SYSTEMATIC REDSHIFTS IN THE QUIET SUN TRANSITION REGION AND CORONA
OBSERVED WITH SUMER ON SOHO

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ABSTRACT

New observations of systematic redshifts of transition region and coronal lines obtained with SUMER (Solar Ultraviolet Measurements of Emitted Radiation) on SOHO (the Solar and Heliospheric Observatory) are presented. With the extensive wavelength coverage of SUMER it is possible to extend the measurements of the redshifts to much higher temperatures compared to previous instruments. Our results indicate that the redshifts are present even in the upper transition region (e.g., O V, S V, and S VI). Even O VI, Ne VIII and Mg X show systematic redshifts in the quiet Sun spectra. The lack of systematic blue shifts in lines like Mg X may raise the question: Where does the solar wind come from? Future work includes the comparison of the systematic redshifts in different solar features, such as plages, coronal holes and a detailed analysis of the center-to-limb variations of the shifts.

Key words: Solar Physics; EUV; Spectra; SOHO.

Measurements of the variation of the flow with temperature are somewhat ambiguous, however.

Doschek et al. (1976) found no significant shift in the O V line at 1218 Å at disk center suggesting an abrupt falloff at higher temperatures. The commonly quoted average velocity variation with temperature above 10⁶ K depends to a large extent on this particular observation of the 1218 Å line. This result has also been extensively used in comparison with numerical simulations of flows in the transition region (e.g. Spadaro, Antiochos, and Mariska 1991; Hansteen 1993). None of the many hypotheses to explain the redshifted emission have been found to be entirely satisfactory.

In this investigation we find the the redshift to extend to much higher temperatures than previously reported. This result will put new constraints on models of the redshifts in the solar atmosphere.

1. INTRODUCTION

One of the most puzzling problems in solar physics is the apparent net redshift of emission lines in the transition region. During the last decades, this phenomenon has been observed with several UV instruments with different spatial resolution (e.g., SKYLAB: Doschek, Feldman, and Bohlin 1976; OSO 8: Lites et al. 1976; SMM: Gebbie et al., 1981; HRTS: Dere 1982; Brekke 1993; Achour et al., 1995; LASP EUV: Hassler, Rottman, and Orrall 1991). Systematic redshifts have also been observed in stellar spectra of late type stars, first with the International Ultraviolet Explorer (e.g., Ayres et al., 1983; Ayres, Jensen, and Engvold 1988; Engvold et al., 1986) and recently by the Hubble Space Telescope (Wood et al., 1996; 1997). Both solar and stellar flows in the transition region have been extensively studied at temperatures around T = 10⁵ K. For the Sun, the typical value of the average downflow velocity, derived from the C IV lines at 1550 Å, is 5–10 km s⁻¹.

SUMER is part of the ESA/NASA Solar and Heliospheric Observatory (SOHO) and is a stigmatic normal-incidence spectrograph operating in the range from 400 to 1610 Å. The detectors cover approximately 40 Å in first order and the full spectral range is obtained by moving a scan mirror. Both 1st and 2nd diffraction orders are superimposed on the SUMER detector, and the dispersion is wavelength dependent, varying from 45 mA/pixel (first order) and 22.5 mA/pixel (second order) at 800 Å to 41.8 mA/pixel and 20.9 mA/pixel at 1600 Å. A more detailed instrument description is given by Wilhelm et al. (1995).

2. Instrument

The results presented in this communication were derived from an observing sequence designed to record a so-called reference spectrum. A reference spectrum covers the entire spectral range of the spectrometer and allows us to study a large number of lines formed
Figure 1. A typical quiet Sun spectrum between 934 – 941 Å which includes the S VI line at 933 Å and several H I Lyman series lines. The right panel shows the detector plane with the recorded spectrum. The position along the slit is in the y direction. The left panel shows the average spectrum along the slit. The reference lines (marked with R), as well as the other most prominent lines are marked. The dot-dashed lines represent the rest wavelengths.
2.2. Wavelength Calibration

The determination of flow velocities requires that an accurate wavelength scale be established. Since there is no absolute wavelength reference available on the spectrograph, a wavelength scale was derived using a set of selected solar chromospheric lines as wavelength references. As reference lines we have chosen lines mainly from neutral and singly ionized atoms. The selected lines are fairly strong and unblended in the solar spectrum and laboratory wavelengths are known with fairly high precision. Since the reference lines are formed over a limited range in temperature and other physical conditions, one would expect that they would have near zero line-of-sight Doppler shifts relative to each other. This, furthermore, seems a reasonable assumption considering the observed small velocity variations along the slit in these lines, particularly in the quiet solar region. Lines formed in the chromosphere are also known to show relatively small average absolute shifts (e.g., Samain 1991) and should therefore allow the determination of an absolute wavelength scale. Comparison of the wavelengths of these lines with an accurate in-flight wavelength calibration source suggests this is a reasonable assumption (Haessler, Rottman, and Orrall 1991)

