Velocities and Linewidths in the Network and Cell Interiors of a Polar Coronal Hole, Compared with Quiet Sun

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Abstract The relative Doppler velocities and linewidths in a polar coronal hole and the nearby quiet-Sun region have been obtained from the Solar and Heliospheric Observatory (SOHO)/Coronal Diagnostic Spectrometer (CDS) observations using emission lines originating at different heights in the solar atmosphere from the lower transition region (TR) to the low solar corona. The observed region is separated into the network and the cell interior and the behavior of the above parameters were examined in the different regions. It has been found that the histograms of Doppler velocity and width are generally broader in the cell interior as compared to the network. The histograms of Doppler velocities of the network and cell interior do not show significant difference in most cases. However, in the case of the quiet Sun, the Doppler velocities of the cell interior are more blueshifted than those of the network for the lowermost line He ii 304 Å, and an opposite behavior is seen for the uppermost line Mg ix 368 Å. The histograms of line width show that the network–cell difference is more prominent in the coronal hole. The network has significantly larger linewidth than the cell interior for the lowermost TR line He ii 304 Å for the quiet Sun. For coronal hole, this is true for the three lower TR lines He ii 304 Å, O iii 509 Å, and O v 630 Å. Also obtained are the correlations between the relative Doppler velocity and the width. A mild positive correlation is found for the lowermost transition region line He ii 304 Å which further decreases or become insignificant for the intermediate lines. For the low coronal line, Mg ix 368 Å, the correlation becomes strongly negative. This could be due to the presence of standing or propagating waves from the lower to the upper solar atmosphere. The results may have implications for the generation of the fast solar wind and coronal heating.

Keywords: Coronal Holes; Transition Region; Spectrum, Ultraviolet

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1. Introduction

The chromospheric network, the bright emission network seen in the chromospheric lines such as Ca\textsc{ii} and H\alpha lines, represents the boundaries of the supergranulation cells (Simon and Leighton, 1964). The convective motions in the cells sweep small flux tubes to the edges of the cells, resulting in magnetic concentrations and enhanced emission there. The EUV emission network is essentially the continuation of the chromospheric network in the transition region (Brueckner and Bartoe, 1974; Reeves \textit{et al}., 1974). The network slowly disintegrates and becomes indistinguishable from the surroundings in the corona.

The morphological properties and the evolution of the network are different in the quiet Sun and the coronal hole. \textit{Skylab} observations in the 1970s have shown that the network emission is weakened in coronal holes as compared to quiet-Sun region (Huber \textit{et al}., 1974). Gallagher \textit{et al}. (1998) have obtained the intensity contrast of the network with respect to the internetwork for different lines in the quiet Sun, and the maximum was found for the O\textsc{v} 629.73 Å line whose formation temperature is about 0.25 MK. Raju (2010) obtained the intensity contrast of the network for different lines in both quiet Sun and coronal hole. The contrast, in general, is lower for the coronal hole as compared to the quiet Sun, but becomes equal in the upper transition region. The maximum contrast for both the regions was found at about 0.2 MK. These results seem to suggest that the Doppler velocities and widths could also be different in the network and the cell interior and also there are possible variations between quiet Sun and coronal hole.

It has been known that there is a systematic difference between coronal hole and the quiet Sun in terms of intensity, velocity, and width (Raju, 2009). Judge, Carlsson, and Wilhelm (1997) report that Transition region (TR) lines show more redshift in the network than in the inter-network and also there is a correlation between line intensity brightenings and increased redshift. Gontikakis \textit{et al}. (2001) also find that velocity distribution is different for network and inter-network with network having more redshift with lower standard deviation. However, Hassler \textit{et al}. (1999) find that plasma outflow in coronal hole originates predominantly along the network boundaries. Popescu, Doyle, and Xia (2004) report a correlation between network intensity and Doppler velocity for the O\textsc{iii} line.

