MAGNETIC FLUX TUBES AND LOCAL HEATING IN THE TEMPERATURE MINIMUM REGION

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ABSTRACT

The photometry and statistical analysis of 160 nm solar filtergrams obtained by the experiment TRC, indicate that the solar surface radiates at the temperature minimum a substantial portion from features at the arcsec scale both in the network and inside the supergranular cells.

The active regions and network can be resolved in bright elements that we relate to the effect of a magnetic field of 120 G at the temperature minimum level in flux tubes. The supergranular cells combine an intermediate organized structure with a 8min period and features at the granular scale that we analyse as the trace of a local heating of 8.8 $10^3$/erg cm$^{-2}$s$^{-1}$ in the low chromosphere driven by periodic or convective motions.

Key words: Sun, ultraviolet - temperature minimum - magnetic flux tubes - chromospheric heating

1. INTRODUCTION

High resolution pictures of the temperature minimum and chromosphere have been obtained from the ground in the wing of strong chromospheric lines, such as CaII H and K (Liu and Sheeley, 1971). The first corresponding pictures in the ultraviolet continuum have been obtained by Brueckner (1979). Both revealed the presence of numerous bright grains or features whose origin remained unexplained.

During the second flight of the Transition Region Camera (TRC) (Bonnet et al, 1982), very high resolution pictures at 160 nm revealed similar structures, i.e. grains in the interior of the cells and bright elements delineating the network.

These pictures provide a view of the fine structure of the temperature minimum region, at the very location between the dense photospheric layers at the top of the convection zone and the chromosphere, where magnetic pressure begins to overcome the gaseous pressure.

In this paper, we investigate the origins of the ultraviolet bright features in the cells and the network elements.

2. DESCRIPTION OF THE 160 nm FILTERGRAMS

We have given a description of the TRC instrument, performances, flight events and TRC program in the Session II of this meeting. We
Figure 1
Comparison of the inhomogeneity of brightness at 160nm in the quiet Sun and in an active region.

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showed that the resolution at level 3σ is equivalent to 1 arcsec, and that we reached an accuracy of 30K on the temperature brightness fluctuations around 4200K (limited by the statistical modulation of 5% due to the photographic noise).

The 160 mm picture can be seen in paper I, where the chromospheric network is resolved in many bright elements; bright grains are also found in dark cell regions. We compare in Figure 1 one dimensional scan of brightness that evidences the various scales of inhomogeneity of the brightness temperature in quiet Sun or active regions.

In Figure 2, we see cell grains with excesses from 40 to 80K and 1.5Mm interdistance, and a wavy mesostructure with amplitude 60K and 8Mm period, inside a cell region.

We have applied in (Foing, 1983) and (Foing and Bonnet, 1983b) three methods for deriving some of the structural and statistical properties of the cell grains and the network elements. The optical Fourier techniques, the analysis of the spatial frequency spectrum density and the use of autocorrelation techniques allowed the derivation of the values of the various parameters characteristic of the structures which appear on the 160Mm continuum pictures.

In particular, the autocorrelation method confirms the existence of a 14Mm scale of organisation corresponding to the network in active regions and a wavy 8Mm mesostructure in the cell centers. The detailed study of the primary peak of autocorrelation provides a statistical estimate of the interdistance, size and density of fine structures in a quiet or an active region (cf Fig. 3).

We list in Table I, the parameters characteristic of these structures: the ratio of intensities $I_i/I_e$ and excess of temperature brightness relative to dark reference Sun.

<table>
<thead>
<tr>
<th>Table I: UV Emission Characteristics</th>
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<tbody>
<tr>
<td>Quiet Region</td>
</tr>
<tr>
<td>Cell grains</td>
</tr>
<tr>
<td>Mesostructure</td>
</tr>
<tr>
<td>Network Element</td>
</tr>
<tr>
<td>Plage Network</td>
</tr>
<tr>
<td>$I_i/I_e$</td>
</tr>
<tr>
<td>1.2 - 1.5</td>
</tr>
<tr>
<td>1.3</td>
</tr>
<tr>
<td>2 to 3.5</td>
</tr>
<tr>
<td>4 to 6</td>
</tr>
<tr>
<td>$\Delta T_b$</td>
</tr>
<tr>
<td>40 - 80K</td>
</tr>
<tr>
<td>60K</td>
</tr>
<tr>
<td>140 to 250K</td>
</tr>
<tr>
<td>280 to 360K</td>
</tr>
<tr>
<td>observed width</td>
</tr>
<tr>
<td>&lt;1Mm</td>
</tr>
<tr>
<td>3Mm</td>
</tr>
<tr>
<td>1 - 2Mm</td>
</tr>
<tr>
<td>4Mm</td>
</tr>
<tr>
<td>interdistance</td>
</tr>
<tr>
<td>~1.5Mm</td>
</tr>
<tr>
<td>8Mm</td>
</tr>
<tr>
<td>14Mm</td>
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</tbody>
</table>

