The Structural Variability of the Solar EUV Network

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Abstract:
Observations of the quiet Sun with the Coronal Diagnostic Spectrometer (CDS) on board the Solar and Heliospheric Observatory (SOHO) are reported for the upper chromosphere, transition region, and corona. The changing structure of the EUV network is examined over a temperature range of $1.5 \times 10^4$ K to $1.2 \times 10^6$ K using a variety of properties of the characteristic intensity distributions.

The distribution of intensity in small (4 × 4 arcmins\textsuperscript{2}) areas of the quiet Sun at Sun centre has been examined. These distributions were found to consist of both a low intensity core distribution combined with an extended tail associated with the transition region EUV network. Network properties such as relative area, emission, contrast, and fractal dimension have been derived by fitting two Gaussians (one representing the cell distribution, the other the network) to each frequency histogram and then using the cross-over point of the two Gaussians as a boundary point between the two components.

The integrity of the network displays a well defined relationship with temperature showing a noticeable structural enhancement in the temperature range $1.1 \times 10^5$ K to $2.5 \times 10^5$ K together with a dramatic change in integrity at coronal ($\geq 10^6$ K) temperatures.

1. Introduction

Observations with the Skylab mission in the 1970’s demonstrated the close similarity of the quiet Sun network structure seen in the chromospheric Ca II K line spectroheliograms and extreme ultraviolet (EUV) images made with the Harvard College Observatory S055 instrument with temperatures characteristic of the chromosphere and transition region (Reeves, Vernazza, & Withbroe 1976). Some of the brighter features can also be identified in coronal emission line images. There is a close correspondence of the network structures with the boundaries of the photospheric supergranules, and it appears that the convection motions within these supergranules result in concentrations of magnetic field at their edges which in turn are responsible for the emission seen in the chromosphere and transition region. Quite possibly, too, the dynamic nature of the network structures result from the continual merging or cancelling of magnetic field elements transported radially outwards from a cell to existing field

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at the edges (Martin 1988). Although only a schematic approximation to the real circumstances, the model of Gabriel (1976) gives some idea of the relation of the supergranules, magnetic field, and network emission structures in the chromosphere and transition region.

Some early investigations of the quiet Sun in the EUV with the Skylab S055 instrument (Reeves, Vernazza, & Withbroe 1976; Huber et al. 1974) indicated that the intensity of EUV features in quiet Sun areas follow a distribution in which there is a strong peak at a relatively low intensity and a tail covering a range with a maximum of up to several times the peak intensity. The tail of the distribution is more pronounced for features outside coronal holes. For images made in chromospheric and transition region EUV lines (i.e., emitted at temperatures between $10^4$ K and several $10^5$ K), the intensities above a value approximately equal to the average can be identified with the bright network structures, while those below this value are related to the cells (i.e., the areas bounded by the bright network structures). For coronal (temperatures $\geq 1 \times 10^6$ K) EUV lines, the distribution was found to be more nearly Gaussian, with only a slight tail which in this case corresponded to the large diffuse structures characteristic of coronal images, which are sometimes associated with network structures, small active region loops etc.

The decomposition of the intensity distribution into a variety of distinct components recalls the findings of Skumanich et al. (1975) and Bocchialini et al. (1994) for observations made in the core of the Ca II K line. Simultaneous line-of-sight magnetic field measurements show that the strongest fields (strengths $\geq 10$ G) are correlated with the network structures.

More recently, this has been investigated using the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) instrument (Wilhelm et al. 1995) on board the Solar and Heliospheric Observatory (SOHO). SOHO was launched on December 2, 1995, and after a three-month cruise phase was placed into an orbit about the L1 Lagrangian point between the earth and the Sun, about $1.5 \times 10^6$ km from the earth. At this stage, observations from the various pointed instruments, including SUMER, were begun. Lemaire et al. (1997) have given intensity distributions for the transition region emission line at 933 Å due to S vi (emitting temperature $\sim 2 \times 10^5$ K) and the chromospheric Ly€ line ($\lambda 937$ Å). They find distributions consisting of a core and tail as before, with the core more sharply peaked in the S vi line, reflecting a more well-defined separation of cell and network in this line. Observations of the quiet Sun have also been made with the Coronal Diagnostic Spectrometer (CDS) on SOHO (Harrison et al. 1997). This instrument consists of two spectrometers (Normal Incidence and Grazing Incidence Spectrometers, NIS and GIS respectively) operating in the EUV spectral region, with the capability of forming images at particular spectral lines. The spectral ranges of the NIS (308–381 Å, 513–633 Å) include lines that are formed over a large temperature range (approximately $10^4$ to $10^6$ K), so that images of the Sun can be formed simultaneously which extend from the upper chromosphere and transition region to the corona. They are therefore ideally suited to examining the intensity distributions within quiet Sun regions.

