CORONAL HOLES VERSUS NORMAL QUIET SUN OBSERVED WITH SUMER

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Abstract. We present a preliminary analysis of spectral lines obtained with the SUMER instrument (Solar Ultraviolet Measurements of Emitted Radiation) onboard the Solar and Heliospheric Observatory (SOHO), as observed during three observing campaigns. From the 70 observed spectral lines, we selected 12, representing 9 ions or atoms, in order to analyse line intensities, shifts and widths in polar coronal holes as well as in the normal quiet Sun.

We find that coronal lines show a distinct blueshift in coronal holes relative to the quiet Sun at equal heliospheric angle, while there is no evidence for such a shift for lines formed at temperatures below 10^5 K. The widths of lines formed at temperatures above $3 \cdot 10^4$ K are slightly increased inside the coronal hole, but unaffected for lower temperatures. Intensity measurements clearly show the center-to-limb variation, as well as an intensity diminution inside the coronal hole for lines formed above approximately 10^5 K.

1. Introduction

Coronal holes are known to be the source of the fast solar wind and the primary example of coronal heating in regions with an excess of one polarity,

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but are not yet well understood. Intensity distribution measurements with Skylab revealed the presence of coronal holes at different layers of the upper solar atmosphere (Huber et al., 1974). Nevertheless, before the advent of SOHO, only a limited amount of data was available, often hampered by limited spatial resolution or sampling. The possibility given by SUMER of observing full line profiles at high spatial resolution allows us to determine plasma properties, in particular flow velocities in the chromosphere, transition region and lower corona. More recently, distinctive differences in center-to-limb intensity variations of lines between coronal holes and quiet Sun regions have been reported by Wilhelm et al. (1998). We report on an ongoing analysis of high spatial and spectral resolution data of coronal-hole and quiet-Sun regions based on the comparison of moments of spectral lines measured at different locations on the solar disk. We stress that the work is still in progress and that this is very much a preliminary report.

2. Data processing

2.1. OBSERVATIONS

The observations have been carried out using the SUMER Spectrometer (Wilhelm et al., 1995) onboard SOHO. Three sets of observations were used.

The first set (Joint Observing Programme JOP055), was obtained between the 10th and 17th of December 1996. This JOP was run 12 times. Each time, 14 different spectral frames were recorded (1024 spectral $\times$ 360 spatial pixels), each exposed for 300 seconds on detector B, using the $1'' \times 300''$ slit on the central meridian. This slit crossed either the northern or the southern coronal hole. The 14 frames cover a large part of the spectrum between 730 and 1420 Å, including more than 70 identified spectral lines. At the time of these observations the solar rotation compensation mechanism of SUMER was not operational.

The second set (JOP55_TR), taken on the 6th of September 1997, is identical to the first set, but consists of only 4 series of 14 frames each. This time, the solar rotation compensation mechanism could be used.

The third set consists of series of 12 different spectral frames each (512×360 pixels) taken during the SOHO roll manoeuver on the 20th of March 1997. Series of frames were obtained at different locations around the disk, with emphasis on the equator (slit: $1'' \times 300''$, exposure time: 150 s). The roll manoeuvre provides us with data taken around the disk every 30 degrees along the limb, but having the slit always oriented radially instead of being parallel to the N-S axis.

The spectral ranges covered by the JOP55 and roll observations do not exactly coincide. We selected 3 spectral regions (common to all data sets)

