MOTIONS AROUND A DECAYING SUNSPOT*

R. MULLER and B. MENA**

Observatoires du Pic-du-Midi et de Toulouse, 65200 Bagnères-de-Bigorre, France

(Received 6 September, 1986; in revised form 19 June, 1987)

Abstract. We have measured the motion of facular points and granules in the same region near a decaying sunspot. It is found that both features move away across the moat surrounding the sunspot. The mean speed of facular points is larger than that of granules: 0.65 km s^{-1} and 0.4 km s^{-1}, respectively. These results are consistent with previous measurements of the speed of bright network features and moving magnetic fields, as well as of non-magnetic photospherical material. They support models in which a decaying sunspot is at the center of a supergranule, whose horizontal motions sweep out granules and magnetic flux tubes associated to the facular points. It is also found that granules are dragged by supergranular motions away of the moat.

1. Introduction

Some large sunspots, usually leading ones, after having reached their maximum size, begin to decay slowly. An annular cell, called the 'moat', develops around the sunspot with a systematic outflow of 0.5–1.0 km s^{-1} at the photospheric level (Sheeley and Bhatnagar, 1971; Sheeley, 1972). The moat extends for 10000–20000 km beyond the edge of the spot. Small magnetic features, $1''$–$2''$ of size, are observed to move outward from the penumbra, throughout the moat, towards the nearest faculae with velocities of about 1 km s^{-1} (Vrabec, 1971; Harvey and Harvey, 1973; Wallenhorst and Topka, 1982). These moving magnetic features (MMF) usually appear in the form of pairs of opposite polarity, but the net flux transported by those features is approximately equal to the sunspot decay rate. CN filtergrams show that bright network features, which are known to be associated to magnetic flux, originated at the outer edge of the penumbra, move outward through the moat and merge with the surrounding photospheric network (Sheeley, 1969). It must be noted that the systematic photospheric and the MMF outflows have never been observed near the same sunspot.

Based on those observational results it was suggested by Sheeley (1972) that a decaying sunspot occupies the centre of a supergranule and that small-scale fragments of magnetic flux are carried away from sunspots by the supergranular flow. Later on Meyer *et al.* (1974) gave a description of the formation and destruction of sunspots that is consistent both with these observations and with their theoretical understanding of the interaction between magnetic fields and convection. In their description, small flux tubes diffuse outwards at a rate which is determined by the allowed, although modified, small-scale convection. They are then torn away from the penumbra and carried across

---

* Contributions from the Kwasan and Hida Observatories, University of Kyoto.

** A part of this work was done while one of the authors (R.M.) was staying at the Kwasan and Hida Observatories, University of Kyoto, Japan, as a JSPS research fellow.

Solar Physics **112** (1987) 295–303.

the moat by supergranular motions, appearing as moving magnetic features in the photosphere.

Thus it is clear that a detailed study of the surrounding motions is of fundamental importance to understand the decay of sunspots. The aim of this paper is, using high-resolution filtergrams, to analyse in detail the motion of facular points near a decaying sunspot and to seek for a possible systematic outflow of granules driven by supergranular convective motions.

2. Description of the Observed Sunspot

The data set used for this work consists of a 1h 30m time series high-resolution photographs of a decaying sunspot taken with the 50 cm refractor at the Pic du Midi Observatory, on June 4, 1980. The time interval between successive frames is 45 s, the spatial resolution close to $0''.3$. The photographs were taken through a 10 Å bandpass interference filter centered on CH molecular lines at 4308 Å. The advantage of such kind of filtergrams is that one can see on the same frame both the granulation and bright facular features at the disk centre (Figure 1).

In fact, Figure 1 shows two small, almost circular sunspots, very close of each other. They are the leading remnants of a bipolar active region (Mt. Wilson 24183) born on the unvisible hemisphere of the Sun, which appeared at the East limb on May 1, 1980. When returning on May 28, the following part of the sunspot group had disappeared and only one, unipolar leading sunspot was then visible. The spot splitted into two smaller spots on June 2; these two spots were still there at the time of the observation, on June 4. But the smaller, westward one, disappeared the next day, while the decaying larger sunspot, which is analysed in this work, disappeared later, after June 10.

