1994A&A...290..285T

Astron. Astrophys. 290, 285–294 (1994)

ASTRONOMY AND ASTROPHYSICS

Time evolution of fine structures in the solar chromosphere

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Received 22 December 1993 / Accepted 12 April 1994

Abstract. We have studied the temporal evolution of two quiet chromospheric regions, one with a typical rosette and another with chains of mottles at the junction of three supergranules. The observations were obtained during 15 minutes with the Multichannel Subtractive Double Pass spectrograph (MSDP) operating in Hα at the Pic du Midi Observatory. We derived intensity maps and Doppler shift velocities at different wavelengths along the Hα profile over a two dimensional field of view. The observed contrast profiles were matched with theoretical contrast profiles using Beckers' cloud model for a more accurate determination of the line of sight velocity. A statistical analysis with cross correlation functions showed that the fine structures were stable in intensity over the observation period (15 min), but the line of sight velocity showed important changes within a few minutes. A detailed analysis of the velocities along the axes of dark mottles showed that the predominant pattern of bulk motion is that of downflow at their footpoints and alternating phases of upflow and downflow at their tops. This motion is consistent with Pikel'ner's model for spicules, which attributes this pattern to the reconnection of opposite magnetic filed lines. This picture is also consistent with the velocity reversals with time observed in spicules and may be associated to the systematic downflows observed in the transition region. Doppler shift velocities in dark mottles are too low compared to those derived with the cloud model; the latter are comparable to those reported for spicules, strengthening the view that these structures are identical.

Key words: lines: profile – sun: chromosphere

1. Introduction

High quality spectroheliograms of the solar chromosphere indicate that it consists of many individual structural components, the variety in morphology of which apparently originates in the difference of the strength and the inclination of the magnetic field (Foukal 1971). Among the chromospheric structures, mottles are probably the most important. Both bright and dark mottles occur at the boundaries of the supergranule cells, where they form groups called coarse mottles, chains or rosettes. Rosettes are the largest mottle arrangements, having a more or less circular form with a central core, which is surrounded by a number of bright and dark mottles aligned radially outwards.

There has been a long discussion on whether mottles (dark, bright or both) are the disk counterpart of the limb spicules (Beckers 1968, 1972; Bray & Loughhead 1974; Athay 1976). Although these jet-like structures have been investigated both observationally and theoretically by many authors the answers to many important questions concerning their temperature and density distributions and the velocity field remain uncertain. Recently, Grossmann-Doerth & Schmidt (1992), using high-resolution Hα spectra of spicules and mottles, concluded that the velocity distributions are not identical for these structures and thus mottles cannot be identified with spicules. However, their velocity distribution for mottles, derived with Beckers' cloud model, included both bright and dark mottles and is narrower than the distribution derived by Tsiropoula et al. (1993, Paper I) for dark mottles alone. These latter authors, exploiting the advantage of the MSDP spectrograph in providing high spatial resolution two dimensional Hα images, matched the observed contrast profiles of dark mottles with theoretical ones using the cloud model and found a consistency between cloud parameters and the corresponding values of spicules.

A basic quantity for the dynamics of mottles is their velocity field. The motion has been studied mainly for structures at the limb. Apparent motions of spicules in the plane perpendicular to the line-of-sight have been derived from measurements of their height as a function of time (Rush & Roberts 1954; Lippincott 1957). A rise velocity of $\sim$30 km s^{-1} has been reported. Lippincott pointed out that for 60% of the spicules the ascending phase is followed by a descending one; she also reported that some spicules appear to rise again from the same source, and suggested that a spicule source may have several times the lifetime of a single spicule. Mouradian (1967) found spicules to diffuse at a rapid rate (10-20 km s^{-1}) while fading. It must be emphasized that these are apparent velocities which may be

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due to temporal variations of the Hα excitation as well as real plasma motion.

