ISSN 0351–2657
HOBUD7 28(1) 1 (2004)

MOTIONS OF PHOTOSPHERIC FEATURES IN A SUNSPOT MOAT

M. SOBOTKA[1], J.A. BONET[2], I. MÁRQUEZ[2],
R. MULLER[3], Th. ROUDIER[3]

[1]*Astronomical Institute, Academy of Sciences of the Czech Republic, CZ–25165 Ondřejov, Czech Republic*
[2]*Instituto de Astrofísica de Canarias, E–38205 La Laguna, Tenerife, Spain*
[3]*Observatoire Midi-Pyrénées, 57 Avenue d'Azereix, B.P. 826, F–65008 Tarbes, France*

UDC 523.942.3-325:523.982
Conference paper
(Received December 25, 2003; accepted January 15, 2004)

Abstract. Two time series, taken simultaneously in $G-$band and in blue continuum, and corrected for instrumental and atmospheric degradation using the method of phase diversity, are employed to study the motions of granules and $G-$band bright points (GBPs) in the moat of an old regular sunspot. Centers of diverging horizontal motions, identified with families of granules formed by recurrently splitting granules, move away from the sunspot. Most of GBPs show radially oriented motions in the same direction, with velocities comparable to those of adjacent granules. However, 7 % of GBPs move faster (> 1.4 km s^{-1}) than the neighbouring granules.

1. Introduction

The moat is an annular cell of systematic horizontal outflows, 0.5 to 1 km s^{-1}, which surrounds sunspots in late phases of evolution (Sheeley, 1972; Muller and Ména, 1987). Soon after the discovery of this flow, which is very similar to that found in supergranules, Sheeley (1972) suggested that a decaying sunspot occupies the center of a supergranular cell, and that small-scale fragments of magnetic flux are carried away from sunspots by the supergranular flows. This was observed, among others, by Harvey and Harvey (1973) in a series of magnetograms, and by Muller and Ména (1987) in a series of high-resolution images taken in the $G-$band (around 4305 Å), showing many local brightenings ($G-$band bright points, hereafter GBPs) moving away from the sunspot.

Like in supergranules in the quiet Sun, Muller and Ména (1987) and Shine et al. (1987) found that the granules in the moat are advected towards its outer boundary. In addition to this systematic drift, granules exhibit local horizontal motions mostly related to splitting and expansion. In the quiet photosphere far from sunspots, repeatedly splitting granules produce long-lived structures called "families of granules" (Kawaguchi, 1980). Using a feature tracking technique, Roudier et al. (2003) found that a significant fraction of granules are organized in the form of spatio-temporal "trees of fragmenting granules", equivalent to families of repeatedly splitting granules, originating from a single granule at the beginning. Families living longer than 1.5 hour cover 62 % of the total area. Such long-lived families produce coherent diverging flows that can be identified to mesogranules. In this work, the relation between families and the centers of diverging flows in the sunspot moat is studied.

Muller and Ména (1987) measured in the sunspot moat, that the magnetic elements, identified as GBPs, move faster in average than the granules. If true, the difference of velocities would show that the magnetic field does not move passively, being carried away by the convective flow but, on the contrary, that the magnetic field and convective flows interact in a complex way. In this work, the velocities of GBPs and adjacent granules are re-compared, using feature tracking techniques.

2. Observations and Data Processing

The leading sunspot of a decaying bipolar group NOAA 8620 was observed on 7 July 1999 at the Swedish Vacuum Solar Telescope, La Palma (Scharmer et al., 1985), close to the center of the solar disk at $\mu = 0.93$. Two strictly simultaneous time series of high-resolution images were taken in the wavelength bands 4507 ± 4.5 Å (blue) and 4308 ± 5.5 Å ($G-$band). After the standard pre-reduction steps (dark- and flat-field corrections and de-rotation), both time series were reconstructed by the phase-diversity algorithm (Gonsalves, 1982; Löfdahl and Scharmer, 1994), thus removing the wavefront distortions introduced by the telescope and by the turbulent terrestrial atmosphere.

