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LETTER

Letter to the Editor

On the relationship between shift and intensity of ultraviolet lines in coronal holes and the quiet Sun

K. Stucki[1], S.K. Solanki[2], U. Schühle[2], and I. Rüedi[3]

[1] ETH-Zentrum, Institute of Astronomy, 8092 Zürich, Switzerland
[2] Max-Planck-Institut für Aeronomie, 37191 Katlenburg-Lindau, Germany
[3] PMOD/WRC, 7260 Davos Dorf, Switzerland

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Abstract. We study the relationship between wavelength shifts and intensities of chromospheric, transition-region and coronal ultraviolet emission lines in polar coronal holes and in the normal quiet Sun using SUMER data. Within coronal holes almost all the lines showing the network and formed above 30 000 K show a correlation between blueshifts and brightness. This extends and supports the conclusion reached by Hassler et al. (1999) that the fast solar wind emanates from the network. In the normal quiet Sun, however, we find that only lines formed above $2 - 3 \cdot 10^5$ K show such a trend, the cooler lines being more redshifted in the network. This suggests that either there is a fundamental difference in the initial acceleration of the solar wind in coronal holes and the normal quiet Sun, or that the wavelength-shift versus brightness relationship in the quiet Sun stems from other processes or structures (loops) than in coronal holes (open field lines).

Key words: Sun: corona – Sun: solar wind – Sun: transition region – Sun: UV radiation

1. Introduction

The fast solar wind emanates in coronal holes, but the mechanism by which this solar wind is accelerated to the high speeds observed in interplanetary space is still a matter of debate (Marsch, 1997). Until recently little was known about the exact source regions of the fast and slow wind (coming from the quiet Sun) on a smaller scale.

Using data obtained with the SUMER spectrometer (Wilhelm et al., 1995) on SOHO, Dammasch et al. (1999) and Wilhelm et al. (2000) report a predominant blueshift of the Ne VIII 770 Å line in polar coronal hole regions, interpreted as bulk outflow motion from the source region of the fast solar wind. Hassler et al. (1999) found that the highest outflow speeds seen in Ne VIII are predominantly located in the chromospheric network. Here we extend their work by analysing more spectral lines and quantifying the correlation between the line-of-sight velocity of the plasma at different temperatures and the intensity of lines that clearly show network structures.

Our comparison is based on data taken close to the limb, but still on the solar disk. This differs from many other studies whose emphasis lies on off-limb, or disk-center coronal hole data (e.g. Landi et al., 2000). Detailed shift-versus-intensity studies have been carried out by Brynildsen et al. (1998), Peter (1999) and Hansteen et al. (2000). All find a correlation between intensity and red-shift in the quiet Sun areas.

The present investigation is an extension of a previous study in which we used SUMER data to show that spectral lines of ions with temperatures of maximum ionic fraction above 10^5 K exhibit a blueshift in coronal holes relative to quiet Sun regions (Stucki et al. 1999, 2000).

2. Observations

The observations consist of 3 different data sets. The first and the second set of observations (JOP055 and JOP055_TR, taken in December 1996, respectively September 1997), consist of series of 14 different spectral frames, recorded with SUMER (1024 spectral $\times$ 360 spatial pixels each, exposure time 300 seconds). Those frames cover a large part of the spectrum between 730 and 1420 Å, including more than 70 identified spectral lines. The slit position was located on the central meridian, where it crossed either the northern or the southern coronal hole and also traversed portions of quiet Sun.

The third data set consists of series of 12 different spectral frames (each 512×360 pixels; exposure time: 150 s) taken during the SOHO roll manoeuver on 20th March, 1997. Series of frames were obtained every 30 degrees along the disk circumference while SOHO was rotated around its sun-pointing axis. During the roll manoeuvre the slit was always oriented radially.

The data cover a range of distances from the limb corresponding to approximately the outer third of the solar disk or $0.1 \lesssim \mu \lesssim 0.67$ (μ is the cosine of the heliocentric angle). The coronal holes were identified using concurrent EIT images.