In the present article, spectroscopic data from \textit{Solar and Heliospheric Observatory} (SOHO)/\textit{Coronal Diagnostic Spectrometer} (CDS) were used to examine the variations of Doppler velocities and emission linewidth in the network and the cell interior in a polar coronal hole (PCH) and the quiet Sun region outside. Observations were made in five different emission lines whose formation temperatures vary from 0.08–0.95 MK and hence represent the lower transition region to the inner corona. In particular, two aspects have been examined; i) evolution of the network in the solar atmosphere, and ii) the correlation between Doppler velocity and linewidth in the different regions.
2. Data and Analysis

SOHO/CDS observations made during the Whole Sun Month (August – September 1996) have been used. Details of the observations and data reduction have been given by Bromage et al. (2000) and Raju (2009). Only five strong lines were selected for the present analysis. Details of the emission lines were obtained from CHIANTI (Dere et al., 1997; Landi et al., 2006) and may be seen in Table 1.

The CDS field of view is 240″ × 60″, which is a combination of three rasters. The spatial resolution is approximately 4″ but a running averaging of five nearby pixels has reduced this to about 20″ and the overall temporal resolution to about an hour. 14 datasets from the north polar region near the central meridian are used in this study. The Normal Incidence Spectrometer (NIS) data suffer from instrumental trends due to the rotation and tilt effects (Brooks and Bewsher, 2006). These are corrected as described by Raju (2009).

The spectra obtained from the CDS windows were fitted with single or multiple Gaussians depending upon the number of lines present in the window using the routine CFIT-BLOCK in Solar Software (SSW). The individual line profiles were always fitted with a single Gaussian. The He window has two strong lines, He II at 304 Å (second order at 607.56 Å) and O IV at 608.31 Å, and hence a double Gaussian fit was used. The O III 599 Å and O V 630 Å windows were fitted with single Gaussian. The Ne VI window was fitted with a double Gaussian to fit Ne VII 561.7 Å and Ne VI 562.8 Å. The Mg IX window was fitted with a double Gaussian to fit Mg VII 367.7 Å and Mg IX 368 Å. It may be noted that the zero point in velocity is kept equal to the most probable value in the data, and hence the Doppler velocities in the present analysis are relative Doppler velocities with respect to the coronal rest frame. Only those line profiles with a signal-to-noise ratio greater than ten were selected for the analysis. With this, the estimated errors are 2 km s⁻¹ in velocity and 0.03 Å in width.

| No. | Ion | λ [Å] | T [MK] |
|-----|-----|-------|--------|
| 1   | He II | 304.78 | 0.083  |
| 2   | O III | 599.59 | 0.11   |
| 3   | O V  | 629.73 | 0.25   |
| 4   | Ne VI | 562.80 | 0.43   |
| 5   | Mg IX | 368.06 | 0.95   |

The coronal hole and the quiet Sun were identified in the images on the basis of the intensity of the Mg X 625 Å line. The network and the cell interior are defined on the basis of the intensity distribution of the O V 629.73 Å line. Those points for which the intensity is above two-thirds of the distribution are taken as network. Reeves (1976) took the average intensity to distinguish the network.
and the cell interior, whereas some authors (Xia, Marsch, and Wilhelm, 2004) have taken the two-thirds criterion. We find that the results remain the same irrespective of the two criteria.

3. Results

Histograms of relative Doppler velocities in the network and the cell interior in the quiet Sun and coronal hole in different emission lines are given in Figure 1. The bin width is 2 km s\(^{-1}\). Also obtained are the mean, its error, and the standard deviation of each distribution, which are given in Table 2. An examination of the figure and the table reveals that the histograms of Doppler velocities of the cell interior are broader than that of the network except in the case of the He line in the coronal hole. The histograms of Doppler velocities of the network and cell interior do not show significant difference in most cases. However, in the case of the quiet Sun, the Doppler velocities of the cell interior are more blueshifted than that of the network for the lowermost line He \(\text{II} 304 \text{ Å}\), and an opposite behavior is seen for the uppermost line Mg \(\text{IX} 368 \text{ Å}\) where it is the velocities of the network that are more blueshifted than that of the cell interior. For the intermediate lines from the quiet Sun, as well as for the lines from the coronal hole, the behavior is inconclusive because of the large uncertainties.