Both sunspots are surrounded by a ring extending for 6–8 arc sec beyond the outer edge of the penumbra, which contains many tiny bright points (the facular points). The diameter of the sunspots is respectively $30''$ and $18''$. We made crude measurements of the size of 72 facular points, directly on an enlarged copy of one of the best photographs. The size histogram in Figure 2 shows that the most frequent size is $0''.42$; the average size is $0''.5$. It is interesting to compare this size histogram with that of facular points in the quiet photospheric network (Müller and Keil, 1983). Most frequent sizes are found to be $0''.35$ and $0''.42$ respectively in the quiet photospheric network and near the decaying sunspot; such a difference is not significant owing to the different technics of measurement used and the different wavelengths at which facular points were observed (5750 Å and 4308 Å, respectively). However, the mean size is significantly different: $0''.33$ in the quiet Sun and $0''.50$ near the sunspot. While there are only very few facular points of size larger than $0''.5$ in the quiet photospheric network, about 40% of them are in the range $0''.5$–$1''.0$ near the decaying sunspot. We have not found facular points of size larger than $1''.0$. In short, when observed with a resolution close to $0''.25$, facular points of size $0''.3$–$0''.4$ are the most frequent in both the quiet photospheric network and near decaying sunspots, but in the latter case there are much more facular

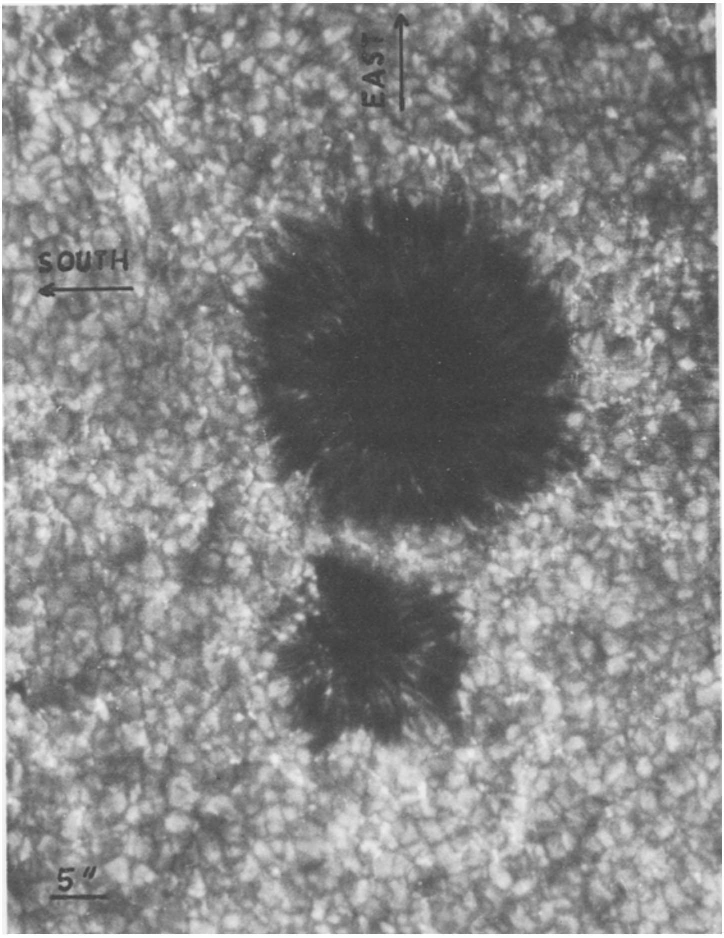

Fig. 1. Decaying sunspots observed on June 4, 1980 with an interferential filter: $\lambda 4308$, $\Delta\lambda$ 10 Å. Facular points appear as tiny bright features.

points of size in the range 0″.5–1″.0. Two such 'large' facular points are nicely visible westward of the smaller sunspot in Figure 1.

In the following we will describe the motions of facular points and granules through the ring surrounding the larger sunspot. Moreover, their lifetime and evolution will be compared to those in the quiet photospheric network.

3. Motion and Lifetime of Facular Points near the Decaying Sunspot

We have measured the motion and lifetime of 102 facular points using the full one hour thirty minutes time series. We have concentrated our study on the points located southward of the large sunspot; all facular points visible in this area were analyzed in order to avoid any selection effect.