For most of the wavelength bands selected in this investigation the wavelength scale is accurate to approximately ±1 km s⁻¹ on a velocity scale. During the wavelength calibration we found a non-linearity in the dispersion just to the left of the KBr section of the detector (pixel positions between 150-300 counted from the left of the detector). This asymmetry is being investigated but in the present study we avoided this part of the detector when deriving a calibrated wavelength scale.
3. Measured Dopplershifts

The reported line shifts in this study represent an average along the spectrograph slit. The average spectrum around the Mg X 624 Å line is shown in Figure 3. The data were obtained on the bare part of the detector and the Mg X line (as observed in 2nd order) is very strong compared to the first order lines. It should be noted that significant variations in line shifts are observed along the slit even in the quiet Sun. The shifts were determined after integrating along the slit to obtain one average line profile. It should be pointed out this yields an intensity weighted result. The average shift was also derived from the measured line position in each pixel along the slit. No significant difference was found between these two methods in the quiet Sun data. However, such a difference has been reported by Brynildsen et al. (1997) near an active region observation where the emission is much higher compared to the quiet Sun values. Similar correlation in the quiet Sun has also been presented by Brynildsen et al. (1995) while conflicting results have been presented (see Dere, Bartoe, and Brueckner 1984, and references therein). In this paper, we were mainly interested in the average shift of the lines in the quiet Sun. Based on the pre-scan showed in Figure 2, and full disk images from both EIT (Delaboudinière et al. 1995) and ground based observatories the data presented here represents a typical quiet Sun area.

Figure 3. Spectral scan around the Mg X 624 Å line. The data were obtained on the bare part of the detector and the Mg X line (as observed in 2nd order) is very strong compared to the first order lines. The thin solid line shows the raw counts while the thick solid line represents the sum of the individual Gaussian profiles fitted to the data.

Our results are summarized in Table 1 and Figure 4 which also includes the commonly quoted variation of the line shifts reported by Dorsch et al. (1976). Table 1 lists the reference wavelengths, observed wavelengths and the corresponding Doppler shifts converted to line-of-sight velocities. The use of velocity to describe the line shifts should not be taken to mean that one should restrict possible interpretations to gas flows only. The errors in the measured Doppler velocities derived from Gaussian fits to the lines listed in Table 1 are on the order of ±1.5 km s⁻¹. In some cases more than one reference wave-

Figure 4. The variation of the redshift with temperature of formation in the quiet Sun as observed with SUMER on August 12 1996. The measured shift of the O IV 790 Å line deviates from the other two O IV lines and is also marked with an open circle. The uncertainties of selected lines are shown. The earlier commonly quoted average velocity variation is shown for comparison.

length can be found in the literature. Such lines are marked with a dagger in Table I. During the observing sequence each wavelength is recorded several times on different parts of the detector. It therefore was possible to confirm independently the observed line shifts.

We find the average redshift of emission lines to persist to higher temperatures compared to previous investigations. Shifts in the range +10-16 km s⁻¹ are observed in lines formed at T=1.3 × 10⁵ K. Even upper transition region and coronal lines (O VI, Ne VIII, and Mg X) show systematic redshifts corresponding to velocities around +5 km s⁻¹. Most previous observations show a peak in the redshift around C IV (100,000 K) while in the present data it peaks around 250,000 K. This, and the fact that we observe systematic redshifts also in the coronal lines are new results.

4. Discussion

The average redshifted emissions appear to be a persistent phenomenon in both quiet and active regions. The estimated downward mass flux around T = 10⁵ K is sufficient to empty the corona in a few minutes. It therefore seems likely that upflows also exist which balance the observed downflow unless the Doppler shifts are due to waves propagating through the transition region. The redshifts often are interpreted as a net downflow of gas, although that conclusion does not directly follow. Both downflows and upflows may occur where, for some reason, the downflowing plasma is slightly brighter than the upflowing plasma. Several hypotheses to explain the redshifted emission have been proposed so far and they include the return of spicular material, siphon flows in coronal loops, nanoflares, a different temporal duration of upflows and downflows, and asymmetric heating.
Table 1. Observed shifts as a function of temperature of maximum ionic abundance