The restored images were aligned, destretched, and filtered for p-modes in the $k - \omega$ space. Two movies were produced, for the blue continuum and the $G-$band, of 288 frames each, spanning over 2 hours ($\Delta t = 25$ s) and covering a field of $46'' \times 75''$ (560×910 pixels), with the sunspot located in the center. Thanks to the phase-diversity reconstruction, the image quality of both movies is excellent and extremely stable during the whole period.

To isolate GBPs, the blue images were aligned exactly with the corresponding $G-$band frames and their granular contrast was reduced to match the contrast observed in the $G-$band. Then the blue frames were subtracted from the $G-$band ones, thus producing intensity difference images with the GBPs substantially enhanced.

3. Motions of Granules in the Surroundings of the Sunspot

The blue-continuum images were used to study horizontal motions of granules in the full field of view by means of the standard local correlation tracking method (LCT, November and Simon, 1988). The technique and results were described in detail by Sobotka et al. (2002); here we only summarize the main results.

A sequence of 24 LCT velocity maps was obtained during the 2-hour period of the time series. Numerous centers of diverging horizontal motions, "rosettas", with average size of $3''$, caused mostly by expansion and splitting of granules, are observed in all maps in the whole field outside the sunspot. The motion of rosettas was measured using this sequence of maps. In an $8''$wide region around the spot, the moat, rosettas show an ordered motion away from the sunspot's border with the mean velocity of 0.51 ± 0.13 km s^{-1}. In the rest of the field, the motion is slower and less regular. For the following analysis, the moat region was defined empirically as an area between the sunspot border and the iso-velocity line of 0.32 km s^{-1}. This line was found to be the best separation between the regular motions directed from the spot and the other motions in the field.

Sobotka et al. (2002) concluded that two types of motions are observed in the sunspot moat: (i) Local divergent motions of granules which do not differ from those in the regions far from the spot and reflect mostly the expansion and splitting of granules. (ii) A large-scale regular outflow, which carries granules and rosettas (divergence centers) away from the sunspot.

4. Families of Granules in the Surroundings of the Sunspot

An alternative description of motions and evolution of granules can be made in terms of families of granules. To do this, each blue-continuum frame is segmented, i.e., non-zero values are assigned to pixels belonging to granules and the rest is set to zero. Then, the evolution of granules is tracked in time, taking into account appearances, disappearances, splitting and merging. A granule during its lifetime and all granules originating from it by splitting are labelled by a unique number. If some of these granules split again, more and more granules are labeled by the same number and form a family. This technique is described in detail by Roudier et al. (2003).

In total, 269 families living longer than 1 hour were detected in the field of view: 131 in the moat (defined in Sect. 3) and 138 in the rest of the field. The presence of long-lived families in the moat indicates that the creation of new granules by splitting is usual also near the sunspot. Each family, at a given time, is characterized by its area and by the position of the centroid (center of weight) of this area. The area of the family is the total area covered, in the segmented image, by the granules belonging to the family.

Roudier et al. (2003) suggested that the long-lived families are fundamental in structuring the horizontal velocity field in the quiet granulation. The collective action of splitting granules generates diverging flows that, after averaging in time, are detected by LCT in the form of rosettas. The coherence of families and rosettas around the sunspot was checked by comparing the LCT velocity maps, computed