In this paper, we will describe the observations that were planned for this work (section 2) and methods of analysis leading to distributions of intensity for a variety of spectral lines emitted over a wide temperature range (section 3).
Figure 1. The transition region supergranular network seen using CDS observations starting 06:29 on February 20, 1997 in He i, O III, O IV, Ne vi, Si VIII and Mg x. Note the almost unchanging visual nature of the network up until the coronal Mg x line.

In section 4 we compare the properties of the network and other bright structures and cells as a function of temperature of the emitting line, relating this to the likely physical structure of the emitting features.

2. Observations

The observations reported in this paper made use of the CDS sequence called INT_DIST, the details of which are given in Table 1. The INT_DIST sequence was designed primarily to provide NIS images of the quiet Sun network pattern in several lines formed at different temperatures and is described in Table 2.

The INT_DIST sequence commands the NIS to move the scan mirror so that the solar image is moved across the entrance slit in 60 different locations, with exposures of 50 s each, so that a $240 \times 240$ arcsec$^2$ area on the Sun is formed. The $4 \times 240$ arcsec$^2$ slit was selected to make these observations in order for images to have maximum spatial resolution with the shortest possible time interval. Thus, brightness fluctuations occurring in any feature in time scales of less than a few tens of minutes would tend to be averaged out in forming a raster.
The sequence was run a total of 20 times on February 20 and 26, 1997 resulting in two continuous sets of observations (data set #1 = s7038r00 → s7038r09.fits and data set #2 = s7103r00 → s7103r09.fits) spanning 8.3 hours each. Furthermore, INTDIST was run during a period of very quiet Sun at close to Sun centre in order to achieve an unobscured plan view of the network features.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>CDS/NIS</th>
</tr>
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<tbody>
<tr>
<td>Slit size</td>
<td>4 × 240 arcsec²</td>
</tr>
<tr>
<td>Exposure time</td>
<td>50 sec</td>
</tr>
<tr>
<td>Number of slit positions</td>
<td>60</td>
</tr>
<tr>
<td>Area imaged</td>
<td>240 × 240 arcsec²</td>
</tr>
<tr>
<td>Total duration</td>
<td>60 × 50 sec = 50 minutes</td>
</tr>
</tbody>
</table>

3. Results and Analysis

The relationship of the quiet-Sun network with emitting temperature $T$ is clearly evident the sample of six images taken in He I, O III, O V, Ne VI, Si VIII, and Mg IX and displayed in Figure 1. The network can be seen to extend almost unaltered from He I ($\log T = 4.2$) through O V ($\log T = 5.39$) up to the coronal Mg IX line ($\log T = 5.9$) where it is unrecognisable with only a small number of bright features traceable from the lower transition region.

The distribution of intensities within each of the ten images has also been calculated, two extreme examples of which (the chromospheric He I line and the coronal Mg X line) are given in Figure 2. It can be seen that the intensity distribution of the He I image shows a significant positive skew, with a high intensity tail extending to higher intensities, while that of the Mg X image shows a more unimodal distribution.

The statistical analysis of the distributions centred on the assumption that the histogram could, to a first approximation, be decomposed into the sum of two Gaussians representing both the network and the non-network contributions. This task was performed using the FIGARO suite of astronomical data analysis software and in particular the GAUSS routine. This routine was first used in an interactive mode where a low-intensity and a high-intensity Gaussian distribution were fitted to the total distribution using the standard minimisation of residuals technique. The parameters of the distributions such as height, width, and central peak position were then adjusted to achieve a least squares fit to the data.

The cross-over point of the two distributions, $I_c$, was then taken as a boundary point between the two populations represent both the network and internetwork regions. For the coronal Mg X line image, the bright structures are more
Figure 2. The distribution of intensities for He I and Mg X each fitted with the sum of two Gaussian curves representing cell and network populations.
Table 2. EUV emission lines observed using INT_D1ST.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Wavelength/Å</th>
<th>log(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He I</td>
<td>584.33</td>
<td>4.2</td>
</tr>
<tr>
<td>He II</td>
<td>303.78</td>
<td>4.7</td>
</tr>
<tr>
<td>O III</td>
<td>525.80</td>
<td>5.041</td>
</tr>
<tr>
<td>O IV</td>
<td>554.47</td>
<td>5.230</td>
</tr>
<tr>
<td>O V</td>
<td>629.73</td>
<td>5.397</td>
</tr>
<tr>
<td>Ne VI</td>
<td>562.80</td>
<td>5.623</td>
</tr>
<tr>
<td>Mg VIII</td>
<td>313.75</td>
<td>5.908</td>
</tr>
<tr>
<td>Si VIII</td>
<td>319.83</td>
<td>5.919</td>
</tr>
<tr>
<td>Mg IX</td>
<td>625.16</td>
<td>5.968</td>
</tr>
<tr>
<td>Mg X</td>
<td>368.07</td>
<td>6.064</td>
</tr>
</tbody>
</table>

in the nature of ill-defined emission regions associated with particularly bright network features. We then mapped onto each image contours corresponding to the intensity $I_c$ finding that the contours outlined the brighter regions of each image quite closely and thus confirming our assumption that the intensity $I_c$ separates network from cell features.

