THE NET REDSHIFT IN EUV EMISSION LINES AND THE CONNECTION BETWEEN INTENSITY AND DOPPLER SHIFT

N. Brynildsen¹, T. Fredvik¹, P. Maltby¹, O. Kjeldseth-Moe¹, P. Brekke¹, S. V. H. Haugan¹, R. A. Harrison², K. Wilhelm³

¹Institute of Theoretical Astrophysics, University of Oslo, Oslo, Norway
²Space Science Dept., Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK
³Max-Planck-Institut für Aeronomie, D-37189 Katlenburg-Lindau, Germany

ABSTRACT

Based on high spatial resolution EUV spectra of both a quiet region and a medium size sunspot and its surroundings, NOAA 7981, observed with CDS and SUMER on SOHO, we study the connection between the line intensity and the wavelength shift for a series of emission lines. Using conditional probability analysis we find that line profiles with large intensities and with redshifts in excess of the average constitute an increasing fraction of the number of profiles in a given velocity interval as the relative Doppler velocity increases. Line profiles with large intensities and blueshifts compared to the average, on the other hand, constitute a decreasing fraction of the number of profiles in a given velocity interval as the relative velocity increases.

We find that the connection between intensity and wavelength shift for individual lines will tend to shift line profiles derived by integrating along the slit towards the red. The differential redshift between the transition region and chromospheric emission lines appears to emerge from the correlation between the intensity and wavelength shift in the transition region lines.

Key words: EUV; redshift; solar physics.

Wood et al., (1996), suggesting that the redshift phenomenon is of a general nature and not limited to the Sun. Since true net downflows of several km s⁻¹ from the corona cannot be sustained, possible explanations have included the return of spicule material (Pneuman and Kopp, 1978), siphon flow through loops (e.g. McClymont, 1989) and episodic coronal magneto-hydrodynamic disturbances that propagate towards the chromosphere (Hansteen, 1993; Hansteen, Maltby, and Malagoli, 1996).

Recently, Brynildsen, Kjeldseth-Moe, and Maltby (1995) were able to detect a connection between the intensity and the wavelength shift for the C IV 1548 Å line. In this paper we study the connection between intensity and wavelength shift for several lines and investigate the possibility that the net redshift emerges from the correlation between the intensity and wavelength shift in the transition region lines.

2. OBSERVATIONS

The observations were proposed and planned as a Solar and Heliospheric Observatory - SOHO Joint Observing Programme (JOP018) for simultaneous sunspot observations from space and from the ground. This paper is based on observations of both one quiet region and one active region with the Normal Incidence Spectrometer (NIS) of CDS (Harrison et al., 1995), coordinated with observations by SUMER (Wilhelm et al., 1995). The observations of the largest sunspot in NOAA 7981 and its surroundings were obtained on August 2, 1996 between 10:58:42 and 14:29:59 UT and contain spectral informations for a series of emission lines, see Tables 1 and 2, see also Brynildsen et al. - this issue. The observed sunspot was slightly elongated in the E-W direction and the white light image showed an umbral size of 20° × 16° and a penumbral size of 50° × 42°. Since the sunspot was situated close to disc centre, θ = 16°, (cos θ = 0.96), upflows and downflows may be measured as line-of-sight velocities without any appreciable reduction, whereas only large velocities in the horizontal plane will be recorded.

The quiet region, observed on May 25, 1996 between
13:11 and 15:52 UT, was observed with the same selection of spectral lines as the active region, see Tables 1 and 2. This region was situated at location 270°E, 5560S, corresponding to a heliocentric angle θ = 41°. Both vertical and horizontal velocities may contribute to the line-of-sight velocity, the reduction factor is cos θ = 0.76 for the vertical velocities and less than or equal to sin θ = 0.66 for horizontal velocities.

This paper focuses on the line profiles derived from rastering an area of 120° × 120°, moving the narrow spectrometer slits of CDS and SUMER perpendicular to the slit direction in steps of 2.0" and 1.14", respectively. The SUMER raster observations were obtained with detector A and a slit width of 0.3", whereas the CDS slit width was 2". Both the quiet and the active region observations contain five CDS rasters. We note that the O V 629 Å line was observed with both instruments. Both before and after the narrow slit raster observations we observed the time evolution by using the viewfinder mode the CDS instrument, which operates with a slit of 90° × 240°.