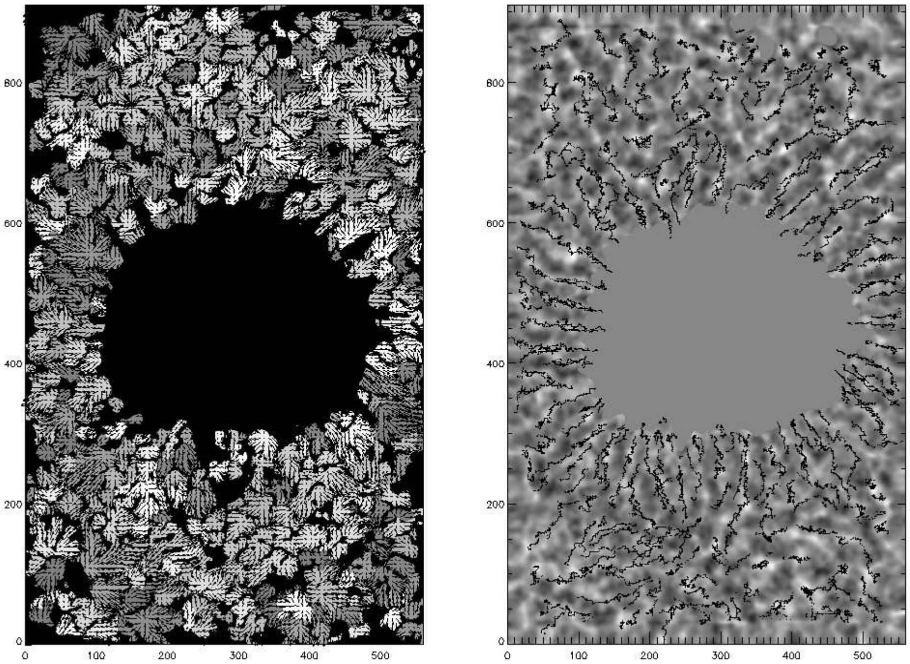

Figure 1: *a (left)* – Areas of families (distinguished by different shades of gray) superposed to the map of horizontal velocities (LCT, 20 minutes averaging). *b (right)* – Trajectories of centroids of families superposed to the map of divergence fluctuations (white = positive) averaged over 2 hours.

with the time-averaging interval of 20 minutes, to spatial distribution of families represented by their areas integrated over the same period. An example is shown in Fig. 1a. We can see from the figure that the cumulative areas of families and the rosettas are co-spatial in the whole field of view, including the moat. This suggests that, like in quiet regions, the local diverging motions in the vicinity of sunspots are connected with the long-lived families.

In the moat, local divergent motions of granules are combined with the radial large-scale outflow. The centroids of families move consistently with this outflow. In Fig. 1b are plotted trajectories of the centroids of all long-lived families during the whole 2-hour period, superposed to a map of LCT divergence fluctuations, computed with the 2-hour time-averaging interval. The trajectories are ordered radially in the moat and they are located mostly in the regions of positive divergence. Outside the moat, the trajectories are oriented more randomly, with the exception of the bottom left part of the field, where they are ordered by the flows near a supergranular boundary. The average velocities of the centroids (0.54 ± 0.21 km s^{-1}) are comparable with the LCT large-scale velocities derived from the motions of divergence fluctuations (Sect. 3).

5. $G-$band Bright Points in the Moat

A feature tracking technique (Sobotka et al., 1997) was applied to the series of segmented images containing GBPs to measure lifetimes, spatial distribution, and velocities. In total, 1508 GBPs living longer than 2.5 minutes, with time-averaged diameter larger than $0\farcs28$, and with time-averaged velocity below 4 km s^{-1}, were detected in the field of view. The criteria above were set to eliminate noise and to improve the reliability of the results. About a half of GBPs (776) was located in the moat, defined in Sect. 3. Outside the moat, GBPs were concentrated mostly around several pores above the sunspot and along the supergranular boundary in the lower part of the field.

The lifetimes of GBPs range from 2.5 to 120 minutes (length of the series) and the mean is 13 minutes. The number of GBPs decreases with increasing lifetime. The lifetimes of GBPs inside the moat do not differ from those in the rest of the field. Positions of all 1508 GBPs measured in all frames of the series are plotted in Fig. 2a, together with the LCT velocities of granules, obtained with the time-averaging interval of 2 hours. This LCT velocity pattern is a combination of diverging flows and of the large-scale flows in the moat. We can see that GBPs concentrate to the locations of convergent horizontal motions. Inside the moat, GBPs are mostly located in “channels” between areas where the repeated granules’ splitting and expansion take place.

