NEW INSIGHT IN TRANSITION REGION DYNAMICS AS DERIVED FROM SUMER OBSERVATIONS AND NUMERICAL MODELLING

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ABSTRACT

Measurements of Doppler shifts in different regions of the quiet Sun obtained with the UV spectrograph SUMER on board SOHO is presented. This work is a continuation of recent studies by Teriaca et al. (1999a,b) who have analysed line shifts and the non-thermal velocities as a function of temperature for several spectral lines formed in the range between 10⁴ and 10⁶ K. It was pointed out by Teriaca et al. (1999a) that possibly the O vi formation temperature (3 x 10⁵ K) corresponds to the height in the solar atmosphere where an inversion from redshift to blueshift takes place. Following a suggestion by Peter & Judge (1999) we explore the idea that nanoflare occurrence in a magnetic loop around the O vi formation temperature could explain the observed redshift of the high transition region lines as well as the blueshift showed by low corona lines (T > 6 x 10⁴ K). Detailed study of the temporal evolution of the parameters of C iii 977 Å and O vi 1032 Å lines is carried out in order to underline the variable nature of the observed Doppler shift.

Observations will be compared to numerical simulations of the response of the solar atmosphere to an energy perturbation representing an energy release during magnetic reconnection in 1-D semi-circular flux tube. The temporal evolution of the thermodynamic state of the loop is converted into C iv 1548.2, O vi 1032 and Ne viii 770 line profiles in non-equilibrium ionisation.

Key words: Transition Region; SOHO–Sun; Doppler shifts.

1. INTRODUCTION

During the last two decades, observations of redshifted emission of lines formed at transition region (TR) temperatures were obtained by many authors using several UV instruments with different spatial resolution (see Brekke et al., 1997 and references therein). In earlier investigations the magnitude of the redshift has been found to increase with temperature, reaching a maximum (around 8 km s⁻¹ in the quiet Sun) at T = 10⁶ K, and then to decrease towards higher temperatures. Doschek et al. (1978) found no significant shift in the O vi line at 1218 Å at disk center and the commonly quoted average velocity variation with temperature above 10⁵ K depended to a large extent on this particular observation of the 1218 Å line. Chae et al. (1998a) have shown that for the quiet Sun the redshift is peaked around 1.5 x 10⁵ K with a value of 11 km s⁻¹ but it is also present at higher temperatures with a value of around 5 km s⁻¹ for Ne viii 770.409 Å in the quiet Sun. Similar results were also obtained by Brekke et al. (1997). Peter & Judge (1999) have found blueshifts at disk center for three coronal lines (i.e., Ne viii at 770 Å and 780 Å and Mg x at 625 Å). This difference in the value of Doppler shift for the Ne viii 770 line is due to the assumption of a new rest wavelength of 770.428 Å. This value for the Ne viii rest wavelength has been confirmed by Dammash et al., 1999). Recently Teriaca et al., (1998a) found evidence of blueshift in the Quiet Sun and in an Active region. Peter (1999) and Peter & Judge (1999) found also, at spatial scales up to 50 arc sec, clear evidence of a center-to-limb redshift behaviour consistent with a cos θ behaviour in all transition region lines and a cos θ blueshift behaviour for the three upper transition region/coronal lines listed above. This suggests an explanation in terms of prevalent vertical mass or wave motions for the observed line shift.

In this paper we present measurements of Doppler shift of transition region lines for the Quiet Sun in two location near disk center. A detailed study of the temporal evolution of the parameters of C iii 977 Å and O vi 1032 Å lines are reported here in order to underline the variable nature of the observed Doppler shift. Our observational results will be further used to model the observed line-shift in Transition Region and corona. Numerical simulations are carried out representing a reconnection-type of physical process. Results are then converted into UV line profiles in non-equilibrium ionisation (see Erdélyi 1999, Erdélyi et al. 1998, 1999, Sarro et al. 1999) and are compared to observations.
2. OBSERVATIONS & DATA REDUCTION