Our observations show that the UV continuum emission occurs on a discrete spatial scale in the cells, the network and active regions. We therefore answer what the origin of this emission is. Is it magnetic or is it the manifestation of a local energy dissipation? We study in the following that if the network elements seen at 160Mm can be related to cross sections of magnetic tubes, the cell grains most probably have a different nature.

3. DO THE BRIGHT NETWORK ELEMENTS CORRESPOND TO HIGHLY CONCENTRATED MAGNETIC FIELDS?

We cannot provide a direct answer to this question, because high resolution, exactly simultaneous magnetograms were not obtained during
Figure 2: Scan of brightness at 160nm in a quiet cell region.
3. Autocorrelation of a one dimensional cut-through of a quiet Sun area
the flight of our rocket. Therefore, we assume that the network elements are the trace of magnetic flux tubes, evaluate the excess of brightness for various magnetic field intensity and check that it is compatible with photospheric observations of these tubes. The ratio of light $I_i$ coming out of a flux tube to the light coming from the vicinity $I_e$ is:

$$I_i/I_e = \frac{S(\tau_i=1)}{S(\tau_e=1)} \exp \left[ \frac{h \nu}{kT_a^2} \Delta T_B \right]$$

where $S$ is the source function, $\tau$ the optical depth, $T_a$ the average brightness temperature at $\lambda = c/\nu$, and $\Delta T_B$ the difference of brightness temperature inside and outside the flux tube.

$\Delta T_B$ can be expressed as $\Delta T_B = \frac{dT_B}{dh} \Delta h$ with the brightness temperature gradient $\frac{dT_B}{dh}$ and the height difference $\Delta h$ between two layers of equal optical depth in the flux tube and its vicinity.

We derived this expression (Foing and Bonnet, 1983a), assuming that the main contribution to $\Delta h$ results from the Wilson effect. We used the first approximation of a tube in hydrostatic equilibrium and isothermal relaxation with the surroundings (Foing and Bonnet, 1983a) which relies on the validity in the region between 0 and 500 km of the thin flux tube approximation, the spatial lateral thermalization by visible continuum and the dynamic relaxation condition $t_{rad} < t_{dyn} = H-V$ (Stenflo, 1976) where $H$ is the pressure scale height, $V$ the vertical velocity in tube. In these conditions, one can show that the ratio $\beta_e$ of gaseous pressure outside the tube $P_e$ to the magnetic pressure $B^2/2\mu_0$ remains constant with height and that the Wilson effect is

$$\Delta h = H \log \left( \frac{1}{\beta_e} \right)$$

We have computed several values of $I_i/I_e$ using these relations for various values of $B$, taking $P_e = 1.3 \times 10^3$ cgs, $H = 130$ km, and $I = 4470$ K as given by VAL81 near the temperature minimum and at 160 nm.

The results are given in Table II and can be compared with the measured ratios $I_i/I_e$ at 160 nm (See Table I). Our observations are consistent with fields of $120$ G in the network at the temperature minimum level and correspond to $\beta_e = 2$. This value is in turn consistent with photospheric fields of $1.5$ K at which is generally quoted for $B$ in flux tubes at the photospheric level.

We should notice that this simple treatment cannot be applied directly in the chromosphere above $600$ km where the thin tube approximation and the thermalization conditions do not hold anymore. We expect that different heating mechanisms occurring in regions of greater magnetic field and quiet regions, can lead to very different and decoupled temperature and radiation stratification above the temperature minimum.