<table>
<thead>
<tr>
<th>Element</th>
<th>( \lambda_{\text{lab}} ) [Å]</th>
<th>( \lambda_{\text{solar}} ) [Å]</th>
<th>Log T [K]</th>
<th>Velocity [km s(^{-1})]</th>
<th>Ref.</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>C II</td>
<td>1036.3287</td>
<td>1036.3471^t</td>
<td>4.36</td>
<td>3 ± 1.5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Si IV</td>
<td>1402.769</td>
<td>1402.8021^x</td>
<td>4.80</td>
<td>7 ± 2.0</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>C IV</td>
<td>1458.195</td>
<td>1458.2531^x</td>
<td>5.01</td>
<td>6 ± 1.5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>C IV</td>
<td>1550.770</td>
<td>1550.8112^nd</td>
<td>5.01</td>
<td>8 ± 1.5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>N IV</td>
<td>765.148</td>
<td>765.1712^nd</td>
<td>5.15</td>
<td>9 ± 1.5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>O IV</td>
<td>787.711</td>
<td>787.7482^nd</td>
<td>5.24</td>
<td>13 ± 2.0</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>O IV</td>
<td>1401.156</td>
<td>1401.2101^x</td>
<td>5.24</td>
<td>12 ± 2.0</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>O IV</td>
<td>790.199</td>
<td>790.2132^nd</td>
<td>5.24</td>
<td>7 ± 2.0</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>S V</td>
<td>786.470</td>
<td>786.5062^nd</td>
<td>5.24</td>
<td>14 ± 2.0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>N V</td>
<td>1424.778</td>
<td>1424.8241^x</td>
<td>5.25</td>
<td>11 ± 1.5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>S VI</td>
<td>933.380</td>
<td>933.4241^x</td>
<td>5.31</td>
<td>14 ± 2.0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>O V</td>
<td>629.730</td>
<td>629.7652^nd</td>
<td>5.37</td>
<td>16 ± 3.0</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>O VI</td>
<td>1031.926</td>
<td>1031.9411^x</td>
<td>5.46</td>
<td>5 ± 1.5</td>
<td>3</td>
<td></td>
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<tr>
<td>O VI</td>
<td>1037.817</td>
<td>1037.8461^x</td>
<td>5.46</td>
<td>6 ± 1.5</td>
<td>3</td>
<td></td>
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<tr>
<td>Ne VIII</td>
<td>770.409</td>
<td>770.4232^nd</td>
<td>5.80</td>
<td>5 ± 1.5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Ne VIII</td>
<td>780.324</td>
<td>780.3412^nd</td>
<td>5.80</td>
<td>6 ± 3.0</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Mg X</td>
<td>624.960</td>
<td>624.9622^nd</td>
<td>6.05</td>
<td>3 ± 1.5</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

1 — Kaufman and Edén 1974
2 — Kaufman and Martin 1993
3 — Kaufman and Martin 1989
4 — Edén 1934
5 — Kelly 1987
6 — Bockasten and Johansson 1968
7 — Böttcher et al., 1996
8 — Moore 1965
9 — More and Gallagher 1993
† — Conflicting reference wavelengths have been reported (see text)

of coronal loops (see Brekke 1993 for an overview of different models). However, none of them have been found to be entirely satisfactory.

The most promising of the theories mentioned are the models by Hansteen, Maltby and Malagoli (1996) and Reale, Peres and Serio (1997). Hansteen, Maltby and Malagoli (1996) suggested that the observed line shifts are caused by MHD waves propagating along magnetic field lines from the corona downward towards the chromosphere. A nanoflare "pulse" strikes the transition region where a large redshift is produced while the intensity increases rapidly. After the pulse has passed the transition region bounces back and a blue shift ensues. The intensity during this phase is reduced due to lower density as the transition region decompresses. The correlation between compression and displacement from several such pulses produce an average redshift of the transition region lines. The average redshift of C III and C IV found from this calculation is 15 and 7.5 km s\(^{-1}\) respectively. However, they find the coronal line (Mg IX) to show a net blueshift of ~15 km s\(^{-1}\), inconsistent with our measured shift of the Mg X line if we assume that lines of similar excitation should show approximately the same shift.

Detailed studies of the redshifted emission observed on the Sun are also important for the understanding of similar observations of stellar spectra. Recent observations of redshifted transition region lines in spectra obtained with the GHRs on Hubble Space Telescope were presented by Wood et al. (1996, 1997). Below temperatures of about 1.8 \( \times 10^5 \) K, the line redshifts of the Sun, α Cen A, α Cen B, and Procyon are all very similar. However, at higher temperatures both α Cen A and α Cen B suggest dropoffs in redshifts similar to that suggested by the solar data presented by Achour et al. (1995). In comparison, no dropoff in the redshifts was found in the spectra from Procyon, which is a hotter and somewhat more active star than the Sun. Comparison of the redshifts observed in active regions and the quiet Sun, as well as in coronal holes are being investigated. Such studies could give new information that can explain the recent stellar observations.

Observations of the solar UV spectrum with high resolution spectrometers have demonstrated that there is a need for improved measurements of laboratory wavelengths of a number of spectral elements. The uncertainties in some of the reference wavelengths complicate the interpretation of the current observations with SUMER as shown in this paper. A general problem when calculating shifts of high temperature ions is the uncertainties in some of the reference wavelengths as discussed earlier by Brekke (1993), Brekke and Hassler (1995) and recently by Warren et al. (1997). To understand and interpret the current and future measurements of line shifts in the SUMER range, we strongly encourage that the accuracies of the laboratory wavelengths and energy levels of the most important lines from 400 to 1600 Å be evaluated, and if necessary, re-measured in the laboratory.

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