3. DATA SELECTION

The study is based on line profiles where an accurate wavelength shift can be determined. The data material consists of line profiles that are well represented by a single Gaussian shape. The line parameters, intensity, wavelength shift, and line width are determined by least squares fit to the observations. Complicated line profiles and regions with rapid time evolution have been omitted from the SUMER data sets. To be included in the SUMER data sets we have required that the uncertainty in the relative line-of-sight velocity must be less than 3 km s⁻¹. For the CDS data sets we require that the velocity should be accurate to 5 km s⁻¹ for He I 584 Å and O V 629 Å and accurate to 15 km s⁻¹ for the other lines.

4. NOTATION

To differentiate between different line-of-sight velocities the following notation will be used:

\[ v = \text{line-of-sight velocity, relative to the chromosphere. The velocity is positive for motion away from the observer.} \]

\[ < v > = \text{average line-of-sight velocity for the rastered area, 120° × 120°.} \]

\[ v_r = v - < v > = \text{relative line-of-sight velocity.} \]

\[ < v_r > = \text{relative line-of-sight velocity, averaged over an interval in line intensity.} \]

\[ v_{120} = \text{line-of-sight velocity derived from one line profile obtained by integrating along the 120° slit.} \]

\[ < v_{120} > = \text{average of the 106 different } v_{120} \text{ values.} \]

\[ V = \text{line-of-sight velocity derived from one line profile obtained by integrating over the rastered area, 120° × 120°.} \]

Figure 1. Corresponding values of the peak intensity and the relative line-of-sight velocity, derived from individual line profiles for six lines observed with SUMER. Data for the active region NOAA 7981 are shown. Line profiles with peak intensity larger than twice the average intensity are not included in these plots.

5. RESULTS

Insight into the data material may be obtained by showing plots of corresponding values of the line profile parameters, such as the peak intensity in the line profile versus the line-of-sight velocity.

5.1. Active Region

Figure 1 shows, as an example, corresponding values of the peak intensity and the relative line-of-sight velocity for the active region. The data points are derived from the individual line profiles for six emission lines observed with SUMER. Although Figure 1...
Table 1. The average relative velocity, \(< v_r > = < v - \langle v \rangle >\) in km s\(^{-1}\), for different intensity intervals, derived from SUMER observations of the active region

<table>
<thead>
<tr>
<th>Ion</th>
<th>(\lambda (\text{Å}))</th>
<th>&lt;0.10</th>
<th>0.10 - 0.30</th>
<th>0.30 - 0.60</th>
<th>0.60 - 1.25</th>
<th>&gt;1.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si IV</td>
<td>1393</td>
<td>-5.9</td>
<td>-2.3</td>
<td>1.2</td>
<td>3.4</td>
<td>4.4</td>
</tr>
<tr>
<td>C IV</td>
<td>1548</td>
<td>-6.1</td>
<td>-3.4</td>
<td>-1.4</td>
<td>1.7</td>
<td>3.7</td>
</tr>
<tr>
<td>N V</td>
<td>1238</td>
<td>-5.4</td>
<td>-1.1</td>
<td>0.6</td>
<td>2.7</td>
<td>3.7</td>
</tr>
<tr>
<td>O V</td>
<td>629</td>
<td>-6.2</td>
<td>-2.8</td>
<td>0.2</td>
<td>0.7</td>
<td>4.4</td>
</tr>
<tr>
<td>O VI</td>
<td>1031</td>
<td>-6.5</td>
<td>-3.5</td>
<td>-0.6</td>
<td>1.4</td>
<td>4.1</td>
</tr>
<tr>
<td>Ne VIII</td>
<td>770</td>
<td>-5.6</td>
<td>-8.2</td>
<td>-4.8</td>
<td>-0.4</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 2. The relative velocity, \(< v_r > = < v - \langle v \rangle >\) in km s\(^{-1}\), averaged over an interval in line intensity.

