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Chromospheric fine structure studies

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Abstract. Mottles and spicules are the most prominent, short-lived, dynamic features residing at the quiet Sun chromospheric network and constitute what is known as chromospheric fine structure. We are reporting a comprehensive study of the dynamical characteristics and physical properties of such structures, from multi-wavelength observations, using line inversion techniques and a wavelet spectral analysis. We are furthermore examining their dynamical evolution and their periodic bi-directional velocity behaviour, their interrelationship and their association with the underlying magnetic field which seems to be their forming and driving mechanism. These studies are crucial to understanding the dynamics of the solar chromosphere, as well as the role such structures play in the mass balance and heating of the overlying solar atmosphere.

Keywords. Sun: chromosphere

1. Introduction

Mottles and spicules are rapidly changing relatively cool jet-like structures of the quiet Sun seen on the solar disc and the solar limb respectively (see review of Beckers 1972) that together with fibrils which reside in active regions (plages and sunspots) constitute the chromospheric fine structure. In this paper we shall concentrate on mottles and spicules which share common properties (Tsiropoula & Schmieder 1997) and thus both terms will be used indifferently hereafter.

Mottles reside at the boundaries of the chromospheric network and cluster into small groups called chains (along the common boundary line of two network cells) and larger groups called rosettes (around the meeting point of at least three network cells). It is well established that inside the network cells there is a continuous emergence of bipolar elements which are swept by the supergranular flow (Wang *et al.* 1996; Schrijver *et al.* 1997) at the network boundaries. There, magnetic fields of same polarities enhance the magnetic flux concentration while fields of opposite polarities cancel or reconnect. Thus, magnetic reconnection could be the forming and driving mechanism of mottles.

Magnetic reconnection is probably the most effective mechanism for both the release of energy into the corona and the transfer of cool plasma from the chromosphere to the corona and eventually the solar wind. Withbroe & Noyes (1977) have estimated that an energy flux of 3 10^5 ergs cm^{-2} s^{-1} is needed to maintain the quiet corona, while Ulmschneider (1971) estimated a typical mass flux of 3 10^{-11} gr cm^{-2} s^{-1} needed to maintain the solar wind. In this paper we discuss the properties, the dynamical behaviour and the energetics of mottles and spicules in an attempt to understand their formation and driving mechanism.

2. Observations and analysis procedure

The present study is based on several mottles observations taken at different dates during the last five years:

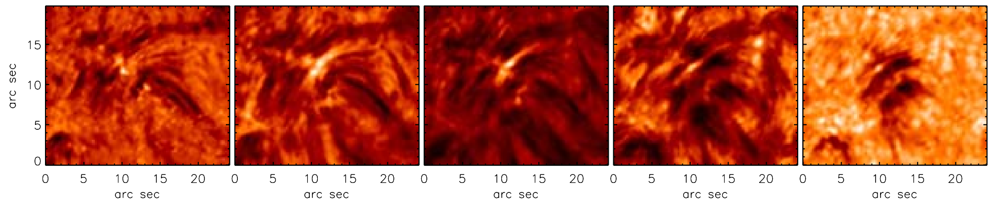

Figure 1. An Hα image of mottles in a rosette taken with the DOT at different wavelengths starting from the blue wing (first panel, Hα-0.7Å) towards the red wing (last panel, Hα+0.7Å) with a wavelength step of 0.35Å. The middle panel shows the Hα line center.

(*a*) a time series ($\sim$40.5 s cadence) of two-dimensional THEMIS/MSDP Hα images at five wavelengths within the Hα profile

(*b*) Hα and Hβ profiles along a slit taken with an echelle spectrograph mounted on the VTT at Sacramento Peak Observatory and

(*c*) a time series (25 s cadence) of two-dimensional Hα images taken at five wavelengths within the Hα profile with the DOT telescope at La Palma (see figure 1 for an example)

The most widely used method for the deduction of different physical parameters of optically thin structures, like mottles, is the cloud model technique introduced by Beckers (1964). Using an iterative least-square procedure for non-linear functions (see Tziotziou *et al.* 2003) and assuming a constant source function we can solve the radiative transfer equation for an observed profile and deduce the values of the source function S, the Doppler width $\Delta\lambda_D$, the optical thickness τ_0 and the velocity v that best describe it. Velocities can also be easily estimated from an observed profile with the analysis procedure described by Tsiropoula (2000) which is a quick variant of the cloud model. Several other parameters, like the temperature T, the number density of the second hydrogen level N_2, the electron density N_e, the total particle density of hydrogen (i.e., neutral plus ionized) N_H, the ionization degree χ, the gas pressure p, the total column mass M and the mass density ρ, can be further estimated by assuming a value for the microturbulent velocity ξ_t and using the relations described in Tsiropoula & Schmieder (1997).

3. Results

3.1. *Physical properties of mottles*

The most important results derived with the cloud model analysis of our Hα and Hβ observations are: a) the almost Gaussian distribution of velocities that range from -15 to $+15$ km/s (Tziotziou *et al.* 2003; Tsiropoula *et al.* 2005) (b) the average Doppler width that defines a temperature for mottles of $\sim$10000–12000 K (Tziotziou *et al.* 2003) and c) the difference between the theoretical and observational linear relations between the respective Hα and Hβ calculated Doppler widths and optical thicknesses which implies that emission in these lines does not come from the same parts of the structures (Tsiropoula *et al.* 2005).

