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Fine structure in sunspots

IV. Penumbral grains in speckle reconstructed images

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Abstract The properties of penumbral grains (PGs) in a large regular sunspot are studied from a 70 minute sequence of G-band images acquired on 20 September 1999 at the Dutch Open Telescope, La Palma. The frames were processed using the speckle masking algorithm, resulting in **an almost** diffraction-limited time series (30 s cadence), **basically** free of atmospheric distortions. **Applying feature tracking to** a movie of 140 frames yields proper motions, intensities, and lifetimes for a set of 1058 PGs with lifetimes longer than 10 minutes. About 54% of the PGs move toward the umbra and 46% toward the photosphere. The inward-moving PGs are located mostly in the inner penumbra (up to 0.6 of the distance from the umbra to the photosphere). **Their average lifetime and median speed are 50 minutes and 0.52 km/s. Most of the outward-moving PGs are** observed in the outer penumbra and their average lifetime and median speed are 31 minutes and 0.75 km/s. These measurements confirm the previous results published by Sobotka et al. (1999a).

Key words. Sun: sunspots

1. Introduction

Bright filaments in sunspot penumbrae are, in fact, chains of elongated bright features called penumbral grains (PGs, Muller 1973a; Muller 1973b). PGs are dynamical objects. Some discrepancies concerning their lifetimes and horizontal motions can be found in the literature. For example, Muller (1973a) and Tönjes & Wöhl (1982) reported lifetimes of 1–3 hours and motions mostly toward the umbra. Wang & Zirin (1992) and Denker (1998), using local correlation tracking, found inward horizontal flows in the inner penumbra but outward motions (toward the photosphere) in the outer parts. Sobotka et al. (1999a, hereafter Paper III), applying a feature tracking algorithm, detected both inward (INW) and outward (OUT) moving PGs with considerably shorter mean lifetimes: 39 (INW) and 25 (OUT) minutes. They found a dividing line in the penumbra, approximately 0.7 of the distance from the umbra to the photosphere, such that most PGs outside this line moved to the photosphere, and those inside moved towards the umbra.

In this work we apply a similar technique as in Paper III to a series of speckle reconstructed images of another sunspot, taken with a different telescope and in a different wavelength band, in order to check the previous results.

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2. Observations and data reduction

The observations were acquired on September 20, 1999 with the Dutch Open Telescope (DOT) at the Observatorio del Roque de Los Muchachos on La Palma (Hammerschlag & Bettonvil 1998). This dome-less open telescope of 44 cm aperture yields a scale of $103''.3$/mm in the focal plane. The image is enlarged by a magnification system to $9''.8$/mm in the image plane, where a video camera (768×572 pixel) records the images at a frame rate of **approximately** 7–8 frames/s and a spatial sampling of $0''.081$/pixel (FOV 62.5×46 arcsec^2). The exposure time was 1 ms using a bandpass of 1 nm centered at 430.5 nm (G-band). The video signal was digitized by an 8-bit frame grabber device in a PC. Data were taken in bursts of 100 images, and were then written to hard disk. A new burst was started every 30 seconds. After the observation, the recorded data were transferred to DAT tape.

A large regular spot (NOAA 8704) at the heliocentric position S22 E32 ($\mu = 0.76$) was observed from 10:34 to 13:35 UT. The first part of the series, from 10:34 to 11:44 UT, was corrected for the instrumental profile of the telescope and for the influences of atmospheric seeing using the speckle masking algorithm (Weigelt & Wirnitzer 1983; von der Lühe 1993; de Boer 1993). **The true aperture, including obstructions in the optical path of the telescope, is included in the speckle recon-**