Send offprint requests to: K. Stucki
Correspondence to: kstucki@astro.phys.ethz.ch

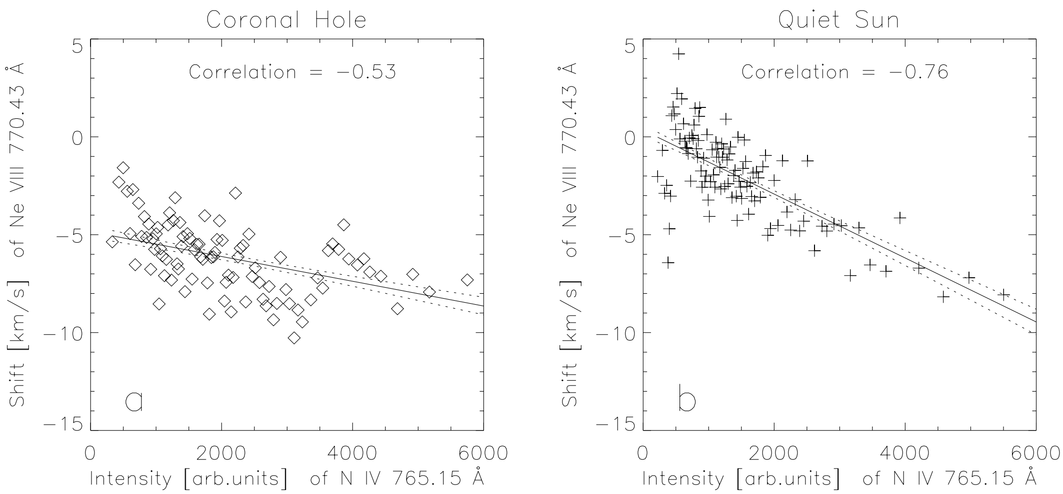

Fig. 1. Wavelength shift of Ne VIII 770.43 Å versus intensity of N IV at 765.15 Å. Each plotted symbol corresponds to the binned values of 20 data points with neighbouring intensity values. **a**: Coronal hole. **b**: Quiet Sun. The solid lines represent linear fits to the binned data, the dotted lines indicate the uncertainties in the fit. The correlation coefficients are indicated.

Their farthest extension towards disk center was $\mu \approx 0.57$ in some of our images.

The data were reduced in the standard manner prior to the analysis, mainly involving flat-fielding and geometrical distortion correction. 10 spectral regions that are common to all data sets and contain spectral lines of diagnostic value covering a wide range of formation temperatures were selected for further analysis.

We retained a total of 24 spectral lines listed in Table 1. The temperatures of maximum ionic fraction in thermal equilibrium of the corresponding ions have been taken from Arnaud & Rothenflug (1985).

To facilitate data interpretation, lines with known blends have been avoided when possible, or a multi-Gaussian fitting routine is employed to separate the contributions of the individual blends. A more complete description of the observations and the chosen lines can be found in Stucki et al. (2000).

3. Results

We calculated the intensity, shift and width parameters of the selected lines at each location along the slit using Gaussian fitting. Here we study the possible relation between line position (Doppler shift) and intensity of the lines showing the chromospheric network. The shift has been measured relative to the position of the maximum intensity of the spectral line averaged over the whole slit.

Fig. 1 shows the wavelength shift of Ne VIII 770.43 Å, which is formed at temperatures above $5 \cdot 10^5$ K, versus the intensity of N IV 765.15 Å at the same location. The cooler line, which is formed at around 10^5 K, was chosen because it clearly shows the structure of the chromospheric network, is strong, unblended, and is coregistered on the same exposure. Negative shifts signify blueshifts. The data were binned over 20 pixels, i.e. each symbol represents the average line shift determined at 20 data points with neighbouring intensity values of N IV (which do not necessarily occur at neighbouring spatial locations). Results for the coronal hole and the quiet Sun are plotted.

Table 1. Analysed spectral lines with the formation temperature † of the corresponding line and the range of wavelength shift covered by the fit in the wavelength shifts versus intensity plots (in kilometers per second).