The time-averaged horizontal velocities of GBPs were calculated from their positions by means of least-squares linear fits. To increase the accuracy of measurement, we used GBPs with lifetimes longer than

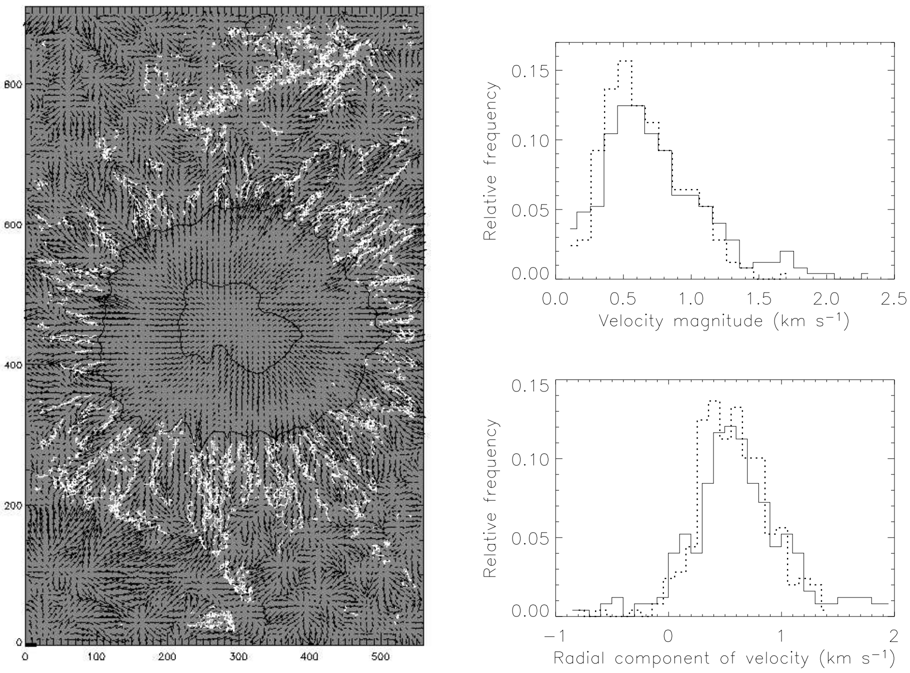

Figure 2: *a (left)* – Positions of GBPs (white) superposed to the map of horizontal velocities (LCT, 2 hours averaging). *b (right)* – Histograms of time-averaged velocities of GBPs (solid) and of adjacent granules (dotted).

10 minutes. In this case, the velocity is measured with a standard deviation of about 0.05 km s^{-1}. We checked visually the trajectories of GBPs to eliminate spurious objects and mistakes in tracking and obtained a final sample of 249 GBPs in the moat and 194 GBPs in the rest of the field. On average, GBPs inside the moat move faster (0.74 ± 0.40 km s^{-1}) than those outside (0.52 ± 0.40 km s^{-1}). The standard deviations characterize the scatter of individual speeds. Inside the moat, 238 GBPs move outwards, away from the sunspot, and only 11 GBPs (4.4 %) move toward the spot.

To check if GBPs in the moat move "passively", pushed by neighbouring granules, or they are driven by a different mechanism, a local comparison of time-averaged velocity vectors of GBPs and adjacent

Table I: Mean velocities of GBPs and neighbouring granules in the moat (km s^{-1}). Standard deviations characterize the scatter of individual values.

Velocity	Magnitude	Radial comp.	Tangential comp.
GBPs	0.74 ± 0.40	0.62 ± 0.46	-0.02 ± 0.33
Granules	0.65 ± 0.29	0.57 ± 0.32	-0.07 ± 0.27

granules was done. For this purpose, we used 249 GBPs with lifetimes longer than 10 minutes and granules that live longer than 5 minutes. The granules were represented by the positions of centers of weight of their areas. To eliminate long-lived small features, possibly identical to GBPs, only granules with average diameter larger than $0\overset{''}{.}35$ were taken into account. The positions of GBPs and granules were compared each 2.5 minutes and the granules within the distance of $1\overset{''}{.}5$ were selected as adjacent to a given GBP. Then, the mean of time-averaged velocity vectors of all granules selected during the GBP's lifetime was calculated to characterize the average velocity vector of granular motions near the trajectory of GBP. Mean values of velocity magnitudes and of radial and tangential components of the velocity vectors, calculated with respect to the sunspot's center, are shown in Table 1.