Many determinations of the Doppler shifts derived from spectroscopic observations have been reported (see Table XII in the review of Beckers 1968; Alissandrakis 1973; Table 2.5 of Bray & Loughhead 1974 and references therein); they yield the velocity component along the line-of-sight and hence in the horizontal direction. The reported values are $\sim$10 km s^{-1} for the rms and $\sim$6 km s^{-1} for the mean absolute Doppler velocity. Recently Heristchi & Mouradian (1992) derived the distribution of the true velocity using Doppler shifts of spicules observed at the limb and taking into account the distribution of spicule inclinations; they found that the true velocity distribution peaks around 40 km s^{-1}.

Motions along the spectrograph slit have also been reported (Pasachoff et al. 1968; Nikolsky & Platova 1971), with speeds ranging from 5 to 60 km s^{-1}. Nikolsky and Platova also reported that spicules oscillate along the limb with a characteristic period of about 1 min.

There is contradictory evidence on the height and time variation of Doppler shifts. Curves illustrating the time variation of the Doppler velocity of spicules during their lifetime have been given by Mouradian (1962, 1965), Nikolsky & Sazanov (1966), Zirker (1967), Passachoff et al. (1968) and Nikolsky (1970). Mouradian suggested that the velocity changes systematically with time, but rarely, if ever changes sign, the motion being directed upwards. Pasachoff et al. concluded that a certain number of spicules do undergo a reversal in their Doppler velocity with a period of minutes. Nikolsky & Sazanov found that the line-of-sight velocities of individual spicules vary irregularly with a mean period of about 1 min. Similar changes have been reported by Zirker (1967). Nikolsky (1970) examining a sequence of Hα photographs and limb spectrograms of spicules suggested a quasi-periodic generation of spicules. An oscillatory behaviour with a period of 100-400 sec has also been reported by Platov & Shilova (1971) and Kulidzanishvili & Nikolsky (1978).

Much less work exists for features seen on the disk and considered as the spicule counterpart. Examining disk features, Beckers (1963) found that dark mottles, after disappearing in the Hα -0.5 Å image, often became visible in the Hα +0.5 Å image; this is consistent with a picture of rising and falling features (cf. Suematsu et al. 1994). Bhavilai (1965) and Title (1967) on the other hand found upflows and downflows in individual mottles but did not confirm a velocity reversal.

Spectra in a two dimensional field of view are necessary to derive properties of chromospheric structures in order to understand the physical mechanisms responsible for the structuring and more important for the transport of mass and energy in the outer solar layers. In Paper I (Tsiropoula et al. 1993) we focused our interest to the physical parameters of dark mottles arranged in a well defined rosette. We detected a small region with upflows at the centre of the rosette, strong downflows at the roots of the mottles, while their upper part was ascending with velocities sometimes greater than 10 km s^{-1}. The aim of this work is the investigation of the spatio-temporal evolution of the mottles by using a 15 min long time series of MSDP data with the objective of determining the typical characteristics of their motion.

2. Observations and data reduction

The present Hα observations were performed with the MSDP (Mein 1977), operating on the solar spectrograph installed at the focus of the 50 cm refractor of the Pic du Midi Observatory on June 17, 1986 at the disk centre (N5, W5). This system, having 11 channels, allows us to observe the same point on the Sun (with coordinates x, y) simultaneously, but at a different wavelength in each channel. Thus at every point of the field of view the line profile can be reconstructed from the 11 values. The wavelength varies within each channel along the y axis by 0.008Å/″, while the shift between two successive channels is 0.256 Å. The instrument yields a 233″×29″ field of view. A map covering a large region ($\sim$4′×2.51′) is built up every minute from several elementary images.

