TIME-DEPENDENT STUDIES OF He I AND He II AND OTHER TRANSITION REGION AND CORONAL LINES

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ABSTRACT

As part of our study of the formation of the lines of He I and He II, observations of these lines and of other transition region and coronal lines have been made with the CDS on SOHO using hi-rate telemetry. These give repeated 25-s exposures of the quiet Sun allowing time-dependent studies which complement our previous studies of the spatial variation of the He I, He II and other transition region lines. Network brightenings are observed which are similar to those previously reported by others. The variations of He I and He II lines with time have a smaller amplitude than those of the other transition region lines. This could be due in part to the higher opacity of the helium lines. Lines shifts and linewidths have also been investigated; some of our results confirm those found earlier, but many of the large downflows in the supergranulation cell boundaries are adjacent to, rather than co-spatial with, the highest intensities. An order of magnitude brightening, followed by a strong upflow and large turbulent velocities is also observed, and may be a small 'network flare'.

Key words: Helium lines; Velocity fields; Blinkers; Network flares

1. INTRODUCTION

Understanding the formation of the resonance lines of helium is a major problem in solar physics. (See Hammer 1997 and Macpherson & Jordan 1999 for summaries of previous work). We recently (Macpherson & Jordan 1999) discussed the spatial variation of these lines and other transition region lines in quiet Sun regions observed with the Coronal Diagnostic Spectrometer (CDS) instrument onboard the Solar and Heliospheric Observatory (SOHO). While the lines of He I and II were found to share a common behaviour, as do the other transition region lines, the behaviour of the helium lines relative to the other transition region lines is significantly different. In particular, the helium lines were found to be about an order of magnitude stronger than expected from the emission measure distribution established from the other transition region lines. Supergranulation cell boundaries and interiors were analysed separately, showing that there is a greater enhancement of the helium lines above cell interior regions.

Here we discuss new high time resolution observations of the helium lines and other transition region and coronal lines. Studies of the dynamical behaviour of the transition region have already been carried out (e.g. Harrison 1997, Berghmans et al. 1998, Gallagher et al. 1999). Harrison (1997) reported observations of transient brightenings in the quiet Sun, dubbed 'blinkers', which showed enhancements of a factor of 2-3 in the transition region line of O IV 554.52 Å with smaller enhancements in He I 584.33 Å and Mg IX 368.07 Å of around 20-25%. Berghmans et al. (1998) gave a panoramic view of quiet Sun EUV transient brightenings as observed in He II 304 Å and Fe XII 195 Å by the EUV Imaging Telescope (EIT) instrument onboard SOHO. They found many events sharing characteristics with the CDS 'blinkers', which appear to be a subset of a large class of EUV brightenings. Gallagher et al. (1999) have found evidence of semi-periodic brightenings in the He I 584.33 Å and O V 629.73 Å lines in the cell boundaries and interiors. Peter (1999) has discussed the behaviour of the He I line over a full Sun raster, including intensities, line shifts and linewidths. Some comparisons with the above results are given below. Since the helium lines are stronger than expected compared to the other transition region lines (Jordan 1975, Macpherson & Jordan 1999, and noted also by Berghmans et al. 1998), their behaviour cannot be regarded as typical of the transition region, and they should not be studied in isolation.

2. OBSERVATIONS AND DATA REDUCTION

The observations were made with the CDS twin normal incidence detector (the NIS). The observing sequence used is based on our HELIUM sequence (Macpherson & Jordan 1999), modified to take advantage of a period of hi-rate CDS telemetry. The exposure time was shortened to 25 s but the hi-rate telemetry allowed us to retain the eight strongest lines important to our study. Details of the modified HELIUM observing sequence are given in Table 1.
Table 1. Details of the HEL HI observing sequences.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>CDS/NIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slit size used</td>
<td>2&quot; × 240&quot;</td>
</tr>
<tr>
<td>Ions</td>
<td>He I 584.33 Å, 537.03 Å, He II 304.78 Å, O III 599.59 Å, O IV 554 Å, O V 629.73 Å, Mg IX 368.07 Å, Mg X 624.94 Å</td>
</tr>
<tr>
<td>Exposure time</td>
<td>25 s</td>
</tr>
<tr>
<td>Window size</td>
<td>30 pixels (≈ 3.4 Å)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HEL HI v1</th>
<th>HEL HI v2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>40&quot; × 240&quot;</td>
</tr>
<tr>
<td>No. of exposures</td>
<td>200</td>
</tr>
<tr>
<td>Duration (mins)</td>
<td>10.8&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Two observing windows used to cover whole multiplet.
<sup>b</sup>Includes dead-time which exists between exposures.

