EVOLUTION OF SMALL-SCALE FEATURES AT THE PENUMBRA-PHOTOSPHERE BORDER

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ABSTRACT

Time series of images of a sunspot, acquired simultaneously in blue light and in $G-$band at the SVST, La Palma, are used to study horizontal motions of granules in the vicinity of the spot and evolution of penumbral grains (PGs) near the outer penumbral border. Local correlation tracking and feature tracking algorithms have been utilized for this purpose. Around sunspots and pores we can observe numerous centers of diverging local horizontal motions, caused mostly by exploding granules. Around developed spots we find an organized motion directed out from the penumbra. The divergence centers are carried away from the spot by this motion. In the outer penumbra, PGs move mostly outwards, toward the surrounding granulation. About 2/3 of PGs disappear near the penumbra–granulation border. The remaining PGs move across the border, they transform either to granules or to small bright features, and continue moving away from the sunspot.

1. INTRODUCTION

Sunspots and pores appear due to strong magnetic field that penetrates the visible solar surface. Sunspots, unlike pores, are surrounded by penumbrae with nearly horizontal magnetic field. The column of cold gas forming a sunspot or a pore interacts with convective motions in the surrounding convection zone. This fact is important from the point of view of the stability of sunspots (pores). The interaction, as observed in the broad-band intensity movies with high spatial resolution, is different for sunspots and pores:

Sunspots:
1. In the outer penumbra, most of penumbral grains (PGs) [1] move outwards, toward the outer penumbral border [2], [3].
2. Cloud-like features in dark penumbral fibrils move outwards as well [4], [5].
3. Granules in a region surrounding the spot (moat) move away from the outer penumbral border [6], [7], and [8].

Pores:
1. Granules inside a 1500 km wide zone around the pore are directed toward the pore. Some of them cross the pore's border and penetrate into the umbra [9].
2. These granular motions seem to be driven by divergence centers (rosettas), i.e., mesogranules or exploding granules [9].

In this work we study in detail horizontal motions of granules around a stable sunspot and relations of outward-moving PGs with photospheric granulation.

2. OBSERVATIONS AND DATA PROCESSING

The sunspot NOAA 8620 was observed on 7 July 1999 at the Swedish Vacuum Solar Telescope, La Palma [10], 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). A complementary series of frames was acquired in the Ca II K line ($\lambda\, 3933 \pm 1.5$ Å). The blue and $G-$band cameras were equipped with beam splitters, making possible the phase-diversity reconstruction.

After the standard pre-reduction steps (dark- and flat-field corrections and de-rotation), the blue images were reconstructed by the phase-diversity algorithm [11] and [12], 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, yielding a movie of 288 frames 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 the movie is excellent and extremely stable during the whole period.

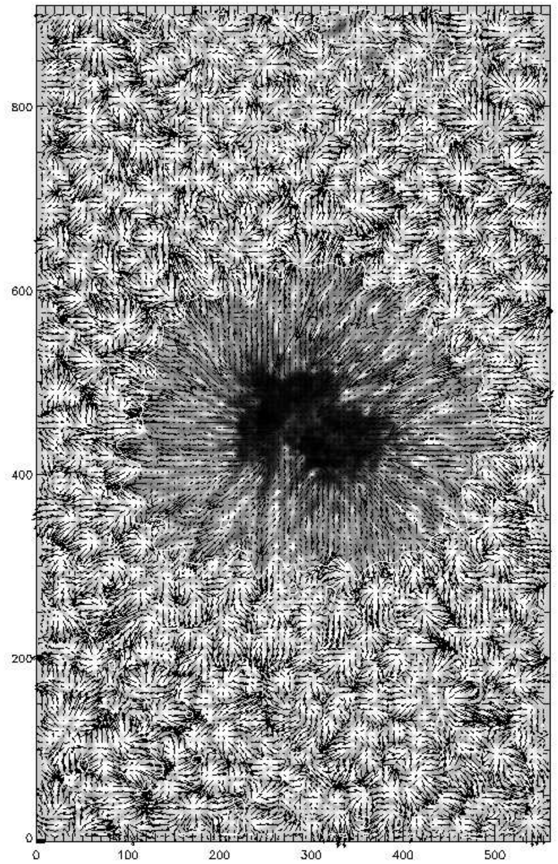

Figure 1. One of the 24 maps of horizontal velocities, averaged over a 5 minute interval. The coordinate unit is 1 pixel, i.e., $0''.083$. The length of the black bar at coordinates (0,0) corresponds to the velocity magnitude of 1 km s^{-1}. The underlying grey-scale image is the average of 288 frames of the series.