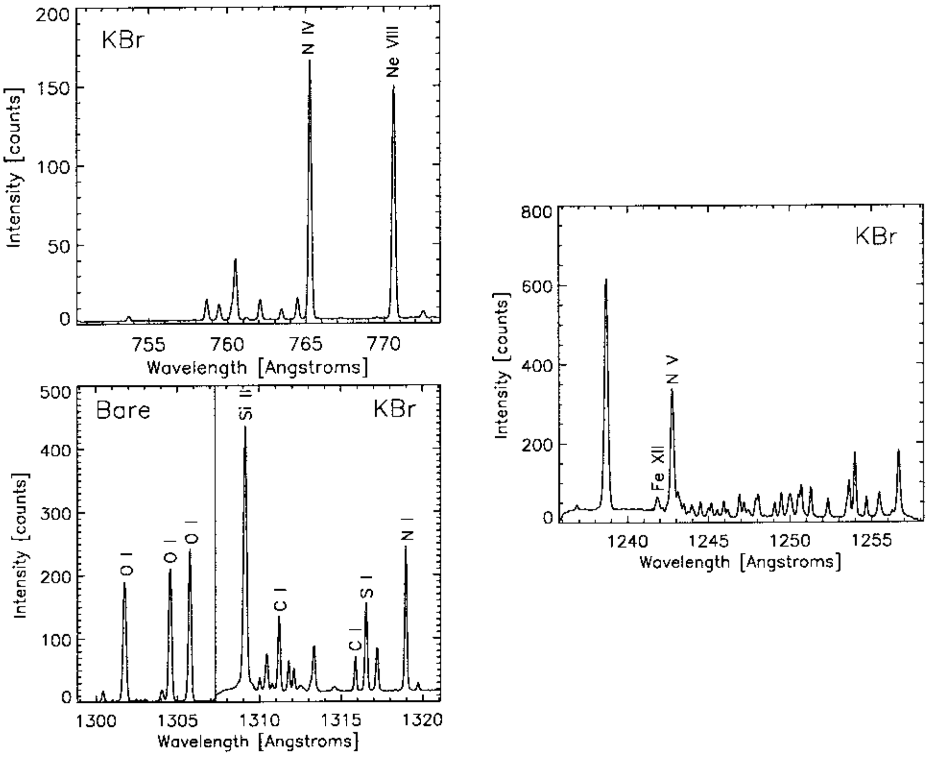

Figure 1. SUMER spectra in Frames 1 and 2 (on the potassium bromide (KBr) photocathode) and Frame 3 (on the bare microchannel plate and KBr). The spectra are averaged over the slit length. The lines analysed are identified.

containing interesting spectral lines for further analysis. Figure 1 shows examples of the three retained frames (spectra averaged in the spatial direction of each frame are plotted). They include two coronal spectral lines, Ne VIII and Fe XII, two transition region lines, N IV and N V, as well as eight chromospheric lines, O I, C I, S I, N I and Si II. Unfortunately, the somewhat blended N V 1242.80 Å line had to be used instead of the cleaner N V 1238.82 Å line, due to its misplacement on the edge of the different photocathodes of the detector in the JOP055 data.

A list of the spectral lines retained for our analysis is given in Table 1. The formation temperatures of the corresponding ions have been taken from Arnaud & Rothenflug (1985).

TABLE 1. Analysed spectral lines with the formation temperature of the corresponding ion

Line	Wavelength	Temperature
N IV	765.15	$1.42 \cdot 10^5$ K
Ne VIII	770.41	$5.75 \cdot 10^5$ K
Fe XII	1242.01	$1.41 \cdot 10^6$ K
N V	1242.80	$1.74 \cdot 10^5$ K
O I	1302.17	$1.51 \cdot 10^4$ K
O I	1304.86	$1.51 \cdot 10^4$ K
O I	1306.03	$1.51 \cdot 10^4$ K
Si II	1309.28	$1.26 \cdot 10^4$ K
C I	1311.36	$1.44 \cdot 10^4$ K
C I	1315.92	$1.44 \cdot 10^4$ K
S I	1316.54	$1.12 \cdot 10^4$ K
N I	1319.00	$1.62 \cdot 10^4$ K

2.2. DATA REDUCTION

The following corrections were applied to the data before the analysis: they were flatfielded using the flatfield image taken closest to the date of the observation, and they were corrected for geometrical distortion according to the procedure described at http://www.mpae.gwdg.de/mpae_projects/SUMER /text/cookbook.html.

The continuum was then substracted, using a linear polynomial fit in Frame 1, a 5th order fit for Frame 2, and two linear fits for Frame 3.

2.3. DATA ANALYSIS

After the data reduction, we calculated the intensity, shift and width parameters for the selected lines at each spatial pixel using the moment method described by Doyle et al. (1997).

An example of the variation of the line parameters along the slit, is shown for N IV 765.15 Å in Fig. 2. An explosive event is seen near the position 110″. In the illustrated case we notice that the intensity is on average higher in the hole than outside, the line is slightly blueshifted in the hole and somewhat broader (even if the points contributing to the explosive event are not considered). From this data set alone it is impossible to distinguish how much (1) the presence of the coronal hole, (2) the center-to-limb variation, and (3) intrinsic (localized) solar variability and structure contribute to these differences between the parameters in the hole and outside it.