The duration of the observations was 15 min. Although the spatial resolution was sometimes better than 0.5″, the spectral resolution was relatively low, giving uncertainties of the order of 10% in intensity and about 0.5 km s^{-1} in velocity. The observations were digitized with the fast microdensitometer of the Observatory of Paris (MAMA) using a slit size of 30 μ and a step of 30 μ (0.17″) in both directions. The film densities were transformed into relative intensities using calibration curves deduced from the profiles (David 1961). The line profiles were determined from the measured values of the intensity at the 11 points (one point by channel) and a 3rd degree spline interpolation was used in order to reconstruct the entire line profile for each pixel of the field of view. Thus the processed MSDP spectra can be used for the computation of two dimensional intensity and velocity maps at several depths in the line.

Maps of intensity and Doppler velocities were computed from the profiles by a method simulating the "lambdameter" technique (Mein 1977). We also analysed profiles corresponding to dark mottles using the cloud model and the methodology developed in previous publications (Alissandrakis et al. 1990; Tsiropoula et al. 1992, 1993).

In Fig. 1 the entire field of view (3.48′ × 2′) is shown at Hα $\pm$0.512 Å. The limitations in spectral resolution lead to uncertainties which appear in the form of a horizontal pattern with a periodicity equivalent to the wavelength separation of two adjacent MSDP channels (0.256 Å), corresponding to 6.5″. In the middle of the field of view lies the corridor of a north-south oriented filament, studied in a previous paper (Schmieder et al. 1991); this filament was located between two plage regions (with field strength of $\sim$100 G), remnants of an old active region. The supergranules are more difficult to identify in the corridor, where they have a more elongated shape in the north-south direction of the magnetic field neutral line.

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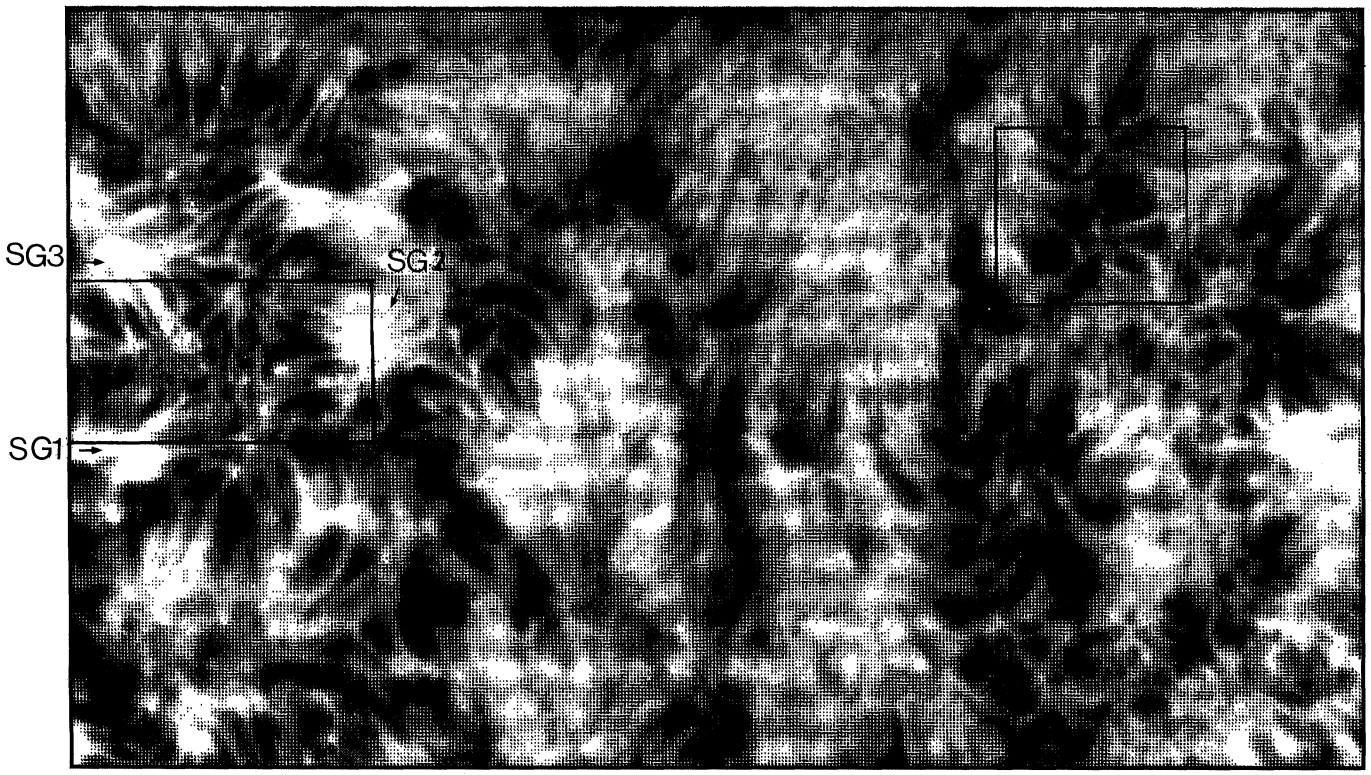