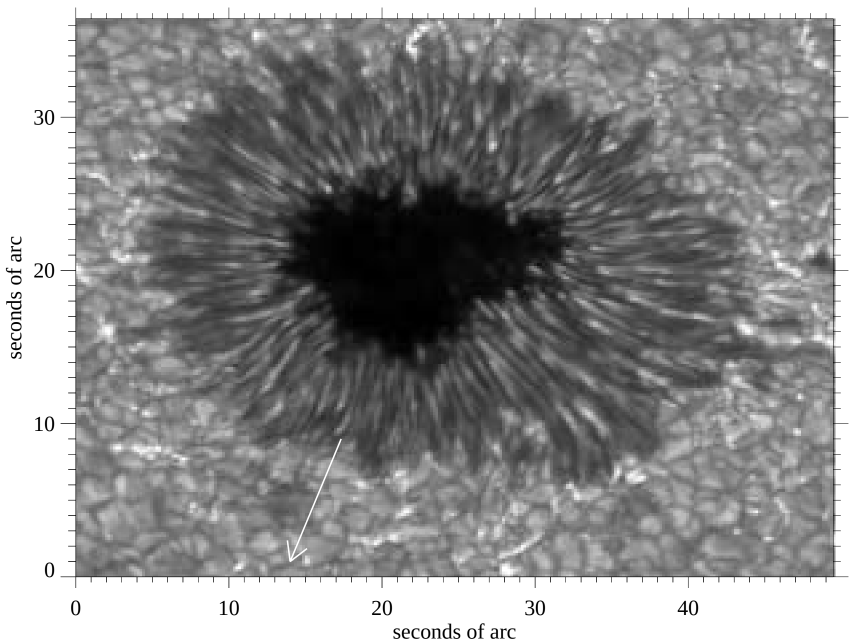

Figure 1. A speckle reconstructed image of sunspot NOAA 8704. The arrow marks the direction towards disk center.

struction code. Due to its simple optical layout, DOT is an extremely low-scattering telescope. The effect of scattered light can be neglected, as seen from observed umbral minimum intensities (about 0.08 of the mean intensity of quiet solar photosphere). The seeing conditions during that period were excellent, as shown by the average Fried parameter (measured at the observation wavelength) of $r_0 = 11\,\mathrm{cm}$ with extremal values of 7.2 cm and 14.6 cm. **The second part of the series was not taken in bursts but in a frame-selection mode, so that the speckle reconstruction was not possible.** All **speckle-reconstructed** images have been correlated and clipped to the common field of view of $49{\times}36\,\mathrm{arcsec}^2$. The DOT has a parallactic mount, **therefore,** no image de-rotation was necessary.

Due to the limited sample size of the bursts, the quality of the reconstruction is still somewhat dependent on the atmospheric conditions. Therefore, in an additional step, the power spectra of all images of the series have been enhanced so that the azimuthally averaged power distribution resembles that of the best image in the series. To the resulting time series we applied a subsonic k-ω filter with a cutoff velocity of 7 km/s to remove the effects of the 5-minute oscillation. This process resulted in a series of 140 reconstructed frames with a constant time lag equal to 30 s. A typical frame is shown in Fig. 1.

All frames were then resampled to compensate for the geometrical distortion due to the position of the spot at $\mu = 0.76$. To remove a residual jitter (stemming from the division of the images into isoplanar subfields), the series was smoothed in time by means of a boxcar spanning over 3 frames.

To isolate PGs from other structures, we masked out photospheric granules, eliminated umbral dots by setting the minimum intensity of bright features to 0.5 of the mean intensity of the quiet photosphere, and applied a segmentation algorithm based on a search for regions with convex intensity profiles. A feature tracking algorithm, described by Sobotka et al. (1997), was applied to the series of segmented frames to follow each PG in time. To be called a PG, each feature had to have a lifetime of at least 3 minutes, a minimum mean area over its lifetime of at least 16 pixels, and a time-averaged velocity smaller than 2 km/s.

This procedure yielded a set of 2900 PGs. Since the duration of the series (70 minutes) was shorter than lifetimes of many long-lived PGs (114 PGs were observed during the full period), we were limited only to a statistical estimate of the mean lifetime based on an average birth rate of PGs (see Sobotka et al. 1999b for details).

Time-averaged horizontal velocities were calculated using linear least-squares fits to the positions of PGs. To increase the accuracy of velocity determination, we chose for analysis 1489 PGs with lifetimes longer than 10 minutes. In this new set, **the velocity is measured with a standard deviation of about 0.05 km/s**. In the last step of the data analysis we checked visually the trajectories of these 1489 PGs to eliminate spurious objects and mistakes in feature tracking (cf. Paper III). After this visual consistency check we obtained a final sample of 1058 PGs.

3. Results

Like in the case described in Paper III, both INW and OUT PGs were observed. Of the 2900 detected PGs, 1477 moved inward toward the umbra, 1407 outward toward the photosphere, and 16 were stationary or had a tangential motion. Of the 1058 PGs that passed the visual consistency check, 575 (54%) moved inward and 483 (46%) outward.

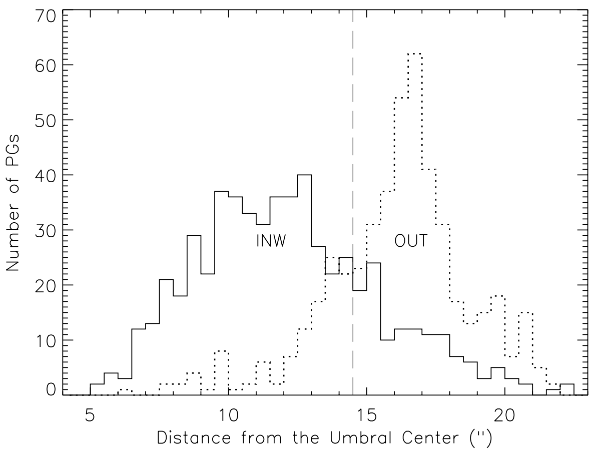

Figure 2. Histogram of time-averaged distances of the INW (solid line) and OUT (dotted line) PGs from the center of the umbra. The position of the dividing line is marked by vertical dashes.