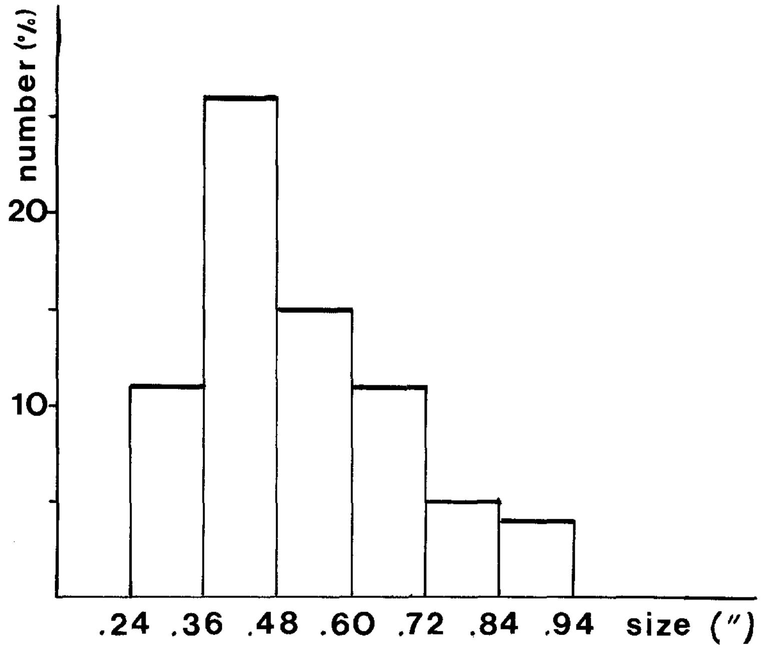

Fig. 2. Size histogram of facular points near the decaying sunspot of Figure 1.

Facular points appear, like in the quiet photosphere, in spaces at the junction of several granules (Müller, 1983). They move radially away from the sunspot. Their lifetime ranges from 4 min to more than one hour, with a mean lifetime of 17 min which is very close to the value found in the quiet photosphere (18 min, Müller, 1983). In most cases they remain brighter than the surrounding granules only during a few minutes. We have found few examples of facular points growing in size, sometimes up to about 1″; during this growing phase they become very bright; then both the size and brightness return to the normal. Such kind of growing facular points was never found in the quiet photospheric network (Müller, 1983). Facular points may appear and disappear at any distance from the outer edge of the penumbra throughout the moat. Although few bright points are appearing at the photosphere-penumbra boundary, we have noticed there unusual modes of formation: a few facular points seem to result from the collapse of a granule (which could have exceeded a size of 1″); other points result from the collapse of diffuse material in spaces at the junction of several granules (this mode of formation was also found throughout the moat, although less frequently); facular points may also appear in dark spaces between granules and penumbral filaments.

Most facular points do not move as isolated features but together with several adjacent points: they are a part of a moving cluster of points. In this moving area, which does not extend more than 2–3 arc sec in size, facular points appear and disappear continuously so that their number varies with the time, not exceeding however a dozen of points at a given time. As facular points have a strong tendency to appear in such clusters, new points often appear very close to an existing point: it should be noted that this is also the case in the photospheric network, away from sunspots, where facular points have a strong tendency to gather together to form clusters (Müller, 1983). The moving clusters of points are probably the bright network features moving across the moat observed by Sheeley (1969) and the moving magnetic features (MMF) observed by Vrabec (1971) and Harvey and Harvey (1973), under moderate seeing conditions. Thus MMF are very likely formed with several individual flux tubes, if we may regard each facular point to be associated to one flux tube.