Fig. 1. The chromosphere at Hα $\pm$ 0.512 Å observed at Pic du Midi with the MSDP on June 17, 1986 at 06:43:24 UT. The boxes enclose the two fields of view selected for our analysis. North is up

3. Results

3.1. Global evolution

In Figs. 2 and 3 we present frames from the time sequence of the two regions selected for our analysis: one is centered on a rosette (29″ × 28″, Fig. 2), the other contains the boundaries of three supergranules (48″ × 28″, Fig. 3). The intensity maps are given at ±0.512 Å, where the dark mottle contrast is maximum and at ±0.768Å, where filigree are visible on the best frames; the velocity maps are at ± 0.512 Å. Contours of intensity at ±0.512 Å are given in Fig. 4. A single frame of the rosette region was analysed in Paper I.

The rosette has a round shape, of about 10000 km in radius; it formed and deformed during our observations. At the beginning (06:39:21 UT), the north part of the rosette consisted of east-west oriented dark mottles; progressively they assumed a more or less radial orientation, with their roots forming a circular pattern and their opposite ends diverging in all directions (Fig. 2). The rosette is well formed from 06:43:24 until 06:49:27 UT. On the Hα wing pictures the radially oriented dark mottles do not reach the centre of the rosette, thus a 4-5″ region appears free of dark mottles. After 06:49:27 UT the mottles turned again and resumed their previous direction, perpendicular to the boundary between two supergranules. This is due to the disappearance of two dark elongated fine mottles. Practically all mottles can be identified from frame to frame in the 13 min series of filtergrams. We can thus conclude that the average lifetime must be greater than 13 min, which is consistent with a recent measurement by Bratsolis et al. (1993).

On a large scale the Doppler velocity is mainly negative (descending) in the central part (circle of a 5000 km radius) of the rosette with some upward velocity regions from time to time. The central region is surrounded by upflows. This global view of the flow, already evident in a single frame (Paper I), is nearly constant with time but it is difficult to follow the flow along individual features, because the limits of Doppler structures do not coincide with the limits of bright and dark mottles.

The second region (Fig. 3) is at the junction of three supergranules, marked Sg1, Sg2 and Sg3 in Fig. 1. The supergranule Sg2 is elongated north-south because it is near the filament corridor. Thus the junction of the supergranules does not form a rosette but a more complicated pattern.

Between Sg1 and Sg3 we can follow mottles organized in a bush forming a small rosette (*A* in Fig. 4b), well visible between 06:41:14 and 06:43:15 UT (Fig. 3). After this time some mottles on the left side of the rosette rotated and became perpendicular to the boundary between Sg1 and Sg3 (at 06:44:16 UT). This is probably due to the appearance and disappearance of one or more fine mottles. Then a corridor or a chain of mottles formed (at 06:45:17 UT) and, subsequently, two parallel corridors (see frame at 06:52:21 UT) with a double alignment of bright points in the image at Hα±0.768 Å. The mottles which extended towards the supergranule Sg3 were well separated from each other and the velocity cells were nearly cospatial with the structures.