Histograms of linewidths are given in Figure 2. The bin width is 0.01 Å. The mean, error, and standard deviation are given in Table 3. It can be seen that the histograms of the cell interior are broader than those of the network in most of the cases. The exceptions are the O \(\text{V}\) and Mg \(\text{IX}\) lines in the quiet Sun and the He \(\text{II}\) line in the coronal hole. Also, the network–cell interior difference is more prominent in the coronal hole. The network has significantly larger linewidth than the cell interior for the lowermost TR line He \(\text{II} 304 \text{ Å}\) for the quiet Sun. For a coronal hole, this is true for the three lower TR lines He \(\text{II} 304 \text{ Å}\), O \(\text{III} 599 \text{ Å}\), and O \(\text{V} 630 \text{ Å}\). This shows that the network–cell interior difference disappears faster in the quiet Sun.

The correlations between Doppler velocity and linewidth for the individual points in the different regions are shown in Figure 3. A straight-line fit is given to show the overall behavior. Also given are the correlation coefficient and the probability that the correlation can arise from two random distributions.

The correlation coefficients obtained from Figure 3 are plotted against the formation temperatures of different lines in Figure 4. A mild positive correlation is found for the lowest TR line He \(\text{II} 304 \text{ Å}\). The correlation reduces or become insignificant for the lower transition region lines O \(\text{III} 599 \text{ Å}\) and O \(\text{V} 630 \text{ Å}\). The correlation is completely insignificant for the upper TR line Ne \(\text{VI} 562.8 \text{ Å}\). For the low coronal line Mg \(\text{IX} 368 \text{ Å}\), the correlation becomes strongly negative. It may also be seen that the correlation coefficients do not show any significant difference between the different regions.

4. Discussion

Observations in recent years have shown that a coronal hole has larger blueshifts and linewidths as compared to a quiet-Sun region (Banerjee et al., 1998; Raju et al., 2000).
Figure 1. Histograms of Doppler velocities for different emission lines. The left panels represent quiet Sun and right panels represent coronal hole. Solid line represents the network and the dotted line represents cell interior.
Figure 2. Histograms of linewidths for different emission lines. The left panels represent quiet Sun and right panels represent coronal hole. Solid line represents the network and the dotted line represents cell interior.
Figure 3. Linewidths [Å] are plotted against Doppler velocities [km s$^{-1}$] for different emission lines. The line details, correlation coefficient and the probability that the correlation can arise from two random distributions are given above each panel. From left to right: First panel represents network in quiet Sun, second represents cell interior in quiet Sun, third represents network in coronal hole, and fourth represents cell interior in coronal hole.
Table 2. Details of velocity histograms (given in Figure 1). Mean of velocity distribution \([\text{vel}]\) in \(\text{km}\ \text{s}^{-1}\), its error, and standard deviation \([\text{stdv}]\) of the network and cell interior in the quiet Sun and coronal hole are given in different columns.

| No. | QS   | CH   | network vel | stdv | cell vel | stdv | network vel | stdv | cell vel | stdv |
|-----|------|------|-------------|------|----------|------|-------------|------|----------|------|
| 1   | 1.65±0.30 | 4.95 | 0.99±0.23  | 5.12 | -1.02±0.69 | 5.29 | -0.90±0.41 | 5.14 |
| 2   | 0.94±0.37 | 6.07 | 0.59±0.29  | 6.38 | 0.08±0.73  | 5.57 | 0.59±0.47  | 5.86 |
| 3   | 0.54±0.31 | 5.17 | 0.04±0.24  | 5.25 | -0.27±0.62 | 4.72 | -0.43±0.40 | 4.96 |
| 4   | 0.80±0.37 | 6.08 | 0.88±0.29  | 6.48 | -0.32±0.78 | 5.98 | 0.08±0.53  | 6.56 |
| 5   | 0.83±0.31 | 5.05 | 1.59±0.24  | 5.19 | -0.17±0.83 | 6.32 | -0.59±0.52 | 6.43 |

Table 3. Details of linewidth histograms (given in Figure 2). Mean of linewidth distribution \([\text{wid}]\) in \(\AA\), its error, and standard deviation \([\text{stdv}]\) of the network and cell interior in the quiet Sun and coronal hole are given in different columns.