The outer edge of the penumbra was used as a reference position for measuring the motion of facular points. The main difficulty was to locate precisely the photosphere-penumbra boundary, for its shape is varying continuously with the time. We estimated that the change of position of the boundary was about $\pm 0''.5$. Another source of error is the image distorsion, which is less than $\pm 0''.5$ in our case (see Müller, 1973). Individual speeds are derived from the distance covered by facular points which is therefore known with an uncertainty of less than $\pm 1''$. Because of this high uncertainty, speeds were derived only for those facular points with lifetimes larger than 12 min (58 points). Thirty frames were used in average to get individual speed values of these 'long lived' facular points. The uncertainty being less than $\pm 1''$ for individual covered distances, it is less than $\pm 1'' \sqrt{58}/58 = \pm 0''.125$ for the average distance, or less than $\pm 0''.07$ km^{-1}; the average speed is found to be 0.65 km s^{-1}. More precisely we found that facular points move with a mean speed of 0.65 km s^{-1} through the moat, except near its inner and outer boundaries where it appears to be smaller. Within 2″ from the edge of the penumbra the speed is of about 0.4 km s^{-1}, and drops to nearly zero at the outer boundary, between 8″ and 11″ from the sunspot. Moreover, near both boundaries some points are moving against the mean flow, probably because of proper motions induced by the continuously changing granular pattern. The speed of facular points is in quite good agreement with the speed of bright network elements and MMF moving throughout the moat. On magnetograms, MMF are observed to be of both polarities; our observations do not give any indication about the magnetic polarity of the mowing clusters of facular points. We have checked that, in the opposite side of the mean sunspot as well as near the smaller sunspot, facular points also move away from the penumbra, although apparently more slowly, with an average speed of 0.4 km s^{-1}.

4. Motion of Granules near the Decaying Sunspot

In order to find a possible granule motion near the decaying sunspot, a rectangular area of 18″ × 12″ was scanned with the microdensitometer of Nice Observatory (Figure 3), with a step of $0''.06$ in the radial direction and $0''.19$ in the direction perpendicular to the penumbral filaments. The size of the slit was $0''.22 \times 0''.22$. Fourteen photographs, taken every $2^{m}42^{s}$ in average were selected from the time series. Such a time interval is a good compromise between a detectable motion and the change of the granular pattern. The granular motion perpendicular to the sunspot boundary was determined by cross-correlation on successive frames. For convenience the scanned area was divided in four regions (Figure 3).

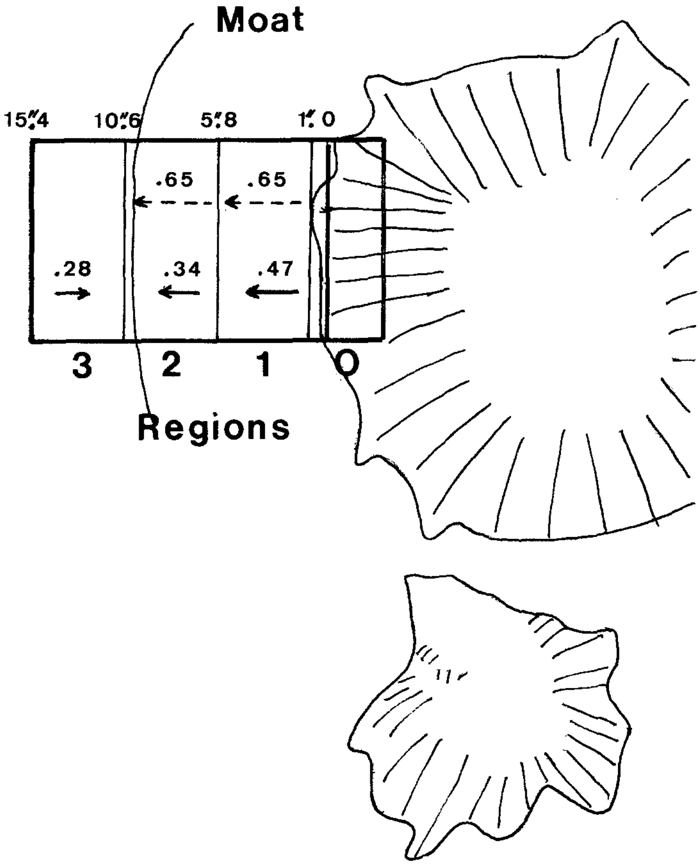

Fig. 3. Motion of granules (———→) and facular points (— — —→) near the main decaying sunspot. Speeds are expressed in km s^{-1}. ———: probable outer boundary of the moat. The rectangle shows the regions where the granule motions were determined; the motion of facular points was measured within a wider area.