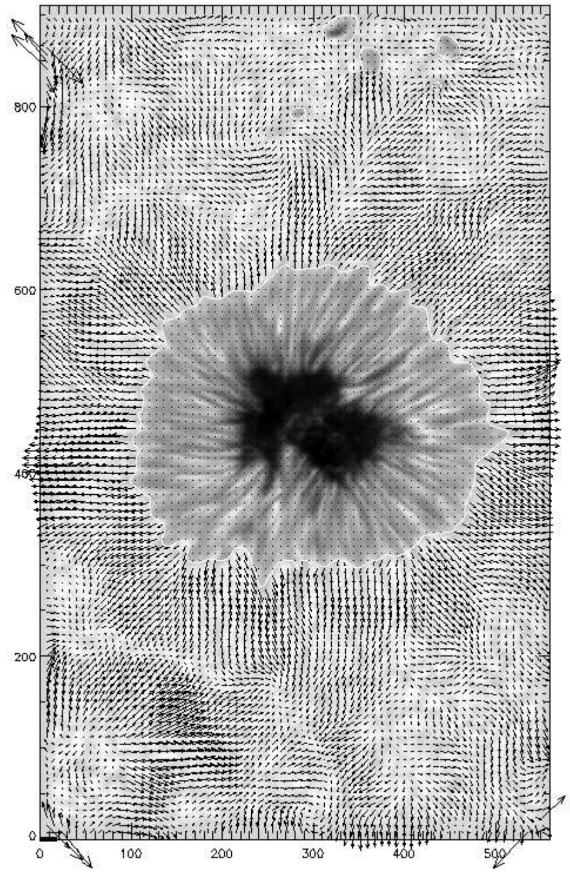

Figure 2. Map of horizontal velocities of divergence fluctuations, showing an outflow in the sunspot moat. Note that the velocity scaling differs from Fig. 1. The velocities inside the spot were set to zero.

3. MOTIONS OF GRANULES IN THE SURROUNDINGS OF THE SUNSPOT

Horizontal motions of granules were studied in the whole $46'' \times 75''$ field by means of the standard local correlation tracking method (LCT) [13]. The FWHM of the gaussian tracking window was set to $0''.75$ (approximately the half of the typical granular size) and the temporal averaging interval to 5 minutes (12 frames). A sequence of 24 velocity maps was obtained during the 2-hour period of the time series. One of the maps (13^{th} in the sequence) is displayed in Fig. 1. Numerous centers of diverging local horizontal motions (rosettas) with average size of $3''$, caused mostly by exploding granules, are present in the whole granular field outside the sunspot.

A movie composed of those 24 velocity maps shows that in an $8''$ wide zone (moat) around the sunspot the rosettas move away from the spot. To study this motion, we converted the velocity maps to a series of images of divergence fluctuations. Since the divergence fluctuations change strongly their shape with time, we had to remove this disturbing small-scale effect by smoothing the images with a gaussian kernel of FWHM = $1''.5$, a half of the typical size of the rosettas. Thus, only significant tracers, representing positions of the rosettas, were preserved. Then the LCT algorithm, with the FWHM of the gaussian tracking window of $2''$ and the temporal averaging interval of 2 hours, was applied to the series of 24 smoothed images of divergences. The resulting velocity map is shown in Fig. 2.

It can be concluded from Figs. 1 and 2 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 presence of small-scale explosive events in the granulation. (ii) A large-scale regular outflow, which carries granules and explosive events away from the sunspot. The limits of this outflow can be seen quite clearly in Fig. 2.

We can also observe in Fig. 2 that the velocities of divergence fluctuations are generally smaller in the top part of the field of view (above the moat), where several small pores are present, than in the bottom part (below the moat), where speeds up to 1 km s^{-1} are observed in the coordinate range (0–250, 0–200).

Table 1. Mean velocities in the regions around the sunspot (km s^{-1}). Standard deviations approximate the widths of distributions of individual speeds.

Region	Moat	Bottom	Top
Granules $\overline{\vec{v}_g}$	0.79 ± 0.43	0.80 ± 0.44	0.73 ± 0.41
Divergen. $\overline{\vec{v}_d}$	0.51 ± 0.13	0.36 ± 0.21	0.25 ± 0.12
$\overline{\vec{v}_g - \vec{v}_d}$	0.64 ± 0.36	0.72 ± 0.38	0.68 ± 0.39

These high velocities can be related to a supergranular boundary.

