger values. The contours repeat the network lanes as seen in the continuum.

unipolar magnetic field is concentrated. A reasonable inference may thus be made, namely, that such blue shifts occur mainly in areal portions of the magnetic network, in which the magnetic field is really open to the corona. This may answer the question why a different blue-red-shift ratio of the C IV line has been obtained in different observations, a puzzling result which has been discussed by Peter & Judge (1999).

3.3. Fine structures and the network in CHs

In equatorial CHs the chromosphere and transition region are highly structured. Small structures with an enhanced emission are present everywhere. The spatial distribution and the size of the fine structures are obviously temperature dependent. Their appearances in the chromosphere and transition region are similar to those observed with SUMER in the QS region (Warren & Winebarger 2000; Feldman et al. 2001). Especially, the brightness of the chromosphere is almost the same for both regions, although the magnetic configuration is different. Above the upper transition region, most of the structures disappear and the corona becomes much darker and more homogeneous than in the QS region, except for some bright points. The results indicate that, at least in the chromosphere and the low transition region, the CH region shows more or less similar properties as the QS region. A further implication is that the two regions

may essentially be heated by a same mechanism, as suggested, e.g., by Marsch et al. (2003). Dissipation of high-frequency Alfvén waves is suggested to be a prime candidate for heating this part of the corona (see, e.g., Marsch 1992; Axford & McKenzie 1992, 1997). The magnetic activities occurring in the magnetic network are believed to produce the waves required for coronal heating by the cyclotron-resonant damping mechanism. Such a dynamic picture of the network has been described by Axford & McKenzie (1992, 1997), which was developed from the static models suggested by Gabriel (1976) and Dowdy et al. (1986).

The different characteristics that are seen between CH and QS regions in spectral lines with high formation temperatures seem to be caused by different magnetic configurations. According to previous model studies of the network (Dowdy et al. 1986; Dowdy 1993), the network is believed to consist of both low-lying loops (of size less than 10^4 km) and large-scale magnetic funnels being open to the corona. Very recently, a model sketch of the transition-region structure has been suggested by Peter (2000, 2001), who studied several components of the transition-region lines observed by SUMER in the QS, and found that the presence of a second broader spectral component is a general feature of transition-region lines. This second component, with a broader and weaker profile, is suggested to originate from the large loops in the QS or open funnels in

the coronal hole, while the core (first component) is from the smaller loops, and has a narrower line width and stronger radiance. Although we have not performed the same analysis to deduce the second component, a positive correlation between blue shift and large width of the total line profile has indeed been obtained.

As expected, all CHs are dominated by a single polarity of the magnetic field (at the resolution of the magnetic measurements), while there are also mixed-polarity features present. Larger mixed-polarity magnetic features, which can readily be distinguished in the magnetogram, usually correspond to locations with bright points seen in upper-transition-region and coronal lines (see also results in Xia et al. 2003). They are assumed to be caused by the interaction of the closed magnetic loops with the unipolar fields in the CH (Xia 2003). On the other hand, many of the bright structures have no connection with the intra-network magnetic field having mixed polarities, as also was found in the QS region (Warren & Winebarger 2000). As a possible explanation, Warren & Winebarger (2000) suggested that these fine features may be related to small loops connected to the inter-network (cell interiors) magnetic field or highly dynamic structures, such as spicules, which are not really loops.

Recent SUMER observations (Budnik et al. 1998; Wilhelm et al. 2000; Wilhelm 2000) showed that the visible structures observed above the limb in polar CHs are mostly related with EUV spicules. They have widths of $\approx 10''$, when seen in transition-region lines, and disappear at a temperature above 5×10^5 K. Geometrically, they appear to be nearly straight, but not as loops. In polar CH regions spicules and macrospicules have various orientations and are not necessarily vertical (see the figures in Wilhelm 2000; Wilhelm et al. 2000). The connection between $H\alpha$ and EUV spicules has not yet been established. However, it is suggested that EUV spicules are very likely the hot sheath of cooler $H\alpha$ spicules (Sterling 2000).

A question that should be asked is what are the structures seen in CHs on the disk: loops, spicules or open funnels? A possible answer is that all these structures are present, anchored in the network. The small loops are less extended in height (less than $10''$) and cannot be distinguished if observed above the limb due to considerable overlapping of such loops (Warren & Winebarger 2000). EUV spicules extend much higher (above $10''$), can easily be seen above the limb, but cannot be distinguished from the loops on the disk, due to either their projection onto or their overlapping with low-lying magnetic structures. If we conjecture that the equatorial CH structures, which have a broader line width and distinct blue shift in the $O\text{VI}$ line, are confined to magnetic flux tubes that are open to the corona, and that those with a narrower line width and red shift are from the cooler, locally closed magnetic loops, these interpretations are in agreement with those made for the quiet Sun by Peter (2000, 2001). Moreover, if it is true that structures with a higher blue shift are open to the corona, it is possible that some of them will appear as visible EUV spicules or macrospicules if seen above the limb. On the disk, however, they may be invisible due to foreshortening.