The observations were made on 1998 March 2 between 20:20 U.T. and 23:15 U.T. and covered a quiet region near Sun centre (Solar X, Y = 104.3", -16.7"). Two types of observation were made, labelled v1 and v2 in Table 1. First, an image of the region under study was built up by making twenty exposures of the 2" × 240" slit, thus providing an image of area 40" × 240". Figure 1 shows the structure of the region as seen in the lines of He I 584.33 Å, O V 629.73 Å and Mg IX 368.07 Å. The slit was then returned to the centre of the image and a series of 200 25-s exposures was taken. There exists dead-time between the exposures amounting to an average of ≈ 7.3 s for each exposure. Hence the total duration for the time series sequence is ≈ 108 minutes from the first to last exposures. In the figures shown, the individual exposures have been joined together by including the dead-time within the exposure time. It is important to take these gaps in the data into account if investigations of periodicities are made. Solar feature tracking was turned off so the Sun was rotating through the slit field of view, at the rate of 9" per hour. Thus a feature just entering the 2" slit in the first exposure would be present within the slit for 726-s or ~ 23 exposures. Over the 108-minute duration, the region sampled has an extent of ≈ 18" in the solar X direction. Further images of size 40" × 240" were taken at the end of the time series.

The data were reduced and analysed as described in Macpherson & Jordan (1999). The intensity calibration was carried out using the original calibration provided by NIS.CALIB, which converts the raw data into intensity (erg cm <sup>−2</sup> s <sup>−1</sup> sr <sup>−1</sup> Å <sup>−1</sup>). These intensities were then 'corrected' according to the results of Landi et al. (1997) so that they use the same calibration as in Macpherson & Jordan (1999). The CDS software calibration has recently been amended (Brekke et al., 1999, in preparation). This results in small corrections to our absolute derived intensities that will not affect our conclusions which are based on the variations of line ratios. The line profiles were fitted with Gaussians to derive the peak intensity, linewidth (FWHM), background level and position, with the total line intensity being calculated using \[ I_{TOT} = \frac{\sqrt{\pi} I_{MAX} \text{FWHM}}{2 \sqrt{ln2}}. \]

Figure 1. Initial structure of the 40" × 240" region studied, imaged in the lines of He I 584.33 Å, O V 629.73 Å and Mg IX 368.07 Å.

3. ANALYSIS AND RESULTS

Figure 2 shows images of the intensity in the lines of He I, He II, O IV and Mg IX as a function of solar Y and time for the 200 exposures. The apparent variations with time are composed of variations of the structure averaged over 2", as new features enter the slit, plus real variations with time of features within the slit. As the Sun rotates the images show dark strips of cell interior regions along side supergranulation network boundaries. Thus in the O IV image at around solar Y ≈ −125", −50" and 30", changes are seen which are consistent with a region of cell interior being replaced by a region of cell boundary, and at Y ≈ 60 – 75" with a region of cell boundary being replaced by a cell interior. Figure 1 confirms this interpretation as we can identify the structures which will rotate into the field of view. The variations on a timescale of much less than ~ 700 s must be intrinsic variations of features within the field of view.