Mean values of velocity magnitudes, together with standard deviations that characterize the dispersion of individual speeds, are summarized in Table 1 for the moat and for the bottom and top parts of the field of view. The first row in the table corresponds to motions of granules $\vec{v}_g$, as derived from the 24 velocity maps averaged over 5 minutes (Fig. 1). The second row characterizes the (large-scale) velocities of divergence fluctuations $\vec{v}_d$ (Fig. 2). The values in the third row represent a difference velocity field $\vec{v}_g - \vec{v}_d$, that is, the "net" velocities in rosettas—small-scale explosive events.

The mean velocities of granules are nearly equal in the moat and in the bottom part of the field, which contains quiet granulation and possibly a supergranular boundary. The top region with granulation and small pores shows a reduced mean velocity, probably due to the presence of magnetic field in and around the pores. The mean velocity of divergence fluctuations is largest in the moat, where the velocities are organized in a radial pattern, and smallest in the top region with pores. The "net" velocities $\overline{\vec{v}_g - \vec{v}_d}$ in rosettas, corresponding to local speeds in exploding granules, are largest in the bottom region, where a very weak or no magnetic field can be expected, and lowest in the moat. This indicates that the magnetic field dispersed in the photosphere reduces the expansion speeds in exploding granules.

4. INTERACTION OF OUTWARD-MOVING PENUMBRAL GRAINS WITH SURROUNDING GRANULATION

A visual inspection of the movie composed of 288 frames, reconstructed by the phase diversity technique, has shown that the outward-moving PGs evolve in three possible ways:

1. They disappear in the penumbra before reaching the penumbra-granulation (P/G) boundary.
2. They cross the P/G boundary and continue to move in the granulation as small bright features.
3. After crossing the P/G boundary, they increase their size and develop into granules that move away from the sunspot.

To study the evolution of PGs quantitatively, a feature tracking technique [14] was applied to a series of 288 subimages covering a field of 12.″5 × 20.″8 with a part of the penumbra and adjacent granulation. 712 bright features were selected using the following criteria: Minimum lifetime = 250 s, maximum average speed = 4 km s^{-1}, minimum average size = 0.″28, and average brightness ranging from 0.9 to 1.15 (the mean photospheric intensity = 1). Finally, trajectories of these features were checked visually to eliminate inward-moving PGs, features originating outside the penumbra, spurious identifications, and mistakes in feature tracking.

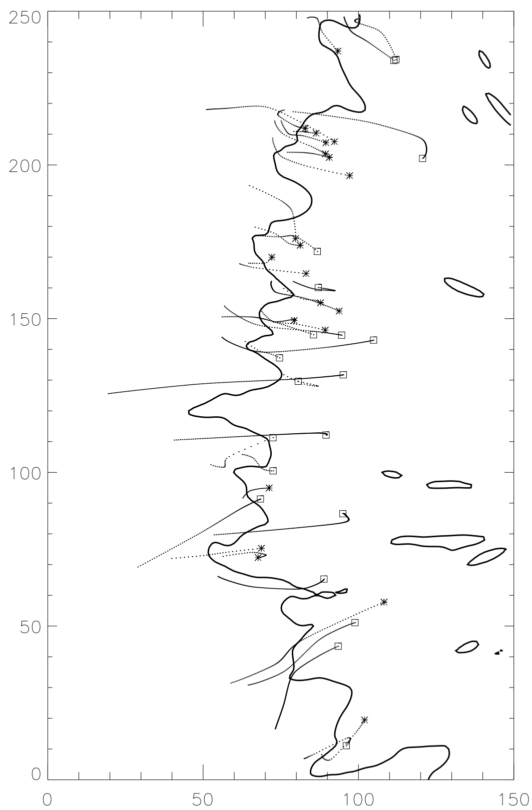

Figure 3. Trajectories of PGs that crossed the P/G boundary. Origins of trajectories are marked by asteriscs for small features and by squares for granules. Dots denote the following positions. In case of slow motions the dots are merged, forming solid lines.