4. Statistical and quantitative studies of line parameters

4.1. Relationship between line parameters and the chromospheric network

The relationship between the Doppler shift and the chromospheric network has recently been studied in polar CHs by Hassler et al. (1999) and Stucki et al. (2000a,b). Their data showed a positive correlation between the Doppler shift of the Ne VIII line and the line radiance of chromospheric and lower transition-region lines. In this study of equatorial holes, we show some more detailed statistical results concerning the relationship between the line parameters for a given line and the network structure seen in the chromospheric continuum.

As discussed above, there exists a very close relationship between a brightening of the chromospheric emission and the magnetic network with a concentration of the photospheric magnetic flux. Thus we can use a radiance map of the continuum as an indicator of the network in order to search for the relationship between line parameters and such network structures. The threshold of the radiance difference between the network and cells can be roughly determined by fitting the low-radiance peak in radiance histograms by a Gaussian profile (see discussion in Mariska 1992). We find that the network area occupies about 1/3 of the total area determined by such a method using the continuum in different wavelengths. We thus adopt a threshold of the radiance determined by assuming that the network occupies 1/3 of the total area. Note that the Doppler width has not been corrected for the instrumental broadening, because we only intend to study its variation between different structures.

The results are shown in Figs. 5 and 6. The solid line in the upper panel is the histogram of the Doppler shift with a speed interval of 1 km s^{-1} , and the middle two panels indicate the average radiance and width of the same line, as calculated in each velocity interval. The plot in the lower panel shows the continuum, which serves as an indicator of the chromospheric network. The dotted line represents the boundary between the network and cell region (above this value is network).

From the left column of Fig. 5, one infers that the Doppler shift of the Si II line exhibits a very clear positive correlation with the line width. It is also clear that the relative blue shifts correspond mainly to the lower radiances of this line and the continuum, which stem from the cell region. The relative red shifts relate to the higher radiances on average, but with a large scatter for both lines and the continuum. This implies that some of the red shifts are also produced in the cell region, although they mainly come from the network.

An apparent correlation between line parameters and the network defined in terms of continuum can be found in Figs. 5 and 6 for He I ($584 \text{ \AA}$ in 2nd order, $\approx 3 \times 10^4 \text{ K}$) and other transition-region lines, except for the C IV line. First, regions with an average Doppler shift (the average value $\langle v \rangle$ is set here to 0 km s^{-1}) usually have the lowest average line width and radiance. They also correspond to the lowest average radiance of the continuum, which indicates that the emissions are mainly contributed by cell regions. Second, the magnitude of the

Fig. 5. Relationship between the chromospheric network and line parameters in CH 1 for Si II (left column), He I (middle column) and C II (right column). The histogram of the Doppler shift with a bin size of 1 km s^{-1} is shown in the upper panel; the average Doppler width, integrated line radiance and continuum for each velocity interval are shown in lower panels. The bars indicate the standard deviation of each parameter. The dotted lines present the threshold of the continuum counts between the network and cell, set by the assumption that the network occupied $\approx 33\%$ of the total area.

relative Doppler shift ($|v - \langle v \rangle|$) seems to have a positive correlation with the line width and radiance. A larger blue or red shift usually has a larger line width and radiance, and also corresponds to a larger radiance of the continuum, which implies that these emissions mainly occur in the network.

However, such a relationship is not clearly present for the C IV line, a result which was also found by Mullan & Waldron (1987) in a low-latitude coronal hole observed by SMM (Solar Maximum Mission) and recently confirmed by Peter (1999) in a polar coronal hole observed by SUMER. This is in contrast with the observations made in other regions on the Sun (Gebbie et al. 1981; Athay et al. 1983a,b; Peter 1999).

The continuum radiance as a function of the local line shift exhibits a general trend to follow the variation of the local line radiance, although they are emitted from different layers in the chromosphere, e.g., Si I ($\approx 1540 \text{ \AA}$) in the lower chromosphere and Si I ($\approx 1170 \text{ \AA}$) and C I ($\approx 1030 \text{ \AA}$) in a higher layer (Vernazza et al. 1981). This result indicates that the bright network structures seen in different layers from the chromosphere to transition region are spatially connected through fine structures discussed in Sect. 3.