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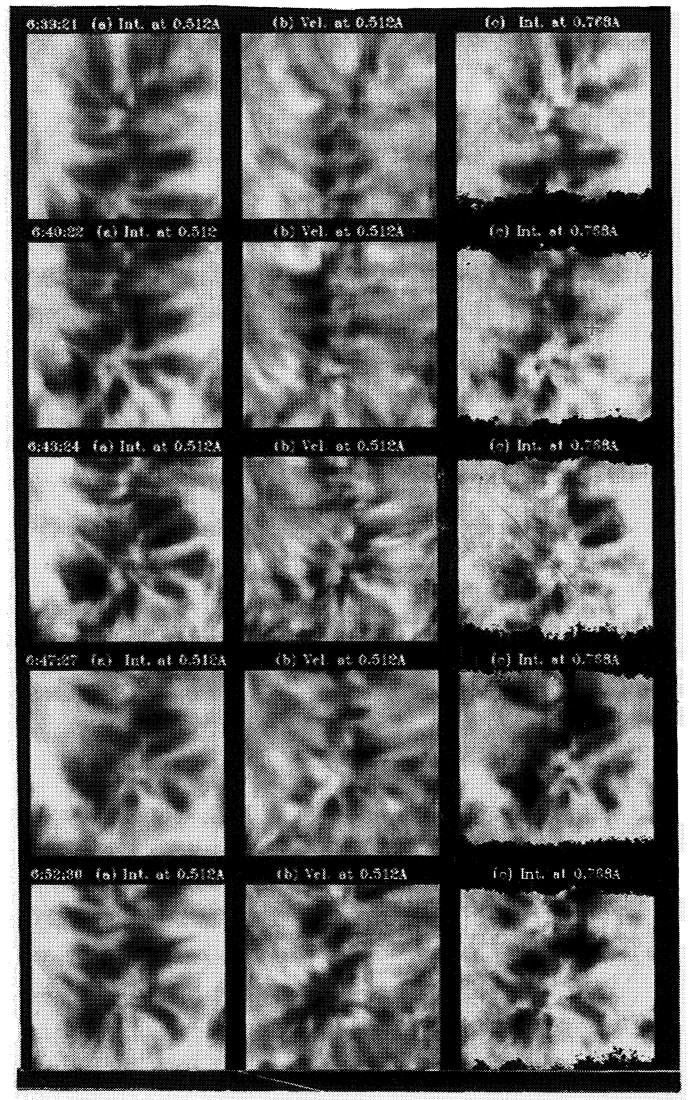

Fig. 2. Time evolution of the intensity (at H$\alpha\pm$0.512 Å and at H$\alpha\pm$0.768Å) and the Doppler velocity (at H$\alpha\pm$0.512 Å) for the rosette region. Note that the field of view shifted by 7″ south between 6:39:21 and 6:40:22 UT. Dark regions in the velocity maps correspond to downflows

Their footpoints were red-shifted most of the time, while their tops appeared first blue then red-shifted.

Between supergranules Sg3 and Sg2 we observe half a rosette (*B* in Fig. 4b), well visible at H$\alpha\pm$0.768 Å as absorbing material (dark on the pictures). The center of the rosette never had a complete downward component but an upflow was visible at 06:40 surrounded by downflows. On the right part of this rosette we can easily distinguish some mottles going to Sg2.

Between supergranules Sg1 and Sg2 we have more or less a chain of dark mottles, perpendicular to the boundary of the supergranules and elongated in the East-West direction. This is clear on the right part of the chain. At the footpoints of this chain we observe red and blue shifts, distributed in two lines oriented North-South like the chain.