3.1. Cell into Normal Network at Solar Y ≈ −125"

Intensities: Figure 3 shows the intensity of the O IV 554 Å line as a function of time at Y = −125", averaged over 5 pixels (~ 8"). The scan starts in a cell interior region and progresses into a boundary region (I > 200 erg cm <sup>−2</sup> s <sup>−1</sup> sr <sup>−1</sup> Å), with a gradual increase in the average intensity. At all intensities there are fluctuations on timescales of < 300 s, which are likely to be variations with time. In the boundary the amplitude of the O IV variations are similar to those found by Harrison (1997) in his 'blinkers'. As also shown in Figure 3, the same slow changes are observed in the He I 584.33 Å line, but these and the faster fluctuations are of lower amplitude than observed in the O IV line, so the variations in the He I (584)/O IV (554) ratios tend to follow the inverse O IV intensity. As reported by Macpherson & Jordan (1999) this ratio is larger in the cell interior region.
Figure 2. Intensities of the He I and II lines, the transition region line of O V and the coronal line of Mg IX, as a function of solar-Y ($''$) and time (s). The right-hand image shows the O V 638.73 Å velocity field (white: downflows, black-upflows).

Figure 3. The O IV 554 Å and He I 584 Å (offset by a factor 2) intensities and their ratio, as a function of time at solar-Y = -125$, averaged over 5 pixels. The scan starts in a cell interior and progresses into a boundary.

than in the cell boundary region. Since, as discussed by Hearn (1969) and Andretta & Jones (1997), the He I line is likely to be optically thick, its lower contrast (also apparent in Figures 1 and 2), could be caused in part by photon scattering from surrounding boundary regions. Within the effective 32.3 s time resolution there is little difference between the times at which the main fluctuations occur in the He I and O IV lines, but if anything the former follow the latter.

Figure 4. The He I/O IV and He II/O IV ratios as a function of the O IV intensity at solar-Y = -125$. Figure 4 shows the He I (584)/O IV (554) intensity ratio as a function of the O IV (554) intensity. This shows more detailed structure than previously ob-
served in the 70-s exposures discussed by Macpherson & Jordan (1999). At a given time, scans in the Y direction show that the He I line contrast is lower than that of the O IV line, which could be due to photons being scattered from the boundaries into the cell interiors. Thus at a given time, it is likely that He I photons have been lost from the regions that are strong in O IV. In the regions weak in O IV, He I photons may be gained from nearby boundaries outside the field of view. As a peak (in time) in O IV is crossed, the He I/O IV ratio is at first relatively large, it then decreases as the O IV peak is approached, then increases again as the peak is passed. If the helium line emission were completely uniform, the gradient in Figure 4 would be 1. Coincident helium and oxygen emission would, of course, give a constant ratio. Thus the overall trend in Figure 4 can be understood in terms of optical depth effects, and in the boundary enhancements the He I opacity must increase as the O IV intensity increases. The same type of trend is observed as the scan moves out of the cell interior, but where the ratio depends on both photons lost and gained, there is less of a correlation. In the cell interior, the ratio is higher because photons are mainly gained. The He II/O IV ratio is also shown in Figure 4, with no second order sensitivity applied. The He II line is expected to have a lower opacity, and this may account for the smaller spread in the ratios. Radiative transfer calculations are needed to interpret the ratio and its variations in a quantitative manner. We stress that even at the high O IV intensities the absolute intensities of the helium lines are enhanced above those expected from the other transition region lines.

The He II/He I (584) intensity ratio decreases by about a factor of 1.7 as the He I intensity increases by a factor of 3.3 and the O IV intensity increases by an order of magnitude. New radiative transfer calculations by Smith using the VAL-C model (Vernazza et al. 1981) including detailed atomic models for He I and He II and including He III show that such a decrease could result from an increase in the coronal radiation field. The Mg IX and Mg X lines are too weak in this region to establish their variations.