In the Ne VIII line shown in Fig. 6, there exists a slightly positive correlation between Doppler shift and radiance. A larger blue shift tends to have a lower radiance and a redder one corresponds to a larger radiance. For the line width, the tendency is inverse. Compared with the continuum, most of the counts with

a larger blue shift have an averaged continuum radiance around the threshold defined as the limit between of network and cells. This result is consistent with that discussed in Xia et al. (2003), in which it was found that larger Doppler shifts come mainly from regions in the network with a concentration of unipolar magnetic field, but with a larger areal extension as compared with the network area when defined in chromospheric lines. Such a tendency that is here deduced for equatorial CHs is similar to the one derived previously for polar CHs.

4.2. Relationship between Doppler shifts of different lines and photospheric magnetic fields

The morphological study in Sect. 3 showed that at the locations with blue shifts seen in the O VI line one usually finds also blue shifts in the H I Ly β and C II lines, but often appearing in the Dopplergrams as small blue points with a smaller value of the blue shift and spatial size. We use here a statistical method to look for the relationship between Doppler shifts of these lines. In Fig. 7, the histogram of the Doppler shift of the O VI line with a bin size of 1 km s^{-1} is plotted in the upper panel. The Doppler shifts of two other lines (H I Ly β and C II) and the magnetic field strengths, averaged in each velocity interval of the O VI line, are shown in the other panels. The two data sets were obtained on 11 March 1999 in CH 1 (left column) and on 8 November 1999 in CH 2 (right column).

Fig. 6. The same format as Fig. 5 but for C IV (left), O VI (middle) and Ne VIII (right).

Fig. 7. Relationship between Doppler shifts of different lines and photospheric magnetic fields. *Upper panel:* the histogram of the Doppler shift of the O VI line with a bin size of 1 km s^{-1} ; the two middle panels: the Doppler shifts of the H I $\text{Ly}\beta$ and C II lines averaged in each velocity interval of the O VI line; *bottom panel:* the magnetic field strengths averaged in each velocity interval of the O VI line. The vertical bars indicate the standard deviation. The dotted lines present the magnetic field strengths averaged over the CH areas observed by SUMER. *Left column:* data observed on 11 March 1999 in CH 1; *right column:* data observed on 8 November 1999 in CH 2.

Fig. 8. Average Doppler shifts in various lines versus the formation temperature in CH 1 and QS. **a)** CH 1; **b)** QS; and **c)** difference of the Doppler shift between the CH and QS regions.

In Fig. 7, one can find a clear positive correlation between the Doppler shifts. The corresponding magnitudes of the Doppler shifts vary with different lines formed in different layers, i.e., a larger value of the Doppler shift seen in the O VI line corresponds to a smaller one in the C II line and an even smaller one in the H I $\text{Ly}\beta$ line. Moreover, the relationship between the Doppler shifts and photospheric magnetic fields shown in the bottom panel of Fig. 7 indicates that the locations with blue shifts have on average larger magnetic field strengths in the photosphere. A close inspection of Figs. 6 (middle column) and 7 together shows a positive correlation between the blue shift, radiance, line width and magnetic field strength. These statistical results nicely confirm our previous results obtained in the morphological study.

4.3. Average Doppler shift in CHs

A temperature dependence of the average Doppler shift is plotted for CH 1 and QS in Fig. 8. The upper and middle panels show the average Doppler shift varying with the formation temperature in the CH and QS region, respectively, while the difference of the Doppler shift between the two regions measured in each line is illustrated in the bottom panel. The curves plotted as solid lines in each panel show the trend of the variation.

Except for the Ne VIII and Mg X lines, all other transition-region lines appear on average red shifted in both CH and QS regions. Average red shifts of the transition-region lines range from 5 km s⁻¹ to 10 km s⁻¹ in the CH region, and 5 km s⁻¹ to 15 km s⁻¹ in the QS region. Small Doppler shifts are measured for the Ne VIII and Mg X lines in the QS region.

On the other hand, both the Ne VIII and Mg X lines have significant average blue shifts in the CH region. The temperature dependence of the average Doppler shifts, in both the CH and QS regions, are consistent with previous results obtained by Chae et al. (1998), Peter & Judge (1999) and Teriaca et al. (1999), i.e., the red shift increases first with increasing line formation temperature, but then drops again at a temperature of about 3×10^5 K.

The difference of the Doppler shift between the CH and QS regions also appears to be temperature dependent. For the chromospheric lines Si II and O I, such a difference is within 1 km s^{-1} (this is very small considering the measurement uncertainties). Except for the C II lines, transition-region lines have systematically smaller red shifts in CHs than in the QS region. It should be emphasized that this relative Doppler shift is derived for each line with the same wavelength, which was recorded in the same pixel address, and calibrated by the same reference lines for the CH and QS regions. So the relative shift should be reliable, because in this case only the fitting uncertainties will influence the accuracy of the measurements. The result obtained in this study is in agreement with that obtained in polar CHs (Stucki et al. 2000b).