The penumbral filaments in the region number 0, which covers the outer half of the penumbra, were used as a common reference system for all the frames, for two reasons: first, the structure of the penumbra changes much more slowly than the granular pattern; second, the average speed of penumbral grains in the outer penumbra is small, less than 0.2 km s^{-1} (Müller, 1973; Tönjes and Wöhl, 1982). Regions 1, 2, and 3 were used to measure the mean motion of granules at various distances from the sunspot outer boundary.

The cross-correlation is expressed by:

$$C_{(j)} = \frac{\Sigma i(x,y)\, i'(x,y+j)}{[\Sigma i^2(x,y)\; \Sigma i'^2(x,y+j)]^{1/2}},$$

where $i(x,y) = (I(x,y) - \bar{I})/\bar{I}$ is the intensity fluctuation in one region, $i'(x,y+j)$ the intensity fluctuation in the same region of the next frame, j-steps shifted in the direction perpendicular to the sunspot boundary, $I(x, y)$ the local intensity and $\bar{I}$ the average intensity of the scaned area. In the region number O, the frames were first shifted in the direction perpendicular to the filaments, then in the direction perpendicular to the sunspot boundary, in order to make penumbral filaments coincident on consecutive frames. In each region, the mean granule shift between frames is given by the position of the maximum of $C(j)$; the total shift of the granular pattern during the $35^{m}06^{s}$ time series is the sum of the 13 shifts derived for consecutive frames. The shifts are shown in Table I, expressed in steps (one step = $0\rlap{.}''06$); a positive value corresponds to an outward motion of the granular pattern. The scatter in the shifts is mainly due to the differential distorsion of the images.

TABLE I

Shift of the granular pattern

Image number	Shift (1 step = $0\rlap{.}''06$)		
	Region 1	Region 2	Region 3
1			
2	+1	+2	0
3	+3	+2	0
4	+3	+2	−5
5	+4	+4	+2
6	+1	+1	+3
7	+3	0	−7
8	+1	+1	−1
9	+2	−3	−5
10	+2	+4	+4
11	0	+2	−2
12	+4	+4	+3
13	+1	−1	−4
14	0	0	−3
Total shift (steps)	+25	+18	−15
Total shift (arc sec)	+1.50	+1.08	−0.90
Mean speed (km s^{-1})	+0.52	+0.38	−0.31

Region 3 is the most distant from the reference area and exhibits the highest scatter, as expected if the differential dispersion increases with increasing distance. The total shift of the granular pattern during the 13 frames (35 min) time series is much larger than the standard deviations (Table I), clearly demonstrating that granules are moving radially near the decaying sunspot.

The uncertainty on the shift derived from two successive frames is ± 1 step ($0\rlap{.}''06$) in the region 1, ± 1.5 step ($0\rlap{.}''09$) in the region 2 and ± 3 steps ($0\rlap{.}''18$) in the region 3. These low values can be explained by the averaging of the image distorsion over the

18″ × 4″ area of each region. The uncertainty on the average shift in the region 1 is ± 1 step × $\sqrt{13}/13$ = 0.3 step or 0″.18 and is 3 times larger in the region 3; consequently the uncertainty on the average speeds is ± 0.08 km s^{-1}, 0.12 km s^{-1}, and 0.24 km s^{-1} in the regions 1, 2, and 3, respectively.

If we take into account that the outer penumbra reference area is moving inward with an average speed of about 0.1 km s^{-1}, then the granule speeds on Table I have to be changed to the values 0.4 km s^{-1}, 0.3 km s^{-1}, and 0.4 km $^{s-1}$ in the corresponding regions. It thus appears that the direction and the speed of the motion is a function of the distance to the sunspot. In the regions 1 and 2, granules move outward, with a speed decreasing from 0.4 km s^{-1} at 3″.5 from the outer sunspot boundary (the mean distance of region 1) down to 0.3 km s^{-1} at 8″ (the mean distance of region 2). In the region 3, granules move in the opposite direction, with a mean speed of 0.4 km s^{-1}. This behaviour can be easily explained as follows: in the regions 1 and 2, granules are carried away by a supergranule surrounding the decaying sunspot, the speed slowing down near the supergranules boundary. Granules in region 3 are swept by a neighbouring supergranule in the opposite direction. The boundary between the two supergranules is located at about 10″ from the sunspot; the diameter of the supergranule surrounding the decaying sunspot would be of about 50″. The change of direction of the granular motion between the region 1–2 and the region 3 demonstrates that these motions are larger compared to that of the penumbral grains along the filaments in the outer half of the penumbra, justifying the assumption we have made earlier in this section. The observed decrease of the granule motion in the region 2 may be interpreted by a constant speed flow of the granules throughout most of the supergranule, and a steep speed decrease near the supergranule outer boundary, just like for the motion of facular points. We have not measured the granule motion within the first 1″ outside the sunspot, because this region is ‘contamined’ by some penumbral material.