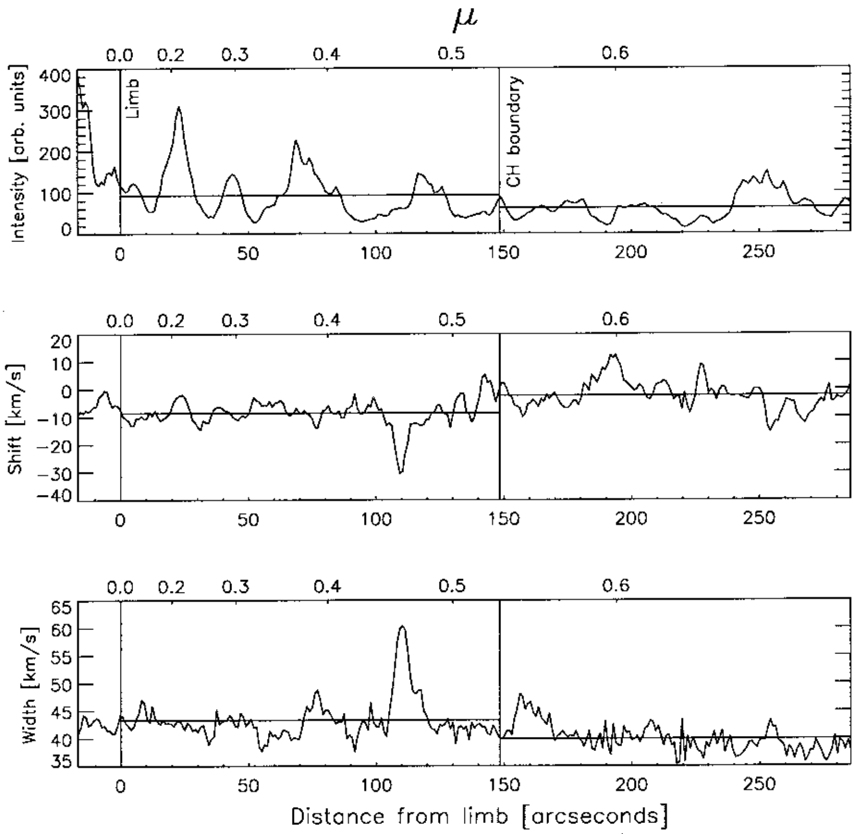

Figure 2. *An example of each of the calculated parameters (intensity, shift and width) using the spectral profiles of* N IV *at 765.15 Å, obtained from the first set of observations (JOP055). The coronal hole boundary is located approximatively* 150″ *from the limb. It is marked by the vertical line near the center of the frame. Horizontal lines represent the average values of the parameters inside (left) and outside (right) the coronal hole. The increased width near* 110″ *marks the presence of an explosive event. The scale at the top of each frame indicates* $\mu = \cos\vartheta$, *where* ϑ *is the heliocentric angle.*

In order to distinguish between these 3 sources we need, on the one hand, better statistics (i.e., more frames containing the same spectral lines), and, on the other hand, also quiet Sun data covering the same μ as the hole data (which is provided by the roll data). By comparing the line parameters averaged over all profiles arising in the coronal hole with averaged line parameter from the quiet Sun at the same μ values it is in principle possible to distinguish between the center-to-limb variation and the hole-non-hole difference. It is, however, still not possible to judge if we have averaged over sufficient data sets to reduce intrinsic solar variability to an acceptable degree. For this reason, and since the instrumental parameters underlying the data obtained along the meridian (containing the coronal hole) and those at other locations at the limb (quiet Sun; roll data) were not the same, we also decided to compare the line parameters obtained along the meridian, but outside the coronal hole, with those from the same μ values at other locations. We therefore computed averages of the line parameters obtained at the same locations (μ values) along the solar radius, for all meridian data (coronal hole at small μ; quiet Sun at large μ), and for all other data (quiet Sun at small μ and at large μ).

Figure 3 shows the variations of line parameters along the slit for the N IV and Ne VIII lines, averaged over all available quiet-Sun data. The center-to-limb variation can be clearly seen in the intensity. Some anomalous effects can be noticed in the plotted line shifts. The differences in the behaviour of the measured shifts above the limb between the two ions is one effect, which might be due to the fact that the N IV signal becomes too weak there to be reliable. Another example is the seemingly regular line shift change every 15 arcseconds for Ne VIII. We expect that it is due to poor statistics (Ne VIII shows a particularly large scatter in the line shift).