<table>
<thead>
<tr>
<th>Ion</th>
<th>(\lambda (\text{Å}))</th>
<th>&lt;0.2</th>
<th>0.2 - 0.4</th>
<th>0.4 - 0.6</th>
<th>0.6 - 0.8</th>
<th>0.8 - 1.0</th>
<th>1.0 - 1.2</th>
<th>1.2 - 1.6</th>
<th>&gt;1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>He I</td>
<td>584</td>
<td>-3.8</td>
<td>-0.2</td>
<td>1.0</td>
<td>2.4</td>
<td>2.0</td>
<td>1.0</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>O IV</td>
<td>554</td>
<td>-8.3</td>
<td>-3.2</td>
<td>-0.9</td>
<td>-0.2</td>
<td>2.6</td>
<td>5.3</td>
<td>6.5</td>
<td>8.4</td>
</tr>
<tr>
<td>O V</td>
<td>629</td>
<td>-3.8</td>
<td>-0.9</td>
<td>-0.1</td>
<td>-1.1</td>
<td>-0.6</td>
<td>0.4</td>
<td>1.5</td>
<td>5.0</td>
</tr>
<tr>
<td>O VI</td>
<td>564</td>
<td>-6.7</td>
<td>-6.8</td>
<td>-5.6</td>
<td>-6.1</td>
<td>-4.5</td>
<td>-0.8</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>Mg IX</td>
<td>368</td>
<td>-8.8</td>
<td>-6.8</td>
<td>-1.5</td>
<td>1.3</td>
<td>2.2</td>
<td>3.5</td>
<td>3.3</td>
<td>5.8</td>
</tr>
<tr>
<td>Fe XVI</td>
<td>360</td>
<td>-6.4</td>
<td>-2.7</td>
<td>-0.6</td>
<td>1.0</td>
<td>-0.1</td>
<td>-0.4</td>
<td>1.5</td>
<td>2.9</td>
</tr>
</tbody>
</table>

shows considerable scatter, the data points are apparently not distributed uniformly. The relative line-of-sight velocities appear to scatter around a value that moves systematically towards the red as the peak intensity increases from low to high values. This property may be illustrated by calculating the average line-of-sight velocity within different intensity intervals. Based on both CDS and SUMER observations of the active region Tables 1 and 2 give the average value, \(< v_r >\), of the relative line-of-sight velocity for different intervals of the peak intensity, \(I\). We measure the intensity in fractions of the average intensity \(< I >\) and to make the results for the different lines comparable we use the same intervals in \(I/ < I >\).

Figure 2. The average value of the "absolute" line-of-sight velocity within different intensity intervals, see Table 1. Data for the active region NOAA 7981 are shown.

Tables 1 and 2 show that the relative line-of-sight velocity, averaged over an intensity interval, \(< v_r > = < v - \langle v \rangle >\), is negative for low intensities, increases systematically as the intensity increases and is positive for the largest peak intensities. This implies that compared to the average wavelength position there is a tendency for the wavelength shift to change from blueshifts to redshifts as the peak intensity of the line profile increases. The point to note is that we observe a systematic shift towards the red as the intensity increases, in spite of the fact that the r.m.s. deviation in each of the listed values are \(\approx 5\) km s\(^{-1}\) for the SUMER observations and between 5 and 15 km s\(^{-1}\) for the CDS observations.

The SUMER wavelength scale is determined from observations of lines formed in the chromosphere. The results shown in Table 1 are converted to "absolute" line-of-sight velocities and the result is shown in Figure 2. It is interesting to note that the differential redshift between transition region and chromospheric lines apparently ceases to exist for line profiles with low peak intensity.

5.2 Quiet Region

Consider next the quiet sun observations. Figure 3 shows the relative line-of-sight velocity, \(< v_r >\), versus the line intensity, after binning the data in ten equally sized groups. Also the quiet region data indicate a systematic shift towards the red as the peak intensity increases, see the results for O V 629 Å, Si IV 1393 Å, C IV 1548 Å, and N V 1238 Å. For O IV 554 Å, Mg IX 368 Å, O VI 1031 Å, and Ne VIII 770 Å little or no connection between intensity and relative velocity is apparent. Interestingly, the He I 584 Å line shows a shift towards the red with increasing line intensity.

We conclude that the observations, most clearly for the active region, show a systematic shift towards the red as the line intensity increases, in spite of the fact that the r.m.s. deviation is large. We note that the observed connection between intensity and wavelength shift may be interpreted as evidence for the presence of compressive wave modes traveling from the corona towards the chromosphere, see Hansteen
and Maltby (1992). To scrutinize the data analysis it may be useful to apply another method of data analysis.