4.4. Doppler shifts and the nascent fast solar wind

The results presented here are important to understand the persistent red shifts and the process of the mass balance in the transition region.

The Doppler shifts derived from the Ne VIII and Mg X lines are on average blue in CHs. In our previous work (Xia et al. 2003), red shifts have been found to be present only in bright structures, with underlying mixed-polarity magnetic structures. Conversely, the larger blue shifts are mainly associated with the network regions, where the strong magnetic flux of a single polarity is concentrated. This also seems to be consistent with a geometry of coronal funnels open to the corona, in which the fast solar wind is initially accelerated. The Doppler shifts measured for the Ne VIII and Mg X lines in the quiet Sun are rather small (usually in the range of $\pm 3 \text{ km s}^{-1}$, and do not show prominent large-scale outflow there). Considering that most emissions of the two lines are constrained to magnetic loops in the QS region, these results are not surprising.

We are able to find a clear positive correlation between the Doppler shifts for different lines by inspection of the spatial distribution of the Doppler shifts. If a Doppler shift is considered to be caused by a steady mass flow and the blue shift to be the signature of the starting fast solar wind, the results naturally agree with a convection pattern obeying the law of mass-flux conservation in an expanding flux tube. This means that the flow velocity should be lower in the chromosphere due to the higher plasma density there than in the transition region.

Considering that a major mass flux is taken away by the solar wind in the CH corona, it is not surprising that we find the average red shift of the transition-region lines to be reduced as compared with that in QS, especially for those lines with higher formation temperatures, even though the absolute average Doppler shift is red.

5. Summary

By combining observations made by SUMER and MDI aboard SOHO, fine structures in equatorial CHs have been studied, in particular the relationship between the ultraviolet emission line parameters (radiance, Doppler shift and width) and the underlying magnetic field.

The bases of CHs seen in chromospheric lines have generally similar properties as QS regions. Small bright patches with sizes of about $2''$ to $10''$ are the dominant features in the network as well as in cell interiors. With the increase of the temperature, these features become more diffuse, and have an enlarged size.

Loop-like structures are the most prominent features when seen in transition-region lines. In CHs, we find that most of such structures seem to have one footpoint rooted in the intra-network and to extend into the cell interiors. Some of them appear as star-shape clusters. In Dopplergrams of the O VI line, fine structures with apparent blue shifts are also present, although they are on average red shifted. Structures with blue shifts have usually also broader line widths. They seem to represent plasma above large concentrations of unipolar magnetic field, without obvious bipolar magnetic features nearby.

There exists a clear positive correlation between the Doppler shifts deduced from different lines, which are observed simultaneously in the same spectral window. Moreover, the corresponding magnitudes of the Doppler shift seem to vary with height, corresponding to different lines formed in different layers, i.e., a larger value of the Doppler shift seen in the O VI line corresponds to a smaller shift in the C II and H I Ly β lines.

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Online Material

Table 1. SUMER observations of equatorial CHs and QS.

Item	Date 1999	Time UTC	Solar coordinate X (″), Y (″)	Wavelength (Å)	Steps (″)	Detector and Slit ^a	Exposure time (s)
CH 1 March	11	08:05–12:05	141 E–249 E, 290 N	1532–1552	1.13	A 2	150
	12	21:00–01:01	234 W–126 W, 330 N	1234–1254	1.13	A 2	150
	13	01:05–05:05	264 W–156 W, 330 N	912–935	1.13	A 2	150
	11	18:50–22:50	31 E–139 E, 280 N	1157–1179	1.13	A 2	150
	11	12:09–13:09	223 E–88 E, 280 N	1020–1045	1.13	A 2	30
	13	06:10–11:43	240 W, 320 N	ref-spec ^b	0	A 2	325
CH 2 November	8	02:10–02:51	50 E–40 W, 95 N	1020–1045	1.12	A 2	30
	8	02:52–08:05	5 E, 95 N	ref-spec ^b	0	A 4	300
QS March	8	15:20–19:21	64 W–44 E, 130 N	1532–1552	1.13	A 2	150
	8–9	23:13–03:14	64 W–44 W, 130 N	1234–1254	1.13	A 2	150
	9	07:22–11:23	64 W–44 W, 130 N	913–935	1.13	A 2	150
	9	03:18–07:18	64 W–44 E, 120 N	1157–1179	1.13	A 2	150
	11	01:25–02:25	67 E–67 W, 0	1020–1045	1.13	A 2	30
	11	02:31–07:58	0, 0	ref-spec ^b	0	A 2	30

^a Slit 2: 1″ × 300″; Slit 4: 1″ × 120″.^b Reference spectrum covering the wavelength range 780 Å to 1600 Å.