Velocities: Velocity fields and non-thermal motions are important in the study of the helium lines (Jordan 1980). Following Gallagher et al. (1999), we measure any wavelength shift, derived from the Gaussian fitting routine, relative to the average position of each line observed over the initial 40' x 240' raster, since an absolute wavelength calibration for CDs is not yet available. These average wavelengths ($\lambda_{avg}$) differ by $\leq 0.01$ Å (or $\Delta\nu \leq 5$ km s$^{-1}$) from laboratory wavelengths. The velocity derived is then $v = c [\lambda_{obs} - \lambda_{avg}] / \lambda_{obs}$. The velocities of the He I, He II and O V lines have been measured in this way. The velocities and intensities found for the O V line, from the scan at solar-Y = -125" , are shown in Figure 5 (bottom and top panels, respectively).

The regions in or near the cell interior show upflows of $\sim 10-20$ km s$^{-1}$. These tend to decrease as the line intensity increases into the boundary until in the region of highest intensities, downflows of up to $\sim 15$ km s$^{-1}$ are observed. Downflows in the network boundaries have been reported since their discovery by Doschek, Feldman & Bohlin (1976). However, here we find that the largest downflows do not occur in the regions of highest intensity, but adjacent (prior) to them. This can be seen in Figure 5 between 3750 s and 4920 s. Although some lack of direct correlation as been noted (e.g. by Gallagher et al. 1999), to our knowledge this distinctive behaviour has not been previously reported. In other boundary regions also examined, the maximum downflows do not correspond uniquely to local maximum in intensity. Gallagher et al. (1999) found upflows in the He I 584 Å (as did Peter 1999) and O V 630 Å lines in quiet Sun cell interiors, which we confirm. The cause of these blue-shifts in transition region lines is not yet understood, but these new data should be useful in constraining models, such as extensions of the chromospheric shocks simulated by Carlsson & Stein (1997) (see also Peter 1999).

Although there is some tendency for the He I/He II ratio to be larger in downflows, the variation is only a factor of 1.7, while the velocities range from $-15$ km s$^{-1}$ to $+15$ km s$^{-1}$. Any treatment of scattered photons will have to take into account their incident wavelength and the velocity field where they are last scattered.

3.2. The Active Network at Solar-Y $\approx 5"$

Intensities: As can be seen from Figure 2, several brightenings occurred in the network at solar-Y $\approx 5"$. Following a short brightening at $\sim 2700$ s there are several peaks which in O V have intensities of 3000 - 5000 erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$, far larger than the 'strong network' observed by Macpherson & Jordan (1999), and factors of 6-10 larger than in typical boundaries. Because of the short timescales of the intensity changes these are real brightenings of a structure within the 2" slit. The event may be the transition region equivalent of a 'network flare' (c/f Krucker et al. 1997, Berghmans et al. 1998, Freš

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& Phillips 1999) rather than a ‘blinker’, particularly since the Mg X 624.9 Å line increases by around a factor of 2.5. The times of the peaks are the same in the helium and other transition region lines. A scan in solar-Y (averaged over 3 exposures) through the enhancement at 4075 s shows that the helium emission is more extended, consistent with photon scattering. The FWHM is $\sim 11.5''$ in He I but only $\sim 9.3''$ in O IV and O V.

Plots of the various line ratios show that neither the relative intensities of the O III, O IV and O V lines, nor the He I 537 Å/584 Å ratio show large variations with the O IV intensity, in spite of the red and blue shifts discussed below. The He I/O IV and He II/O IV ratios decrease with increasing O IV intensity, but with distinct branches, as in the boundary discussed above. The times (and thus the location) over which the ratios occur are indicated in Figure 6 by different symbols. The form of the overall trend can again be understood in terms of high optical depths in the helium lines. If the large ratios at the lowest O IV intensities (upper branch-vertical crosses) are due to photon scattering then these photons may originate from the strong boundary not yet within the slit at these times. However, Macpherson & Jordan (1999) did find regions of enhanced helium emission with no obvious source of scattered photons. The lowest branch (crosses) is observed between $\sim 5890$ s and 6471 s, where the O IV line decreases faster than the He I line (the direction with time is up the branch) and this would be consistent with photons being scattered from the strong region that has left the slit. At a given O IV intensity, the difference in the ratio between the two branches would then originate from the difference in the He I radiation field present. The triangles are from the preceding region where there is a large blueshift and linewidth (see below).