Spectral line	[Å]	Temp. [K]	Range of shift-intensity curve: Coronal hole	Quiet Sun
O V	629.70	$2.35 \cdot 10^5$	−22.7	−7.1
S IV	661.44	$1.04 \cdot 10^5$	−5.6	6.5
S IV	753.76	$1.04 \cdot 10^5$	−6.0	−2.9
O V	758.67	$2.35 \cdot 10^5$	−5.9	−1.9
N III	764.36	$8.04 \cdot 10^4$	−12.6	5.4
N IV	765.15	$1.42 \cdot 10^5$	−6.9	4.1
Ne VIII	770.43	$5.75 \cdot 10^5$	−3.7	−9.7
Ne VIII	780.32	$5.75 \cdot 10^5$	3.9	−2.5
S VI	933.39	$1.74 \cdot 10^5$	−1.7	3.4
C III	1175.71	$6.76 \cdot 10^4$	6.2	6.0
Si III	1206.51	$3.00 \cdot 10^4$	−1.8	6.7
Fe XII	1242.01	$1.41 \cdot 10^6$	0.1	3.2
N V	1242.80	$1.74 \cdot 10^5$	−2.5	6.1
Si I	1258.80	$8.00 \cdot 10^3$	9.8	3.4
O I	1302.17	$1.51 \cdot 10^4$	0.4	2.6
O I	1304.86	$1.51 \cdot 10^4$	0.2	0.0
O I	1306.03	$1.51 \cdot 10^4$	1.8	3.9
C I	1315.92	$1.44 \cdot 10^4$	1.0	2.5
Ni II	1317.22	$1.40 \cdot 10^4$	4.0	3.0
N I	1319.00	$1.62 \cdot 10^4$	1.8	2.8
C II	1334.50	$3.72 \cdot 10^4$	−2.1	−0.7
Si IV	1393.75	$7.08 \cdot 10^4$	0.0	4.1
O IV	1401.16	$1.66 \cdot 10^5$	−5.8	4.5
Si IV	1402.80	$7.08 \cdot 10^4$	−2.5	3.3

† Warning: Atomic lines and those from optically dense regions require special consideration. The given temperatures are not directly applicable to them (Mason & Monsignori Fossi, 1994).

The solid lines represent linear fits and the correlation coefficients are indicated. The binned data are plotted since they reveal a clearer trend. The correlation coefficients for the unbinned data are smaller, being -0.11 and -0.21 for the coronal hole and the quiet Sun, respectively. Since we do not use an

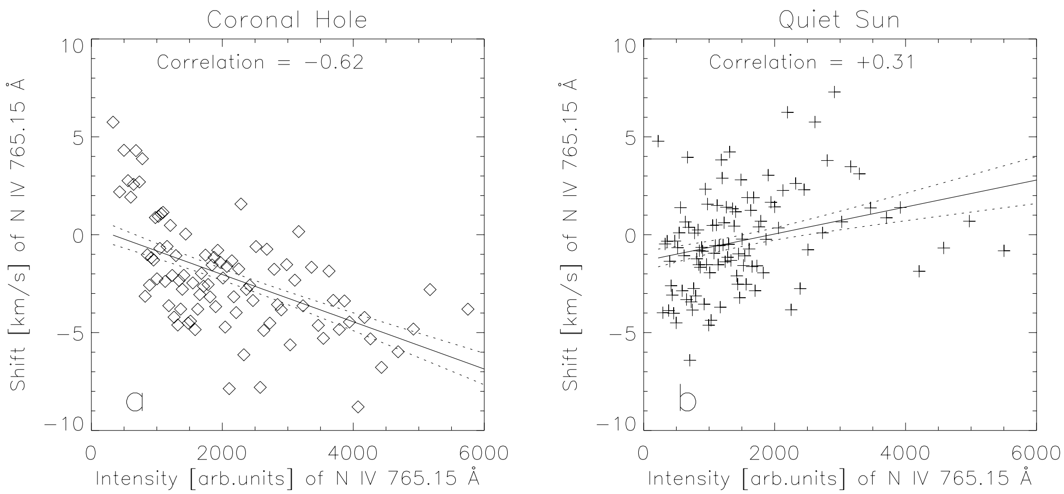

Fig. 2. Wavelength shift versus intensity for N IV 765.15 Å. See Fig. 1 for details.

absolute scale for the shifts, the line shifts at the meridian cannot be compared directly with those obtained at other locations on the disk. Hence only the meridian data (JOP055) have been plotted here. Note that quantities such as the correlation coefficient or the gradient of the least-squares fit are not affected by this ambivalence and can be compared between the data sets.