All further analysis was based on all available data, a total of 106 images.

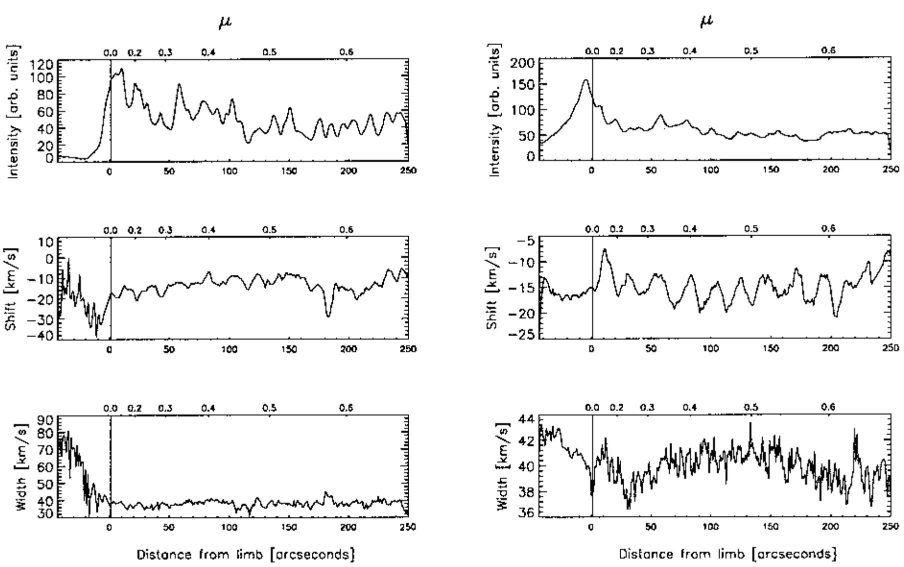

Figure 3. *Line parameters (intensity, shift and width) of the spectral profiles of* N IV *at 765.15 Å (left) and* Ne VIII *at 770.41 Å (right) obtained with the third set of observations (roll data), averaged over all available data in the quiet Sun .*

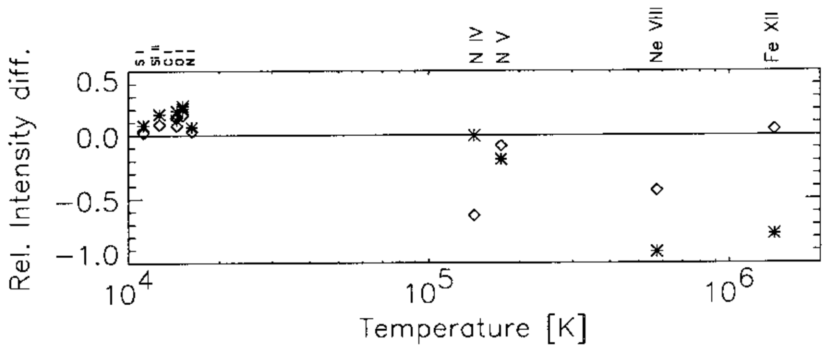

Figure 4. *Relative intensity difference (see text for a definition) vs. formation temperature.* **Diamonds**: *large μ sector;* **Stars**: *small μ sector.*

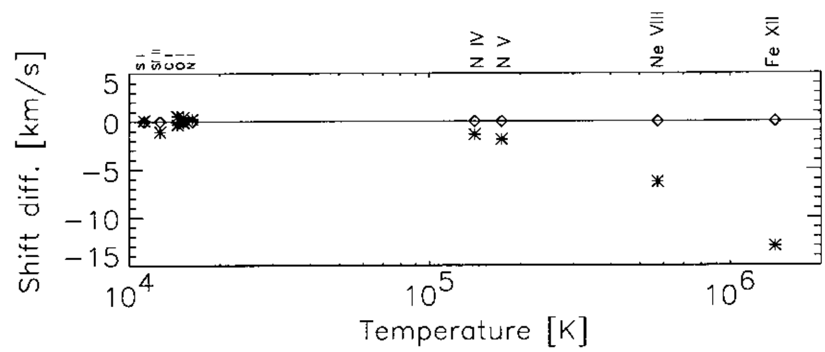

Figure 5. *Wavelength shift difference in velocity units vs. formation temperature. The "shift difference" represents the difference between the shifts observed on the meridian and the ones observed at other locations at the same μ. Since the wavelength scale is not absolute, we equalized the shifts between meridian and equator outside the hole.*
Diamonds: *large μ sector (identically zero due to shift equalization);* **Stars**: *small μ sector (i.e. shift of hole profile relative to non-hole profiles).*