The relative area and intensity of the network structures has been derived for each image. These are given in the top two panels of Figure 3 as a function of the emitting temperature $T$ of each ion. As can be seen, the transition region network area and emission increases slowly with $T$ with a dramatic change in relative area and emission at coronal temperatures. We also investigated the relation with $T$ of the contrast of bright features to their surroundings. Contrast in this context was defined as

$$C = \frac{I_{\text{mean(cell)}} - I_{\text{mean(network)}}}{I_{\text{mean(cell)}} + I_{\text{mean(network)}}}$$  \hspace{1cm} (1)

The contrast was found to decrease with $T$ for most of the temperature range between $10^4$ K and a few $10^5$ K with the notable exception of the transition region line due to O IV ($T = 1.7 \times 10^5$ K), for which $C$ can be seen to be noticeably higher. Values of $C$ are plotted in the bottom left hand panel of Figure 3. Our result for the O IV line appears to confirm the visual impression from the images that the network displays a significantly higher contrast in this line compared with neighbouring lines.

We also investigated the complexity or space-filling capability of the network as a function of $T$ by evaluating the fractal dimension, using a box-counting method as first introduced by Mandelbrot (1982). The boundaries of the network and other bright structures were first isolated using standard image processing techniques followed by the use of a Sobel edge detection routine. The fractal dimension $D$ of the processed images was then calculated using a box-counting algorithm described in the work of Liebovitch & Toth (1989). The algorithm

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Figure 3. The behaviour of the normalised network area, emission, contrast, and fractal dimension as a function of temperature.

...operates by covering the image with square boxes of side $\epsilon$ and then counting the number of boxes $N(\epsilon)$ containing some structure. As the size $\epsilon$ of the boxes is varied, the number will obey the power law

$$N(\epsilon) \propto \epsilon^{-D}$$

which can be expressed as

$$\log_2(N(\epsilon)) = D \log_2(1/\epsilon) + C$$

where $C$ is a constant intercept fixed by a linear fit of $\log_2(N(\epsilon))$ to $\log_2(1/\epsilon)$ and $D$ is the slope. If the geometric object is a line, then we find $D = 1$ and if it fills the plane with uniform density, then $D = 2$. For the case of solar magnetic flux in the solar photosphere the fractal dimension has been found to...
have a value $D \approx 1.6$ (Tarbell et al. 1990) while Balke et al. (1993) have found $D = 1.54 \pm 0.05$. The values of the fractal dimension calculated by us using the code FD3\(^4\) occupied the range of values given by $1.55 \leq D \leq 1.68$ which is in good agreement with previous quoted results — see bottom right hand panel of Figure 3.

4. Conclusions and Summary.

As can be seen from Figure 3 the chromospheric and transition region network displays a well defined relationship with temperature showing a general increase in both area, emission, and fractal dimension and a decrease in image contrast. This behaviour can be related to the magnetic model of Gabriel (1976), in which vertical magnetic field is concentrated at the boundaries of photospheric supergranule cells and expands with height in the solar atmosphere to form a magnetic ‘canopy’. Isotherms in this model show that chromospheric and transition region structures should be highly concentrated at regions immediately above supergranule boundaries and also be concentrated within a narrow height range, though the concentration should decrease with increasing temperature and merge with overlying coronal structures at temperatures of $10^6$ K or more.

This is more or less in agreement with our observations, in which the relative area and brightness of bright structures increases with $T$. Thus, the relatively low-temperature ion emission would on this basis originate from locations relatively low in the atmosphere, near where the field lines are most concentrated, while those at higher temperatures would come from higher up in the atmosphere. In time, it should be possible to make a more quantitative relation of the observed emission with solar atmospheric models such as the early one of Vernazza, Avrett, & Loeser (1981). Such a comparison may give us some insight into the general decrease of contrast with $T$, with the anomalous behaviour of the O iv point, which we are currently investigating. Finally, we plan to carry our investigations of fractal dimension further, relating it to measured values for the solar photospheric magnetic field.

References