| No. | QS   | CH   | network wid | stdv | cell wid | stdv | network wid | stdv | cell wid | stdv |
|-----|------|------|-------------|------|----------|------|-------------|------|----------|------|
| 1   | 0.573±0.001 | 0.012 | 0.566±0.001 | 0.013 | 0.593±0.003 | 0.020 | 0.579±0.002 | 0.019 |
| 2   | 0.534±0.001 | 0.013 | 0.533±0.001 | 0.017 | 0.545±0.002 | 0.015 | 0.539±0.002 | 0.019 |
| 3   | 0.546±0.001 | 0.010 | 0.546±0.001 | 0.009 | 0.555±0.001 | 0.013 | 0.548±0.001 | 0.015 |
| 4   | 0.547±0.001 | 0.018 | 0.545±0.001 | 0.024 | 0.560±0.003 | 0.020 | 0.558±0.002 | 0.028 |
| 5   | 0.294±0.001 | 0.010 | 0.295±0.001 | 0.009 | 0.307±0.002 | 0.017 | 0.306±0.001 | 0.018 |

This has been understood as due to the origin of fast solar wind in the coronal hole (Harra, 2012). The network and cell interior show large differences in their intensities (Reeves et al., 1974; Gallagher et al., 1998; Raju, 2010) and widths (Figure 2) and therefore we expect large differences in their velocities, which is not seen. However, the pattern of difference seen in the lower-TR line \(\text{He} \text{II} \lambda 304 \AA\) and the low-coronal line \(\text{Mg} \text{IX} \lambda 368 \AA\) in the quiet Sun is interesting and is being reported for the first time. This also poses challenges for interpretation. Judge, Carlsson, and Wilhelm (1997) and Gentikakis et al. (2001) report that the lower-TR lines show more redshift in the network than in the internetwork in the quiet Sun, which agrees with our result. Hassler et al. (1999) observe large blueshifts in the network in coronal hole in the \(\text{Ne VIII} \lambda 770 \AA\) line which is formed at the base of the solar corona. Our results on the low coronal line \(\text{Mg} \text{IX} \lambda 368 \AA\) from the coronal hole are inconclusive. Before going further, these results need to be verified.

The larger linewidths in the network as compared to the cell interior are expected because the network is hotter than the latter. The results also show that the evolution of the network is faster in the quiet Sun than in the coronal hole. This is expected to be due to the difference in the thickness of the TR which is five times large in the coronal hole (Huber et al., 1974).
Plumes are known to have smaller linewidths and velocities compared to interplumes [Wilhelm et al., 1998]. The excess width in the network of the coronal hole raises some questions regarding the network-origin of plumes. If plumes are indeed the extensions of the network, then we might expect lower widths in the network. The results on the velocity distributions are, however, inconclusive.

The change of sign of the correlation coefficients of linewidth and velocity for lines from transition region to the corona is being reported for the first time, although some evidence of this can be seen by Xia, Marsch, and Wilhelm [2004]. In their work with Solar Ultraviolet Measurements of Emitted Radiation (SUMER) data, the Si II 1533 Å line shows a positive correlation while the O vi 1038 Å line shows a negative correlation and the behavior of other lines is ambiguous. The behavior of correlation coefficients could be due to the presence of standing or propagating waves from the lower to the upper solar atmosphere. For example, Alfvén waves can cause simultaneous variations in width and velocity. Alfvén waves are known to be one of the candidates for coronal heating.
5. Conclusions

We have obtained the Doppler velocities and emission linewidths in a coronal hole and the nearby quiet Sun in five different emission lines originating at different heights in the solar atmosphere from the lower TR to the inner corona. The behavior of the velocities and widths in the network and the cell interior in the coronal hole and quiet Sun were examined. Histograms of Doppler velocity and width are generally broader in the cell interior as compared to the network. The histograms of Doppler velocities of the network and cell interior do not show significant differences in most cases with exceptions in the lower-TR line He II 304 Å and the low-coronal line Mg IX 368 Å in the quiet Sun. Doppler velocities of the cell interior are more blueshifted than that of the network for the He line and an opposite behavior is seen for the Mg line. The histograms of line width show that the network–cell difference is more prominent in the coronal hole and the network–cell merger happens faster in the quiet Sun. A mild positive correlation between the relative Doppler velocity and the linewidth is found for the lowermost transition region line He II 304 Å, which further reduces or become insignificant for the intermediate lines, and becomes strongly negative for the low coronal line, Mg IX 368 Å. This could be due to the presence of standing or propagating waves from the lower to the upper solar atmosphere.

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