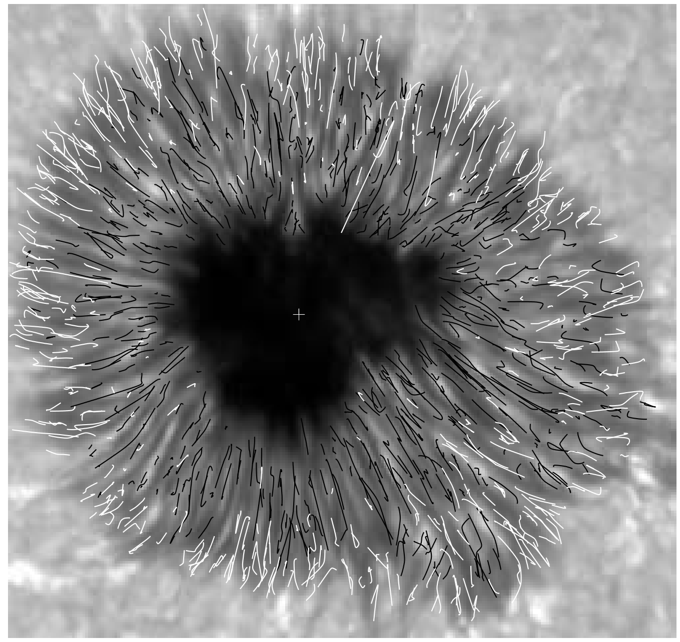

Figure 3. Trajectories of INW (black) and OUT (white) PGs. The underlying image is an average of all frames in the series. The center of the umbra is marked by a white cross. The image size is 29.8 × 28.4 Mm.

3.1. Estimated mean lifetimes

Considering all 2900 detected PGs (minimum lifetime set to 3 minutes), the estimated mean lifetimes are 25.2 minutes (INW) and 18.4 minutes (OUT). These values are very similar to the estimates (INW: 27, OUT: 19 minutes) obtained in Paper III for all the observed PGs.

Based on the final sample of 1058 PGs (minimum lifetime set to 10 minutes), the estimated mean lifetimes are 50.3 and 30.8 minutes for INW and OUT PGs, respectively. These values are by about 25% higher than those presented in Paper III for the final sample (INW: 39, OUT: 25 minutes). The lifetimes of both INW and OUT PGs depend on the position in the penumbra: The average lifetime near to the penumbra-umbra boundary is 55 minutes, it reaches the maximum, 70 minutes, at about 1/4 of the width of the penumbra and then it decreases gradually to 30 minutes at the outer penumbral border. This trend is consistent with the result shown in Paper III.

3.2. Spatial distribution and trajectories

The final sample of 1058 PGs was analyzed to obtain the spatial distribution of positions and trajectories. The histograms of time-averaged distances of the INW and OUT PGs from the center of the umbra are plotted in Fig. 2. The INW PGs dominate in the distance range $5''$–$14.''5$, *i.e.* in the inner penumbra, while the OUT PGs in dominate the range $14.''5$–$22''$ (outer penumbra). The distance $14.''5$ from the umbral center can be considered as a dividing line between the regions of prevailing INW or OUT PGs. In units of a relative distance in the penumbra, measured from an average position of the penumbra-umbra border (position 0) to an average position of the penumbra-photosphere boundary (position 1), the dividing line is located at about 0.6.

The trajectories of PGs were determined from the positions tracked in time and smoothed by cubic splines. In Fig. 3 we show trajectories of the INW and OUT PGs as black and white lines, respectively. The average length of trajectories is $1.''3$ for both INW and OUT PGs (similar values are given in Paper III). **Only 16% INW and 19% OUT PGs travelled longer than $2''$. The maximum observed length of trajectory is $6''$(2 INW and 1 OUT PGs) in a penumbra of average width $12''$, so that none of the PGs crossed the penumbra completely.**

3.3. Horizontal velocities

The time-averaged horizontal velocities of the 575 INW PGs, included in the final sample, show an asymmetric histogram with a maximum around 0.4 km/s, **a mean of 0.60 km/s,** and a median of 0.52 km/s. Velocities of the 483 OUT PGs have a broader histogram than that of INW, with a maximum around 0.5 km/s, **a mean of 0.80 km/s,** and a median of 0.75 km/s. These speeds are only slightly higher than those presented in Paper III.