3.2. *Periodicities in mottles*

A spectral analysis with wavelets of intensity and velocity variations of areas containing mottles, locations within mottles and along the main axis of mottles (Tziotziou *et al.* 2004) shows that the dominant oscillation period in mottles is $\sim$5 min. This is the photospheric p-mode oscillation period and thus this result could be of great importance

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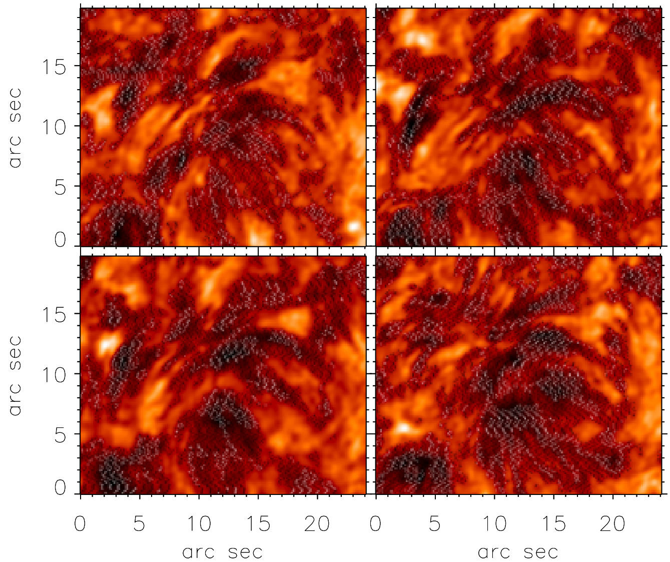

Figure 2. DOT Hα line center images of a rosette of mottles with overplotted downward velocity positions (white points) and upward velocity positions (black points) showing a bi-directional behaviour of velocity along mottles.

for understanding the driving mechanism of mottles. We shall further discuss this is the following subsection.

3.3. *What drives mottles?*

Recently, simulations conducted by De Pontieu *et al.* (2004) suggested that p-mode energy leakage powers shocks and drives upward flows in inclined structures, which manifest as mottles and spicules. Such a mechanism could explain the observed 5-min periodicity in mottles, however, the obtained final velocities from their simulations are too low and the assumed coronal magnetic boundary values are too high.

Tziotziou *et al.* (2003) have derived from Hα observations with a cloud model the line-of-sight velocity along mottles and its temporal evolution. They have found a) that the predominant motion is downward at their footpoints and alternatively upward and downward at their tops, recurring with a period of $\sim$5 min and b) a temperature enhancement at zero velocity positions. The same bi-directional velocity behaviour along mottles is seen in the recent Hα DOT observations (see figure 2).

These results are consistent with the phenomenological model proposed by Tziotziou *et al.* (2003) according to which mottles are formed and driven by magnetic reconnection of coalescing opposite polarity fields at the network boundaries. Reconnection explains the observed velocity bi-directional behaviour and provides high velocities. Probably both proposed so far mechanisms, p-mode driving and reconnection, come into play with the first one probably acting at lower atmospheric heights and the latter higher up.

3.4. *Contribution of mottles to the coronal energy and mass balance*

Based on the Hα THEMIS/MSDP observations Tsiropoula & Tziotziou (2004) have shown that by assuming a birthrate for mottles derived from the observations the total

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energy flux produced by mottles that flows upwards is 6 10^4 ergs cm^{-2} s^{-1} which is only 20% of the total energy needed for the solar corona. On the other hand, the upward mass flux is estimated to be 7.1 10^{-9} gr cm^{-2} s^{-1} and only 1% of it is necessary to maintain the mass budget of the solar corona. Assuming that the rest 99% of the mass is falling back then one can estimate a fall velocity at the transition region of 11 km/sec which is the derived downflow velocity from EUV observations (Hansteen *et al.* 2000).

If the calculated energy produced by mottles is attributed to magnetic reconnection then the average magnetic field is estimated to be of the order of 11 G (Tsiropoula & Tziotziou 2004). Trujillo Bueno *et al.* (2005) have deduced from spicule observations in the He I 10830 Å multiplet with the Hanle and Zeeman effect a magnetic field strength of 10 G which is very close to our value.

4. Conclusions

The comprehension of the properties and dynamics of the chromospheric fine structure (mottles and spicules) is extremely important for understanding and modeling the dynamics of the solar chromosphere and the energy and mass outflow to the upper solar atmosphere. Magnetic reconnection seems to be the responsible mechanism for forming and sustaining the chromospheric fine structure. It provides a plausible explanation for the observed amplitudes and bi-directional behaviour of velocity in mottles. However a driver below (i.e. p-modes) can not be excluded since it would naturally explain the observed 5-min periodicity in mottles. The mass outflow from the chromospheric fine structure is almost two orders of magnitude larger than that needed to maintain the quiet corona, while the energy flux available for heating the solar corona is only ∼20% of the required energy. The results of our studies show that high resolution magnetograms are necessary for understanding the nature and driving mechanisms of the chromospheric fine structure.

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