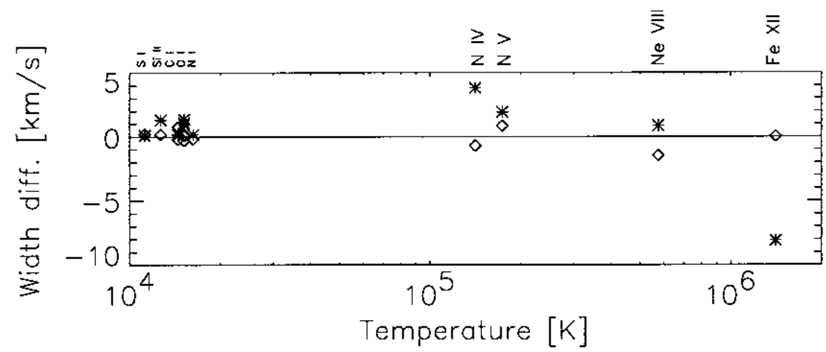

Figure 6. *Width difference vs. formation temperature. The "width difference" represents the difference between the line width observed on the meridian and that at other locations.* **Diamonds**: *large μ sector;* **Stars**: *small μ sector (i.e. widths of hole profile relative to non-hole profiles).*

3. Results

Figure 4 shows the relative difference of the averaged intensity at the meridian to that at the other directions along the limb. It was calculated using the expression $2{\cdot}(\mathrm{I_{meridian}} - \mathrm{I_{other\ locations}})/(\mathrm{I_{meridian}} + \mathrm{I_{other\ locations}})$. As described in Sect. 2.3, the data at small μ and at large μ were treated individually and are represented by different symbols in Fig. 4.

The diamonds represent the relative difference for the data in the spatial range near the limb (small μ sector). The stars represent this difference for the data in the spatial range closer to disk center (large μ sector). For the hottest lines, the relative intensity is smaller for data sampled in a coronal hole than for the quiet Sun data. The scatter shown by the diamonds suggests that there is still some residual solar scatter, even after averaging over all the available data.

Figure 5 presents the difference between the shifts observed on the meridian (data with coronal hole) and the ones observed at other locations (quiet Sun) at the same μ. Since the wavelength scale is not absolute, we equalized the shifts between meridian data and other data for the sector outside the hole (large μ) and measure the shifts in the small μ sector relative to this arbitrary zero point. The figure shows a distinctly higher blueshift at high temperatures in the coronal hole. In addition, this blueshift increases steadily with temperature. This may represent evidence of solar wind outflow in coronal holes.

Figure 6 shows the difference between the line width observed on the meridian (data with coronal hole at small μ and quiet Sun at large μ) and that observed at other locations (only quiet Sun) at the same μ ($\mathrm{W_{meridian}} - \mathrm{W_{other\ locations}}$).

For temperatures below $2 \cdot 10^4$ K, there is no evidence of a difference in line width due to the presence of the coronal hole. But the difference between the two sectors increases with temperature, and could show that the coronal spectral lines are slightly broader inside the hole, although the scatter is rather large. In particular the Fe XII line exhibits an anomalous behaviour. This small increase in line width, if real, could indicate higher non-thermal velocities for lines formed above 10^5 K. The apparently contradictory result for Fe XII could be due to a blend in its wing, which may contribute to its anomalous behavior. This blend may also influence the other parameters of this line, so that their values in Fig. 4 and 5 must be considered with caution.

4. Conclusions

We have analysed the line intensity, shift, and width of selected spectral lines observed by SUMER in coronal holes and in quiet Sun regions.

We find evidence for the presence of a coronal hole in spectral lines formed above 10^5 K. The intensity differences confirm the well-know reduced intensity inside the holes, while the widths may be larger. Most interesting is the blueshift in the coronal hole shown by all the lines with formation temperatures above 10^5 K, and the fact that its increase with temperature is steep. This may be the signature of solar wind acceleration in the polar coronal holes.

It is planned to continue, refine and extend the current research in order to obtain a more reliable picture of solar wind acceleration in coronal holes.

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