The Ne VIII line shows larger blueshifts with increasing intensity of the cooler N IV line (Fig. 1) in both the coronal hole and in the quiet Sun. Although the correlation with the network intensity is higher in the quiet Sun, this line is distinctly more blueshifted inside the coronal hole than in the quiet Sun (cf. Stucki et al., 2000). Both results are in agreement with the findings of Hassler et al. (1999) and Wilhelm at al. (2000).

In Fig. 2 we plot line shift versus intensity for a transition-region line, N IV at 765.15 Å. Here also, we used only the meridian data. We observe stronger blueshifts with increasing intensities inside the coronal hole. The trend is reversed in the quiet Sun, however. One must keep in mind that the blue- and redshifts are arbitrary since we are looking at *relative* shifts only. Peter (1999), in contrast, sees no correlation between Doppler shift and intensity inside the coronal hole for another transition-region line, C IV at 1548 Å. This is not inconsistent with our result since the correlation we obtain between the two parameters is rather weak for the unbinned data.

An analysis of the remaining lines in our data set is necessary to reveal whether the trends seen in Figs. 1 and 2 can be related to their temperatures of formation.

Table 1 shows the range in speed covered by the linear fit to the wavelength shift versus intensity data points for the coronal-hole and the quiet-Sun regions, for all analysed spectral lines. The range is here defined as the difference between the minimum and the maximum shift reached by the linear fit in the intensity range of the data, expressed in kilometers per second. Most chromospheric lines show similar positive slopes in both regions, while transition-region lines have a positive slope in quiet Sun and a negative slope inside the coronal hole. For almost all the lines, the gradient is higher (more positive) in the quiet Sun than in coronal holes.

In Fig. 3, the correlation coefficients between line shifts and intensities of all the spectral lines in our sample are plotted versus their formation temperature. We plotted only the results from the binned data. Both the binned and unbinned data display the same trend, but it is accentuated after binning (larger correlation coefficients).

The chromospheric lines show a larger redshift in the network (i.e. positive correlation coefficient) for both coronal-hole and quiet-Sun regions. Most transition-region lines show the same trend in the quiet Sun, but the opposite trend inside coronal holes. Finally, lines formed above 2-3$\cdot 10^5$ K show an increasing blueshift with increasing intensity in both coronal holes and the quiet Sun (this includes the Ne VIII lines). For the Fe XII line, the line with the highest formation temperature in our sample, the shift has been correlated with the intensity of Si I 1̃258.79 Å, which is coregistred on the same frame (since the network cannot be seen in Fe XII; for the same reason as Ne VIII is correlated with N IV at 765.15 Å). The result for the Fe XII line is marginal, due to its weakness and to blends, but has nevertheless been plotted since it is by far the hottest line in our sample.

The plotted coefficients have been calculated using all available data pixels, which means that although the coronal hole results include only meridian observations, the quiet Sun profiles at the other locations have also been employed, in order to achieve better statistics.

4. Conclusions

We have analysed the wavelength shift as a function of the intensity of selected spectral lines observed by SUMER in coronal holes and in quiet Sun regions. The correlation of line shift with the network intensity confirms the results of Hassler et al. (1999). In particular, the Ne VIII line at 770.43 Å shows increasing blueshift with increasing intensity of N IV at 765.15 Å in both quiet Sun regions and coronal holes. We find, however, that the result depends on the choice of spectral line. Particularly for transition region lines, formed between $2 \cdot 10^4$ K and $2 \cdot 10^5$ K, we need to distinguish between coronal holes and the normal quiet Sun. In this temperature range, this relation is one