In this region we observe high flows at the boundaries of the supergranules: upflows and downflows were of the same magnitude, while the downflow cells were more extended. The evolution of the intensity structures was again very slow and we could follow each one of them; some changed in direction or split into two different structures or merged with others into a unique structure. We estimated that 10% out of 30 identifiable structures in this field evolved in 15 min.

3.2. Statistical analysis

For a quantitative estimate of the temporal changes we computed the value of cross correlation function (CC) over the two dimensional field of view, after careful positioning of the frames. Each frame of the time series was considered as the reference frame and the CC value was computed as a function of time, both for the intensity and for the velocity; the individual cross correlation curves show some differences, probably due to seeing variations and they were averaged to give a mean cross correlation function.

Figure 5a shows the intensity CC curve for the rosette region, at $\pm$0.512 Å. The first frame of the series was not used because of its shift with respect to the other frames. The crosses show the values of individual curves while the solid line shows the average cross correlation function. The intensity CC at $\pm$0.512 Å decreases from 1 to 0.65 in 12 min, reflecting the changes of the features. As the dark mottles are preponderant at this wavelength, the CC reflects primarily their behaviour. The decay is more rapid at $\pm$0.768 Å, where it drops to 0.55 in 12 min; here the correlation is an indicator of time changes of both the dark mottles and of the filigree. It drops to the same value at $\pm$ 0.256 Å, where bright mottles are also visible. The form of the intensity CC function at $\pm$0.512 Å for the supergranule boundary region is very similar to that of the rosette region, the CC dropping to 0.6 in 12 min.

The decay of the CC function is a measure of the lifetime of features; our results verify the qualitative assessment of the previous section that the average lifetime of the dark mottles is at least 12 min. This is consistent with the visibility curve analyses of Beckers (1963) and Bhatnagar & Tanaka (1972) who concluded that the visibility of mottles does not drop significantly over a time interval longer than 10 min. The stability of the intensities is clearly shown in the scatter plot diagram of intensity between two frames 10 min apart, shown in Fig. 6a.

Figure 5b shows the CC function of the velocity as a function of time at $\pm$0.512 Å for the rosette region. The cross correlation curves are similar for the two regions and the three wavelengths studied ($\pm$0.256, $\pm$0.512 and $\pm$0.768 Å). They show much more rapid changes than the intensity curves: the CC drops from 1 to about 0.1-0.2 in less than 4 min, with an e-folding time of about 2.5 min. The scatter plot of velocity values between two frames 10 min apart (Fig. 6b) is very different from that of the corresponding intensity plot (Fig. 6a) and confirms the lack of correlation. The average cross correlation function shows no clear secondary maxima, which would be an indication of oscillations.

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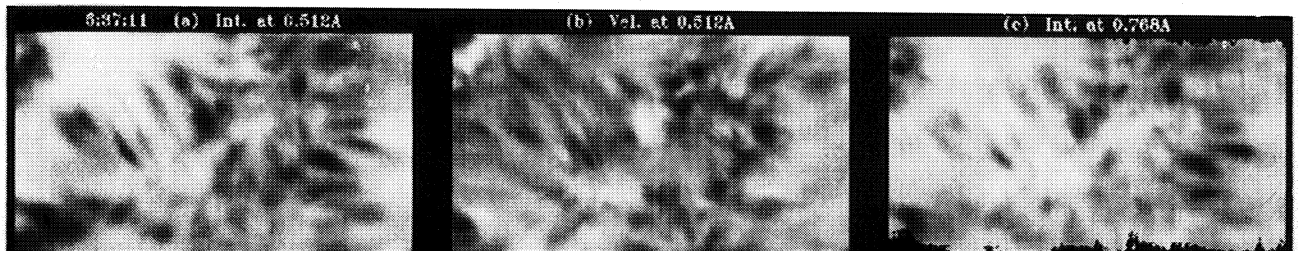
8:37:11 (a) Int. at 0.512A
(b) Vel. at 0.512A
(c) Int. at 0.768A