The He I/He II ratio versus I(O IV) shows far less variation than the O III, O IV and O V lines, and again shows two distinct branches. As mentioned above, radiative transfer calculations using the VAL-C model (which refers to the average quiet Sun) show that this ratio tends to increase as the radiation field increases. The He I 584 Å intensity is predicted to increase with the coronal radiation field, since the contribution from recombination increases, while the He II 304 Å decreases as the peak N/He II/N He ratio shifts to lower temperatures, reducing the collisional excitation rate. If these were the only effects occurring, the He I (584)/He II (304) ratio should increase with increasing Mg X intensity. As shown in Figure 7 the upper limit to the He I/He II ratio decreases as the I(Mg X) increases, and there is a significant spread in the He I/He II ratio, as in Figure 6. It is clear that both opacity effects and the coronal radiation field must be treated together to account for the form of Figure 7.

**Velocities:** Figure 8 shows the velocities measured in the O V line, together with the line intensity and linewidth. The velocities start as small upflows of $\sim 5$ km s$^{-1}$, but become downflows of up to $\sim 17$ km s$^{-1}$ by $\sim 2600$ s (with variations around 1940-2330 s that are also present in He I and He II. As the O IV intensity increases the redshifts become on average larger, with peaks of over 20 km s$^{-1}$. He I and He II show a similar behaviour except the high redshifts continue longer after the main peak at 4075 s. Unlike in the more normal boundaries, the main O IV peaks do correspond to peaks in the redshifts. Between $\sim 5175$ s and $\sim 5390$ s there is a dramatic change in the velocities. The O V line shows a blueshift (upflow) of up to $\sim 25$ km s$^{-1}$, which is also present but smaller in He I and He II (up to $\sim -5$ km s$^{-1}$). This large upflow can be seen easily in Figure 2. The line intensities all pass through a broad maximum during this time interval. Finally, in the last 580 s the velocities return to relatively small downflows of up to $\sim 10$ km s$^{-1}$. We have examined the He I/He II and He I/O IV intensity ratios and the O V intensity as a function of the O V flow velocity. The only clear correlation is between the O V intensity and velocity in the initial phase where the intensities are lowest but steadily increasing.

**Linewidths:** The relatively low spectral resolution of the CDS instrument (FWHM $\simeq 0.50$ Å) means that
only exceptional large linewidths can be detected. Figure 8 also shows the O V linewidths observed. Up to ~3880 s no significant additional broadening is detected, but a distinct broadening is observed at the time of the larger intensity peak in O V. The largest linewidths are observed during and around the time of the upflow. The upflow region is therefore a region of large turbulent motions. Since the upflow begins at 5175 s, this region is not that which brightens at ~4010 s, as they cannot be within the 2" slit at the same time. One can say that within a 3" region of boundary, a large brightening and large upflow have occurred within about 22-min of each other, which could be consistent with a network flare. A more detailed analysis of this event is in progress.

4. CONCLUSIONS

The area studied at high time resolution contains examples of supergranulation cell interiors and boundaries. Transient brightenings in the boundaries are observed that are comparable to the 'blinkers' described by Harrison (1997). However, a larger event was also observed which could be a 'network flare'. Although here we present only qualitative discussions, which will be followed up later with more quantitative analyses, some general conclusions can be drawn. In the boundary regions we find that the largest redshifts (downflows) are usually adjacent to the regions of highest intensity, rather than being coincident in location/time. Blueshifts (upflows) are found in cell interior regions both in He I and in O V which should be optically thin at Sun-centre. The He I/O IV ratio appears to depend on photon scattering, but this does not account for the overall anomalously high intensity of the helium lines.

The active boundary shows variations in the He I/O IV and He I/He II ratios, some of which could be due to opacity effects. These make it difficult to discern any dependence of the ratios on the coronal radiation field, line shifts or linewidths, which are significant in this boundary. Further radiative transfer calculations are being made to simulate the more active boundary, but to understand the range of data obtained will require two-dimensional modelling and velocity fields will need to be included.

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