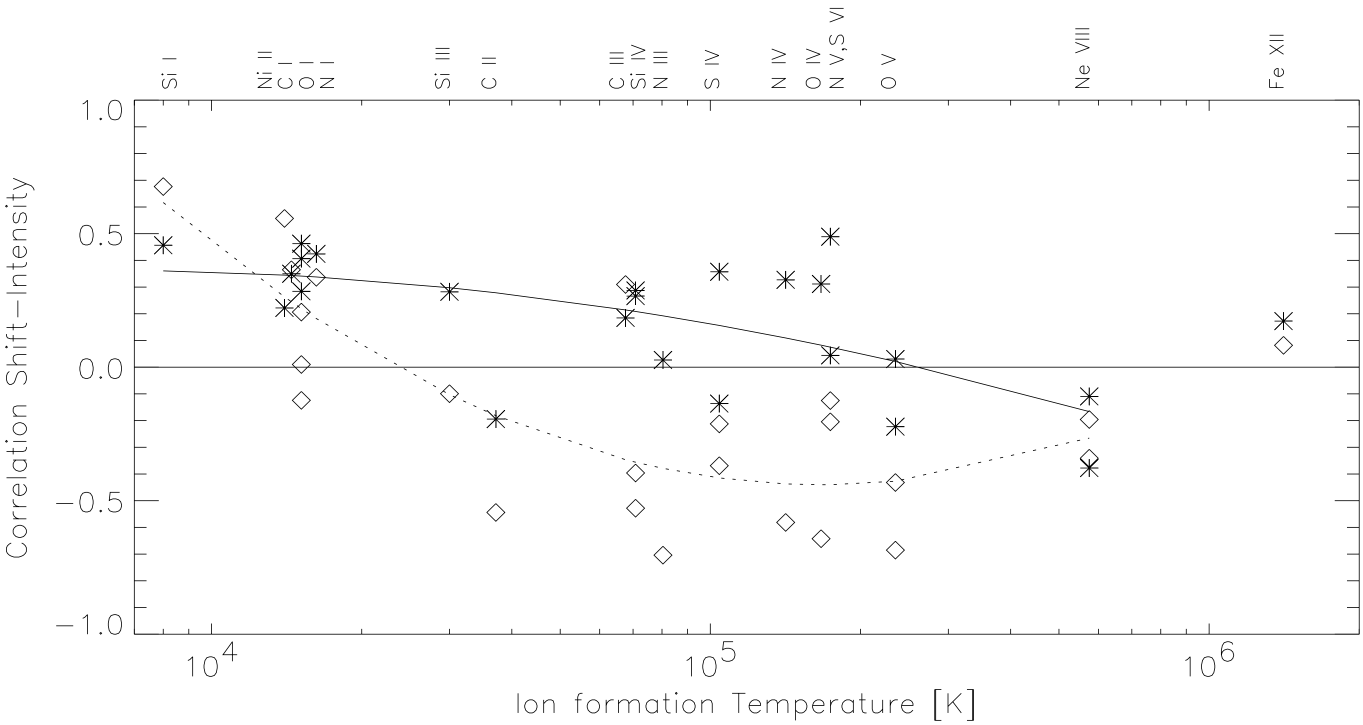

Fig. 3. Correlation coefficient between wavelength shifts and intensities, versus the ion formation temperatures. **Diamonds**: Coronal hole. **Stars**: Quiet Sun. The data are binned in intensity bins of 20 data points. The curves are quadratic fits to coronal hole (dashed) and quiet Sun (solid) data, not including the results of the Fe XII lines.

of the few distinguishing characteristics between coronal holes and the quiet Sun. This suggests a difference in the acceleration mechanisms of the fast and slow solar wind. Alternatively, in the quiet Sun, the brightness-lineshift correlation of transition-region lines stems from other processes or structures (loops) than in coronal holes (open field lines).

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References

Arnaud M., Rothenflug R., 1985, A&AS 60, 425
Brynildsen N. et al., 1998, Solar Phys. 181, 23
Dammasch I.E. et al., 1999, A&A 346, 285
Hansteen et al., 2000, A&A 360, 742
Hassler D.M. et al., 1999, Science 283, 810
Landi E. et al., 2000, A&A 357, 743
Marsch E., Tu C.-Y., 1997, Solar Phys. 176, 87
Mason H.E., Monsignori Fossi B.C., 1994, A&AR 6, 123
Peter H., 1999, ApJ 516, 490
Stucki K. et al., 1999, Space Sci. Rev. 87, 315
Stucki K. et al., 2000, A&A , submitted
Wilhelm K. et al., 1995, Solar Phys. 162, 189
Wilhelm K. et al., 2000, A&A 353, 749