To study the dependence of time-averaged velocities on position, we divided the relative distances in the penumbra into 10 bins. Velocities of all PGs whose time-averaged positions fell into a given bin were averaged. The results are plotted in Fig. 4 together with 1 σ error bars (which characterize the scatter of individual values) and with numbers of PGs in each bin. For the INW PGs speeds increase from 0.5 km/s at the penumbra-umbra boundary to a maximum of 0.7 km/s at the relative distance 0.6–0.7 (just outside the dividing line) and then drop to 0.6 km/s in the outer

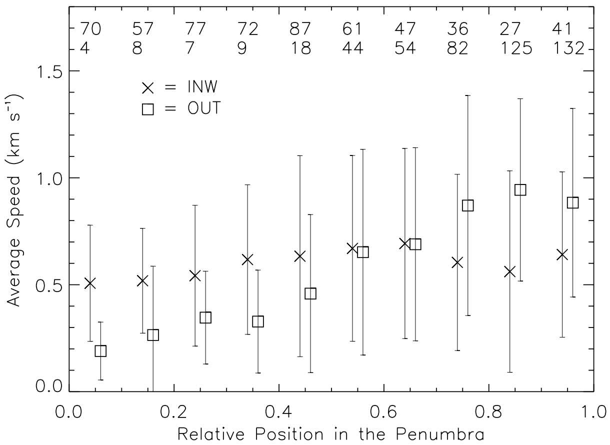

Figure 4. Average speed of PGs as a function of their relative positions in the penumbra. INW PGs are represented by $\times$, OUT PGs by $\Box$. Position 0.0 is at umbra, 1.0 at photosphere. The bars indicate a scatter of $\pm 1\sigma$. Numbers of INW (OUT) PGs in each bin are displayed in the upper (lower) row.

penumbra. Speeds of the OUT PGs increase from a minimum value of 0.2 km/s at the penumbra-umbra border to a maximum of 0.9 km/s near the outer penumbral boundary. These velocity distributions are very similar to those obtained in Paper III.

We calculated instantaneous velocities of each PG as derivatives of positions smoothed by cubic splines. Individual velocity curves, showing acceleration/deceleration, were divided into four types and corresponding numbers of PGs were counted:

1. **Acceleration: 144 (25%) INW, 143 (30%) OUT PGs.**
2. **Deceleration: 215 (37.5%) INW, 141 (29%) OUT PGs.**
3. **Acceleration, then deceleration: 83 (14.5%) INW, 110 (23%) OUT PGs.**
4. **Deceleration, then acceleration: 133 (23%) INW, 89 (18%) OUT PGs.**

These numbers are in a good agreement with those published in Paper III. Most of INW PGs (60.5%, types 2 and 4) decelerate at least in the initial phase of their life, what is partially consistent with the prediction given in the model by Schlichenmaier et al. (1998).

4. Discussion and conclusions

In this work we **extend** the study of lifetimes and horizontal motions of PGs, described in Paper III, using observations and image processing that differ in the following points:

- The spot NOAA 8704 was large and nearly circular. The sunspot studied in Paper III was medium-size and had four umbral cores. In Paper III, we mentioned that the character of the motions of PGs may vary with the size and evolutionary stage of a spot. Therefore, it is important to compare the results obtained from observations of different sunspots.
- The wavelength is different – G-band at λ 430.5 nm instead of λ 468 nm.
- The images are speckle-reconstructed, so that not only the instrumental profile of the telescope but also the influence of atmospheric blurring is corrected. This results in a very high and stable image quality during the whole time series.
- The segmentation algorithm, based on a search for local intensity maxima, differs from that used in Paper III, which applied a variable intensity threshold computed as a function of image sharpness.
- The final sample of PGs is more than twice larger than that analyzed in Paper III.

In spite of all the differences mentioned above, the results of our present analysis are consistent with those shown in Paper III. The main differences are in the estimated mean lifetimes that are by about 25% longer and in the larger fraction of OUT PGs (46% present work, 27% Paper III). The relative position of the dividing line between the regions of prevailing INW or OUT PGs is 0.6 instead of 0.7. All the other results do not show any important difference. We can conclude that, using a new and independent observation, we confirm the previous results published in Paper III.

Schlichenmaier et al. (1998) suggested that PGs are intersections of hot, rising fluxtubes with the photosphere. They move toward the umbra, continuously decreasing their speed. Predictions of this model are only in partial agreement with our observations. Further numerical simulations are needed to account for interactions of several flux tubes and to explain both the inward and outward motions of PGs.

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