We can see from the table that the average tangential velocity components of GBPs and of adjacent granules are small compared to the velocity magnitudes. This means that motions in the moat have predominantly radial directions. On average, magnitudes and radial components of velocities are greater for GBPs than for the granules. More information about this effect can be retrieved from Fig. 2b, where the histograms of these quantities are overplotted. The distribution of velocity magnitudes of GBPs (solid line) is very similar to that of granules (dotted line) until 1.4 km s^{-1}, where a new population of "fast" GBPs begins. This population has no counterpart in the velocities of granules. The same is true for the distribution of radial components, from which we can see that the "fast" GBPs are moving away from the sunspot. Several GBPs move also toward the spot (negative values), coherently with adjacent granules. In summary, most of GBPs move "passively" with velocities comparable to those of neighbouring granules but there is a small population (7 %) of GBPs that move faster, with speeds higher than 1.4 km s^{-1}.

6. Discussion and Conclusions

Two time series of broad-band images of an old regular sunspot, taken simultaneously in the $G-$band and blue continuum and restored for instrumental and atmospheric degradation using the phase-diversity technique, were used to study motions of granules, families of granules, and GBPs in the sunspot moat and to measure their time-averaged velocities. It should be noted that the time-averaged velocities are used to describe the general trends of the motions. They differ from instantaneous velocities, which, for GBPs, can reach 2–3 km s^{-1} and characterize mostly the kinetic energy of the motion.

Two types of motions of granules are observed in the sunspot moat (Sobotka et al., 2002): (a) Local divergent motions reflecting mostly the expansion and splitting of granules. (b) A large-scale regular outflow, which carries granules and centers of divergent motions away from the sunspot. Families of repeatedly splitting granules are present in the sunspot moat. The two types of motions (a,b) mentioned above can be identified with the internal evolution of long-lived families (a) and with the radially oriented drift of centroids of the families away from the spot (b).

Inside the moat, GBPs are mostly located in radially oriented "channels" between families of granules that produce local divergent motions. GBPs are swept by moving granules into these channels. Most of GBPs move with the same average speeds like the neighbouring granules. These "passively" moving GBPs are pushed by granular motions. A small population (7 %) of GBPs moves away from the spot faster than the neighbouring granules, so that it must be driven by a mechanism different from the moat outflow. The velocity limit between the two populations of GBPs is 1.4 km s^{-1}.

Acknowledgments

M.S. and J.A.B. thank the Paul Sabbatier University in Toulouse for the stay at the Pic du Midi Observatory. R.M. and M.S. thank IAC for hospitality. The Swedish Vacuum Solar Telescope was operated in the island of La Palma by the Royal Swedish Academy of Sciences at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. Partial support by the Spanish Ministerio de Ciencia y Tecnología and by FEDER through project AYA2001-1649 is gratefully acknowledged. A part of this work was done in the frame of the Key project K2043105 and of the grant A3003404 of the Academy of Sciences of the Czech Republic. This research was partially supported by the European Community's Human Potential Programme (European Solar Magnetism Network, contract HPRN-CT-2002-00313).

References

Gonsalves, A.R.: 1982, *Opt. Eng.* **21**, 829.

Harvey, K., Harvey, J.: 1973, *Solar Phys.* **28**, 61.

Kawaguchi, I.: 1989, *Solar Phys.* **65**, 207.

Löfdahl, M.G., Scharmer G.B.: 1994, *Astron. Astrophys. Suppl.* **107**, 243.

Muller, R., Ména, B.: 1987, *Solar Phys.* **112**, 295.

November, L. J., Simon, G. W.: 1988, *Astrophys. J.* **333**, 427.

Roudier, Th., Lignières, F., Rieutord, M., Brandt, P. N., Malherbe, J. M.: 2003, *Astron. Astrophys.* **409**, 299.

Scharmer, G.B., Brown, D.S., Petterson, L., Rehn, J.: 1985, *Appl. Opt.* **24**, 2558.

Sheeley, N. R.: 1972, *Solar Phys.* **25**, 98.

Shine, R. A., Title, A. M., Tarbell, T. D., Topka, K. P.: 1987, *Science* **238**, 1203.

Sobotka, M., Brandt, P.N., Simon, G.W.: 1997, *Astron. Astrophys.* **328**, 682.

Sobotka, M., Muller, R., Bonet, J.A., Márquez, I.: 2002, in SOLMAG: Magnetic Coupling of the Solar Atmosphere, *ESA SP-505*, 579.