SUMER is a normal incidence spectrograph operating over the wavelength range 450 Å to 1610 Å. It is a powerful UV instrument capable of making reliable measurements of bulk motions in the chromosphere, transition region and low corona with a spectral resolution of 45 mÅ/pix at 800 Å (first order) and a spatial resolution of 1 arcsec across and 2 arcsec along the slit (Wilhelm et al. 1995; Lemaire et al. 1997). The observations discussed here were obtained in April '96 and March '97 and consist of temporal series of spectral images centered at 1032 Å and 977 Å, respectively. Locations, pointing and wavelength range of these observations are given in Table 1. Every single spectrum in C III was exposed for 2.5 seconds using the 0.3 x 120 slit at the bottom of detector B in the quiet Sun center for a total of 150 spectra covering 375 seconds. During the sequence there was no solar rotation compensation. At Sun center, the solar rotation is ~ 1" every 360 seconds, giving a very good spatial resolution. In order to increase the signal to noise ratio (S/N) we binned the original image over 4 spatial pixels along the slit and over 3 consecutive images, with a final spatial resolution of 4 arcsec along the slit and final temporal resolution of 7.5 seconds. We, hence, identified 25 different regions along the slit and for each one the temporal evolution of the line shift was studied. The temporal series in O VI consist of 1024 images with an exposure times of 6 seconds each. An integration along the slit over groups of five pixels was performed in order to improve the S/N ratio. Here we present only the first quarter of the dataset. A detailed analysis of the entire dataset will be presented in Terraca et al. 1999b. In this case the evolution of 20 regions along the slit was studied. Also for this dataset there was no rotational compensation. It is, then, important to bear in mind that after ~ 360 s, the slit is not pointing to the same region. In the present work we are primarily interested in the 60-120s sudden variations in the line shift, so rotational compensation is not so important.

Reduction of SUMER raw images follow several stages, i.e., dead time correction, local gain correction, flat field subtraction, radiometric calibration (in order to pass from count px^{-1} s^{-1} to erg cm^{-2} s^{-1} Sr^{-1} A^{-1}) and a correction for geo-

Table 1. Log of SUMER observations of the Quiet Sun.

<table>
<thead>
<tr>
<th>Date</th>
<th>Line</th>
<th>Slit (arcsec)</th>
<th>Detector</th>
<th>Solar X-Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>April '96</td>
<td>O VI</td>
<td>1x120</td>
<td>A</td>
<td>199 - 105</td>
</tr>
<tr>
<td>March '97</td>
<td>C III</td>
<td>0.3x120</td>
<td>B</td>
<td>0 - 0</td>
</tr>
</tbody>
</table>
metrical distortion. All these stages were applied to our data (see Teriaca et al. 1999a for details).

Particular attention needs to be paid to the problem of the wavelength calibration. For SUMER there is no on-board calibration source, so the wavelength calibration is done using some chromospheric lines of neutral atoms. These lines are formed in the chromosphere at temperatures around 6500 K (e.g., Si i and Si II, Chae et al. 1998a) and are supposed to be at rest (Samain 1991). These should therefore allow determination of an absolute wavelength scale. It is important to remember that all the absolute velocity measurement made with SUMER will be relative to these chromospheric reference lines. The measurement of the central line position, together with amplitude and full width half maximum, was performed using the Genetic Algorithm (GA) of Charbonneau (1995) (see Teriaca et al. 1999a for details).

Full frame images with an exposure time of 300 seconds were taken just before the temporal series in C III allowing us to perform the wavelength calibration. The dispersion relation was calculated performing a first order polynomial fit to the pairs central pixel - laboratory wavelength of the reference lines.

For the O VI dataset an half detector image with an exposure time of 150 seconds is available. Unfortunately the dispersion relation calculated using five O I lines yield a shift value (~3 km s\(^{-1}\)) for the O VI 1031 line that is largely in disagreement with the average published values (~7 km s\(^{-1}\)). This is probably due to local non-linearities at the left hand side of the detector (as also reported by Brekke et al. 1997). The problem was solved by taking a simple average of all the calculated line positions (5220) and assuming a redshift of 7 km s\(^{-1}\) for this value. Due to the large average in time and space, we are convinced the average shift value can not be too much far away from the generally observed one.

3. OBSERVATIONAL RESULTS

In the present study we have observed the temporal evolution of Doppler shifts for C III and O VI, gaining informations about the behaviour of the transition region at 8 \(10^4\) K and 3 \(10^5\) K (for formation temperatures see, e.g., Landi & Landini, 1999; Landini & Monsignori Fossi, 1990). Results are plotted in Figs. 1 & 2. In both datasets we also found the oscillatory nature of the observed Doppler shift. In Fig. 1 the time behaviour of intensity and redshift in C III is shown at 6 different locations along the slit. For reference an averaged image of the slit of the entire dataset is shown in the left hand side of Fig. 1. At location (b) one can notice that a very small amount of shift is characterising this very faint
Figure 3. SUMER measurement of Radial Velocities in Active Region NOAA 7946 (top panel) and in the Quiet Sun (lower panel). Solid lines represent a forth order polynomial fit (Teriaca et al. 1999a).