6. CONDITIONAL PROBABILITIES

Following Brynildsen, Kjeldseth-Moe, and Maltby (1995) we consider an estimate of the conditional probability \( \tilde{p}(I, r | v) \) for finding a redshifted pixel with line intensity \( I \) larger than a preselected value \( I_p \), given that the line-of-sight velocity is \(| v - \delta v | < | v - \| v_r | < | v_r + \delta v | \). Similarly let \( \tilde{p}(I, b | v) \) be an estimate of the conditional probability for finding a blueshifted profile within the same intensity and velocity ranges. To derive estimates for these conditional probabilities we determine the area \( A_{|v|} \) with line-of-sight velocities between \(| v - \delta v | \) and \(| v + \delta v | \) for each interval of, say, 2\( \delta v = 2.5 \text{ km s}^{-1} \). Note that \( A_{|v|} \) varies with the velocity \(| v | \). Next, for each area \( A_{|v|} \) we determine the area fractions with intensity \( I > I_p \), for red– and blueshifted profiles. Hence,

\[
\tilde{p}(I, r | v) = \frac{A_{|v|} (v > 0 \text{ and } I > I_p)}{A_{|v|}},
\]

\[
\tilde{p}(I, b | v) = \frac{A_{|v|} (v < 0 \text{ and } I > I_p)}{A_{|v|}}.
\]

This approach is only applicable to the SUMER data where we know the “absolute” line-of-sight velocity. To study data observed simultaneously with both instruments we need to estimate the conditional probability \( \tilde{p}(I, r | v_r) \) \( (\tilde{p}(I, b | v_r) \) for finding a pixel that is redshifted (blueshifted) compared to the average velocity \( v \) and has a line intensity \( I \) larger than a preselected value \( I_p \), given that the relative line-of-sight velocity is \(| v - \delta v | < | v_r | < | v_r + \delta v | \). This may be expressed as,

\[
\tilde{p}(I, r | v_r) = \frac{A_{|v_r|} (v_r > 0 \text{ and } I > I_p)}{A_{|v_r|}}
\]

\[
\tilde{p}(I, b | v_r) = \frac{A_{|v_r|} (v_r < 0 \text{ and } I > I_p)}{A_{|v_r|}}.
\]

Figure 3. Corresponding values of the peak intensity and the relative line-of-sight velocity, \(< v_r > \), derived from individual line profiles for four lines observed with CDS (top) and six lines observed with SUMER. The plots show the results for the quiet region observed on May 25, 1996, after binning the data in ten equally sized groups. Line profiles with peak intensity larger than twice the average intensity are not included in these plots.

Figure 4. Estimates of the conditional probabilities \( \tilde{p}(I, r | v_r) \) (solid line) and \( \tilde{p}(I, b | v_r) \) (dotted line) versus the relative line-of-sight velocity \(| v_r | \). Based on the SUMER observations of the active region. Uncertainties are set equal to the r.m.s. deviations between five equally sized parts of the data.
6.1. Conditional probability analysis

Using equations 3 and 4 we have estimated the conditional probabilities \( p(I, r|v) \) and \( p(I, b|v) \) for several values of the preselected intensity value, \( I_p \). Based on SUMER observations the results for \( I > 1.00 < I > \) are shown in Figures 4 and 5, for the active and the quiet region, respectively.

![Figure 5. Estimates of the conditional probabilities \( p(I, r|v) \) (solid line) and \( p(I, b|v) \) (dotted line) versus the relative line-of-sight velocity \( |v| \). Based on the SUMER observations of the quiet region. Uncertainties are set equal to the r.m.s. deviations between five equally sized parts of the data.](image)

For the active region the estimated conditional probability \( p(I, r|v) \) increases as the relative line-of-sight velocity \( |v| \) increases, whereas the conditional probability \( p(I, b|v) \) decreases slightly with increasing values of \( |v| \). Also for the quiet region differences between \( p(I, r|v) \) and \( p(I, b|v) \) versus \( |v| \) are present. For Si IV 1393 Å and C IV 1548 Å the results are similar to those found for the active region. Significant differences between \( p(I, r|v) \) and \( p(I, b|v) \) are also present for the other lines, with the exception of the results for the Ne VIII 770 Å line. In other words, as the relative Doppler velocity increases we find that line profiles with large intensities and redshifts in excess of the average constitute an increasing fraction of the number of profiles in a given velocity interval. Line profiles with large intensities and blueshifts compared to the average, on the other hand, constitute a decreasing fraction of the number of profiles in a given velocity interval as the relative velocity increases. This result gives support to the finding (see section 5 above) of a significant systematic shift towards the red as the line intensity increases, in spite of the fact that the r.m.s. deviations in the data are large.