We conclude that our observations agree with the existence of concentrated magnetic fields in the network, with a maximum average magnetic field of $120$ G at the temperature minimum level.
Table II

Wilson effect in magnetic tubes

<table>
<thead>
<tr>
<th>Magnetic field intensity</th>
<th>10G</th>
<th>50G</th>
<th>100G</th>
<th>150G</th>
<th>180G</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^2/8\pi Pe = 1/\rho_e$</td>
<td>3 $10^{-3}$</td>
<td>7.7 $10^{-2}$</td>
<td>0.3</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>$\Delta h$ (km)</td>
<td>-0.4</td>
<td>-10</td>
<td>-46</td>
<td>-150</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$I_i/I_e$</td>
<td>1.007</td>
<td>1.2</td>
<td>2.3</td>
<td>15.4</td>
<td></td>
</tr>
</tbody>
</table>

4. WHAT IS THE ORIGIN OF THE BRIGHT CELL FEATURES?

The preceding interpretation, based upon the Wilson effect for the network elements, cannot hold for the origin of the ultraviolet brightness excess inside the cells. In effect, with an excess of temperature of brightness of 80K, the intensity of the magnetic field would be 60G, which is much higher than the fields measured inside the cells, in the magnetograms presently available. Therefore, in the context of today's observations of concentrated magnetic fields in the cells, we propose an alternative explanation. As noticed by Bonnet et al. (1982), the UV bright grains look very similar to the cell points observed in the wings of the H and K lines (Liu et al., 1971). On space-time resolved CaH line profiles, Damé (1983) and Cram and Damé (1983) observe inside the cells periodic brightenings propagating from the wing and dissipating in the K2 peaks.

We suggest that the excess brightness of the cell grains and of the mesostructure at 80m results from a local dissipation of energy, whatever its origin might be. Our results allow us to estimate how much energy would be necessary to account for the excess brightness of the grains.

The increased continuum intensity $\Delta I$, due to local energy dissipation processes which raise the temperature by $\Delta T$ is given by $\Delta I = \int \Delta A \lambda e^{-\tau_\lambda} d\tau_\lambda$, where $\Delta h$ is the thickness of the slab of the solar atmosphere where the energy is dissipated. We will simply assume that $\Delta h$ corresponds to the height of formation 350-550 km investigated at 160nm (VAL 81).

The main contribution to the radiated energy, coming from the visible around 500nm, derived in (Foing and Bonnet, 1983a), is:

$$ E = \pi dL = 4\pi dL \Delta T \overline{\Delta T} $$

where $T$ refers to the average temperature and $\overline{\Delta T}$ is the optical width at 500nm of the investigated layer between 350 and 550 km.

According to VAL 81, $\overline{\Delta T} = 310^{-4}$ around $\tau = 10^{-4}$. For $\Delta T = 80$K and $T = 4470$K we find $E = \pi dL = 8.8 \times 10^{5}$ erg cm$^{-2}$s$^{-1}$.

This simple calculation gives only an estimate of the observed dissipated energy $E$. It is interesting to notice that this value of $E$ is equivalent to the amount of mechanical energy which is contained in acoustic waves in the temperature minimum (Mein, 1981).

Then the filtergrams would provide an essential information on the dissipated energy, while the spectra would give information on the dynamics through Doppler shift measurements and phase relationship.
5. CONCLUSION

The filtergrams of the Sun obtained by the Transition Region Camera at 160nm provided a high resolution investigation of the temperature minimum. The results show that in this region, the radiative output occurs on a discrete scale (from a fraction to a few arcsec) for both magnetic and non magnetic regions, with brightness temperature excess from 40K to 360K according to the structures. We suggest that the network elements may appear bright because of the Wilson effect in magnetic flux tubes. Assuming that the thin tubes are thermalized with their surroundings up to the temperature minimum, we derive a magnetic field intensity of 120G which corresponds to an intensity of 1.5kG at the photospheric level. We propose for the cell grains, an alternative explanation in terms of a local dissipation of energy contained in periodic motions. The amount of energy involved that we estimate from the measured intensity excess at 160nm, is very close to the amount of mechanical energy contained in acoustic waves at the temperature minimum level.

Longer time series of UV filtergrams, jointly with ground based filtergrams and spectra might offer a way of checking these interpretations, and studying the dynamics of magnetic structures and local energy dissipation.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


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6. LOW-RESOLUTION OBSERVATIONS BEARING ON
SMALL-SCALE DYNAMICAL PROCESSES
IN THE SUN