internetwork region while bright network regions like (c) are marked by high values of redshift as well as by high variability. The same kind of behaviour can be noted in the OVI dataset shown in Fig. 2. The bright network location (b) of Fig. 2 displays the highest observed redshift of the entire OVI dataset reported here. Another very important aspect is the absence of any relevant amount of blueshift. In almost all the dataset we found that the redshift reduces occasionally to zero. This seems to point towards an intermittent mechanism for the observed Doppler shift. The short length of time of the CIII dataset does not allow any consideration about a periodicity, but it is anyway possible to see many transient increase of redshift with width between 50s and 100 s (Fig. 1, location (c) at time 180 s and 300 s; as well as location (f) at time 90 s; location (e) at time 100 s). The much more extended O VI dataset permits to observe some periodicity in the shifts. An example can be clearly seen in the second half of the time series at location (c) where a periodicity of around 150 s is evident.

4. DISCUSSION

Teriaca et al. (1999a) have shown that the temperature variations of the Doppler shifts and non-thermal velocities in the quiet Sun and active region have important implications for the validity of the physical models for the red shift (or down flow) problem. In Fig. 3 we show the behaviour of the Doppler shift versus temperature of formation for quiet Sun and active region as reported by Teriaca et al. (1999a). From their measurements it is possible to infer that the Doppler shift reversal from redshift to blueshift takes place around log T = 5.7 K (5.0 \times 10^5 K) for the active region while in the quiet Sun a value between log T = 5.7 and log T = 5.75 (5.0 \times 10^5 - 5.6 \times 10^5 K)
to explain the presence of blueshift together with redshift within one model.

Following the suggestion of Peter & Judge (1999) we support the idea of prevalent occurrence of nanoflares (or better to say: magnetic reconnection) around the O VI formation temperature \(3 \times 10^5\) K as a source for the redshift observed in the low and middle transition region and for the blueshift seen in the upper transition region and coronal lines. This can also explain the peak of the non-thermal velocity versus temperature curves at the O VI formation temperature (see Chae et al. 1998b; Teriaca et al. 1999a). From this point of view the larger range of values detected for the active region could be explained in terms of higher frequency of occurrence and/or energy of nanoflares events in the Active region with respect to the quiet Sun.

5. MODELLING

We compare our observations with the response to an energy deposition representing nanoflares due to reconnection in the high part of a 1-D semi-circular magnetic flux tube (Erdelyi et al. 1998, 1999; Erdelyi 1999; Sarro et al. 1999). After the (M)HD computations, results are turned into UV line profiles applying the non-equilibrium ionisation condition in order to make a direct comparison with observable quantities. Note, the condition of non-equilibrium ionisation has a serious effect on the line formation and was already discussed by Sarro et al. (1999).

In the simulation shown in Figs. 4 & 5, an energy input of \(4 \times 10^{24}\) ergs was released at an height of 5400 km (corresponding to \(T = 5.71\)) in a 1-D magnetic loop. The temporal evolution of the thermodynamic state of the loop is converted into C IV 1548.2 Å, O VI 1031.9 Å, and Ne VIII 770.4 Å line profiles (see Fig. 4).

Further, Fig. 5 shows the time evolution of the total intensity (upper panel) and the central position (lower panel) for the three modelled UV lines. An analysis of Fig. 5 shows that indeed purely redshift is produced in C IV while blueshift is produced during the second part of the simulation in O VI and in Ne VIII. Due to the much higher intensity of the latter two lines during the blue shift part, this will turn in a predominance of blueshift in Ne VIII and, in small amount, in O VI. Performing an integration over the entire period of 55 seconds of simulations carried out a redshift of \(6 \mathrm{km} \mathrm{s}^{-1}\) is found in C IV, while a blueshift of \(-2 \mathrm{km} \mathrm{s}^{-1}\) and \(-10 \mathrm{km} \mathrm{s}^{-1}\) were derived for O VI and Ne VIII, respectively. Results for C IV and Ne VIII are in good agreement with previous and recent observations, while some discrepancy is present for O VI results.

We trust our results shed further light into the physics and modelling of the complexity of the solar (and stellar) transition region modelling. Furthermore, our observations provide clues for the possible role of nanoflares events in the transition region as a suitable source for the observed Doppler shift. We plan to develop the modelling of the nanoflares mechanism exploring in detail the parameter space calculating the response of the model to different amount of
The deposited energy at different temperatures. We further plan to perform 2-D simulations (e.g., the work by Roussev et al. in this Volume).

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