After the visual consistency check we obtained a sample of 126 outward-moving PGs, including their trajectories and instantaneous velocities. About 2/3 of PGs disappear before reaching the P/G boundary, 1/6 cross the boundary and convert into small (diameter < 0.″5) bright features, and about 1/6 cross the boundary, expand in size, and develop into granules. All the features that cross the P/G boundary preserve their outward motion with average speeds of 1.4 km s^{-1} (small features) or 1.1 km s^{-1} (granules). Their trajectories smoothed by cubic splines are plotted in Fig. 3. Two series of frames demonstrating the transformation of an outward-moving PG into

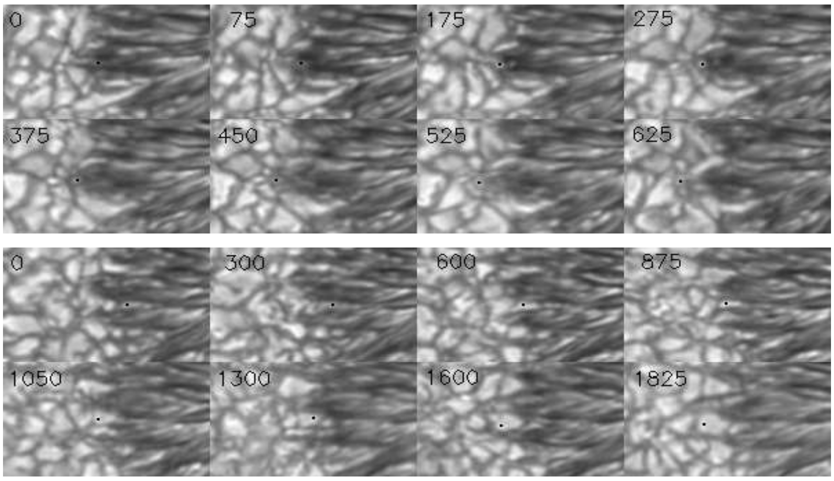

Figure 4. Series of frames showing two examples of PGs crossing the P/G boundary and converting into a small bright feature (top) and into a granule (bottom). The tracked features are marked by small black dots. Numbers in the upper left corners show the elapsed time in seconds. The field of view is 12.″5 × 7.″5.

a small bright photospheric feature (*top*) and into a granule (*bottom*) are shown in Fig. 4.

Numbers of PGs that disappear in the penumbra before crossing the P/G boundary, that cross the P/G border and convert into small bright photospheric features, and that convert into granules, are summarized in Table 2. We also show numbers of PGs which accelerate or decelerate their motion before and during the crossing of the boundary. It is very interesting that most of the PGs that continue as small features decelerate before they escape from the penumbra, while those that expand and develop into granules accelerate. This acceleration might be related to the expansion of a non-magnetic (or less-magnetized) gas squeezed between dark penumbral fibrils with a strong, nearly horizontal magnetic field.

Table 2. Summary of PGs near the P/G border

PGs	Total number	Accel.	Decel.
Non-crossing	85 (67%)		
→ small features	21 (17%)	6	13
→ granules	20 (16%)	11	6

We have shown that about 1/3 of outward-moving PGs located near the outer penumbral boundary escape from the penumbra and penetrate into the surrounding granulation. This direct relation between the outward-moving PGs and granulation points to a complex interaction of subphotospheric convection with the nearly horizontal magnetic field of the penumbra and to the heat exchange along the outer penumbral boundary in the subphotospheric layers, as proposed by [15].

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REFERENCES

1. Muller R., 1973, *Solar Phys.*, 29, 55.
2. Sobotka M., Brandt P.N., Simon G.W., 1999, *A&A*, 348, 621.
3. Sobotka M., Sütterlin P., 2001, *A&A*, 380, 714.
4. Zirin H., Wang H., 1989, *Solar Phys.*, 119, 245.
5. Shine R.A., Title A.M., Tarbell T.D., Smith K., Frank, Z., 1994, *ApJ*, 430, 413.
6. Muller R., Mena B., 1987, *Solar Phys.*, 112, 295.
7. Shine R.A., Title A.M., Tarbell T.D., Topka K.P., 1987, *Science*, 238, 1203.
8. Wang H., Zirin H., 1992, *Solar Phys.*, 140, 41.
9. Sobotka M., Vázquez M., Bonet J.A., Hanslmeier A., Hirzberger J., 1999, *ApJ*, 511, 436.
10. Scharmer G.B., Brown D.S., Petterson L., Rehn J., 1985, *Appl. Opt.*, 24, 2558.
11. Gonsalves A.R., 1982, *Opt. Eng.*, 21, 829.
12. Löfdahl M.G., Scharmer G.B., 1994, *A&A Suppl.*, 107, 243.
13. November L.J., Simon G.W., 1988, *ApJ*, 333, 427.
14. Sobotka M., Brandt P.N., Simon G.W., 1997, *A&A*, 328, 682.
15. Jahn K., Schmidt H.U., 1994, *A&A*, 290, 295.