5. Discussion and Conclusion

In this work we have measured the motion of the granules and facular points in the same region near a decaying sunspot. We have found that both features move away from the sunspot, the speed of the facular points being substantially larger than that of the granules: 0.65 ± 0.08 km s^{-1} and 0.4 ± 0.1 km s^{-1}, respectively, throughout most of the region. Our results are consistent with previous measurements of the speed of bright network features and moving magnetic fields, as well as of non-magnetic photospheric material (see the Introduction). They thus support models in which a decaying sunspot is at the center of a supergranule (Sheeley, 1972; Meyer *et al.*, 1979; Schmidt *et al.*, 1985). It should be pointed out, however, that our granule and facular points velocities have been measured, for the first time, in the same region and at the same time. Furthermore, they are smaller than those reported previously.

Granules are very likely swept out by supergranules and their motion reflects supergranular motions near the photosphere. The motion of magnetic flux tubes embedded in a convective cell depends on the competition between the surface outflow and the inflow at the base of the cell, as well as on the buoyancy of the tubes and on the magnetic tension (Schmidt *et al.*, 1985). For facular points are tracers of magnetic flux tubes it is not surprising to find a different speed for facular points and granules. One of the main results of Schmidt *et al.* is that flux tubes with flux $< 10^{18}$ Mx are driven toward the supergranular cell boundary. The observed typical size of facular points is $0\overset{''}{.}42$ (~ 300 km), the real typical size is smaller, but not much smaller because the resolution of the observation, as shown by the size of the smallest features, is about $0\overset{''}{.}25$ (see also Müller and Keil, 1983). If we assume that the size of flux tubes is the same as that of the associated facular points, and the magnetic field strength is 1500 G (Stenflo, 1973), then the typical flux carried by flux tubes is 10^{18} Mx or less. This gives some support to the Schmidt *et al.*'s result, even if we must keep in mind that, in this work, we have studied motions driven by a supergranule perturbed by a sunspot located in its center.

Acknowledgements

R. Müller likes to thank the Japan Society for the Promotion of Science (JSPS) for providing a grant and Prof. I. Kawaguchi for his kind hospitality at the Kwasan and Hida Observatories and at the University of Kyoto. The microphotometry was made with the PDS of the Centre de Dépouillement des Clichés Astronomiques (CDCA) of the Nice Observatory.

Note added in the proof: the granular motion reported here has been spectacularly confirmed by A. Title and co-workers from the SOUP experiment data.

References

Harvey, K. and Harvey, J.: 1973, *Solar Phys.* **28**, 61.
Meyer, F., Schmidt, H. U., Weiss, N. O., and Willson, P. R.: 1974, *Monthly Notices Roy. Astron. Soc.* **169**, 35.
Müller, R.: 1973, *Solar Phys.* **29**, 55.
Müller, R.: 1983, *Solar Phys.* **85**, 113.
Müller, R. and Keil, S. L.: 1983, *Solar Phys.* **87**, 243.
Schmidt, H. U., Simon, G. W., and Weiss, N. O.: 1985, *Astron. Astrophys.* **148**, 191.
Sheeley, N. R.: 1969, *Solar Phys.* **9**, 347.
Sheeley, N. R.: 1972, *Solar Phys.* **25**, 98.
Sheeley, N. R. and Bhatnagar, A.: 1971, *Solar Phys.* **19**, 338.
Stenflo, J. O.: 1973, *Solar Phys.* **32**, 41.
Tönjes, K. and Wöhl, H.: 1982, *Solar Phys.* **75**, 63.
Vrabec, D.: 1971, in R. Howard (ed.), 'Solar Magnetic Fields', *IAU Symp.* **43**, 329.
Wallenhorst, S. G. and Topka, K. P.: 1982, *Solar Phys.* **81**, 33.