7. Net redshift

The connection between the line intensity and the wavelength shift presented in Table 1 gives us a hint about a possible connection between 1) the systematic change in wavelength with line intensity and 2) the net redshift observed in transition region lines. Furthermore Figure 2 suggests that the net redshift ceases to exist for line profiles with low peak intensity. Let us therefore consider the possibility that the net redshift emerges from the correlation between the intensity and wavelength shift in the transition region lines.

The net redshift is usually determined from an observation with one slit position. The redshift and the corresponding line-of-sight velocity are determined after integrating along the slit to obtain one averaged line profile, see Brekke, Hassler, and Wilhelm - this issue. The present observations contain 106 slit positions. For each slit position we have determined an integrated line profile and derived the corresponding line-of-sight velocity, \( v_{120} \). Comparing the 106 different values of \( v_{120} \) we find considerable variation from one slit position to another. In Table 3, which is based on observations of the active region, we compare the average value, \( < v_{120} > \), with the average velocity \( < v > \), derived from individual line profiles without any integration along the slit. In addition we give the line-of-sight velocity, \( V \), derived by integrating over the whole area, \( 120^\circ \times 120^\circ \).

### Table 3. Active region line-of-sight velocities, see notation in section 4

<table>
<thead>
<tr>
<th>Ion</th>
<th>( \lambda (\text{Å}) )</th>
<th>( &lt; v &gt; )</th>
<th>( &lt; v_{120} &gt; )</th>
<th>( V )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si IV</td>
<td>1393</td>
<td>2.1</td>
<td>3.4</td>
<td>4.4</td>
</tr>
<tr>
<td>C IV</td>
<td>1548</td>
<td>4.0</td>
<td>5.4</td>
<td>6.2</td>
</tr>
<tr>
<td>N V</td>
<td>1238</td>
<td>8.3</td>
<td>11.5</td>
<td>11.9</td>
</tr>
<tr>
<td>O V</td>
<td>629</td>
<td>7.1</td>
<td>11.5</td>
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</tr>
<tr>
<td>O VI</td>
<td>1031</td>
<td>3.6</td>
<td>6.6</td>
<td>7.9</td>
</tr>
<tr>
<td>Ne VIII</td>
<td>770</td>
<td>5.6</td>
<td>7.5</td>
<td>8.3</td>
</tr>
</tbody>
</table>

### Table 4. Quiet region line-of-sight velocities, see notation in section 4

<table>
<thead>
<tr>
<th>Ion</th>
<th>( \lambda (\text{Å}) )</th>
<th>( &lt; v &gt; )</th>
<th>( &lt; v_{120} &gt; )</th>
<th>( V )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si IV</td>
<td>1393</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>C IV</td>
<td>1548</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>N V</td>
<td>1238</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>O V</td>
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<td>10</td>
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<td>O VI</td>
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<tr>
<td>Ne VIII</td>
<td>770</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

For the quiet region \( V \) is estimated from a deep exposure at one slit position.

It is apparent from Table 3 that \( V \) is larger than \( < v_{120} > \), which again is larger than \( < v > \) in the active region. For the quiet region the corresponding differences are small, but the trend is in the same direction. This result combined with the large variation in wavelength shift with position on the solar disk and the small wavelength shift for line profiles with low intensity, see Figure 2, give support to the working hypothesis: i.e. that the net redshift emerges from the correlation between the intensity and wavelength shift in the transition region lines. A complete discussion of the possible explanations for the correlation between the intensity and the wavelength shift...
is outside the scope of this paper. We note, however, that a connection of this kind is expected for compressive wave modes propagating from the corona towards the chromosphere (Hansteen, 1993; Hansteen, Maltby, and Malagoli, 1996).

ACKNOWLEDGMENTS

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