A&A 472, 277–282 (2007)
DOI: 10.1051/0004-6361:20077552

Astronomy & Astrophysics

Properties of sunspot moats derived from horizontal motions

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Received 27 March 2007 / Accepted 21 May 2007

ABSTRACT

Context. Sunspots in late phases of evolution are usually surrounded by annular moats, regions where systematic horizontal flows are observed to be directed radially away from the spot. These flows are considered to be a manifestation of the sub-photospheric convection.

Aims. The characteristics of moats are derived at two different heights in the solar atmosphere from horizontal motions around sunspots of different sizes, shapes, and phases of evolution. We also study the temporal evolution of moats.

Methods. Local correlation tracking is applied to approximately 70-min long time series of white-light and 1600 Å images, acquired by the satellite TRACE, to analyse the horizontal motions of photospheric granules and C IV emission structures in the vicinity of 32 sunspots. Moat regions are defined by means of radially-oriented, outward velocities.

Results. Relations between sunspot types and the occurrence, areas, and horizontal velocities of moats in the photosphere and transition region are described. Moats do not show substantial changes during the period of about 12 h. Observed asymmetries in moat shapes and velocities are related to the height in the atmosphere, to sunspot age, and to proper motion. It is suggested that the sub-photospheric convective flows around sunspots may be influenced by the spots' proper motion through the convection zone.

Key words. Sun: sunspots – Sun: photosphere – Sun: transition region – convection

1. Introduction

Sunspots, the largest coherent structures visible at the solar surface, are highly dynamical systems. They are accompanied by specific motions of plasma in the convection zone, photosphere, chromosphere, and transition region. The existence of an annular region around a sunspot, where magnetic fields are not static, was first reported by Sheeley (1969). He termed this region *a moat*. From Doppler spectroheliograms, Sheeley & Bhatnagar (1971) found radially oriented outflows in moats. Sheeley (1972) reported the Doppler speed of the outflows 0.5–1.0 km s^{-1} for distances 10–20 Mm beyond the outer boundary of the penumbra and suggested that these motions carry small-scale fragments of magnetic flux away from sunspots. Harvey & Harvey (1973) claimed that moats are associated with decaying spots. Using daily full-disk magnetograms, Pardon et al. (1979) found that moats start to form approximately 3 days after the sunspot appearance, remain stable for several days, and sometimes live longer than the associated sunspots. Moats were observed mainly around old, well-developed spots. From a compilation of 49 observations, Brickhouse & Labonte (1988) concluded that the moat radius is roughly proportional to the penumbral radius. They also noted that the moat shapes are often asymmetric, even with some missing sectors.

Time series of spectroheliograms, magnetograms, white-light, and *G*-band images have shown strong organised horizontal motions in moats. Magnetic elements, *G*-band bright points, and granules move predominantly away from sunspot border with speeds of about 0.5–0.7 km s^{-1} (Muller & Mena 1987; Shine et al. 1987; Brickhouse & Labonte 1988; Bonet et al. 2005. These speeds are about twice as fast as the supergranular ones (Brickhouse & Labonte 1988)). Hagenaar & Shine (2005) find that magnetic elements move faster (1.5–1.8 km s^{-1}) than the average moat flow and often follow preferred paths. When observed in white light with sub-arcsecond spatial resolution, moat flows show azimuthal variations with zones of azimuthal divergence and convergence, resulting in a radial "spokes" pattern (Shine et al. 1996). This is due to the combination of the moat outflow with local divergent motions caused by recurrently expanding and splitting granules (Bonet et al. 2005). Vargas Domínguez et al. (2007) studied moat flows in the specific case of a complex sunspot group with a δ-configuration. They claim that these flows are closely associated with the presence of a penumbra and appear only in the direction delineated by penumbral filaments.

Brickhouse & Labonte (1988) associated the observed radial outflow in moats with convective flows assumed in the theoretical sunspot model published by Meyer et al. (1974). The heat excess below a sunspot causes upflows around the spot's flux tube in the convection zone and diverging horizontal flows in the photosphere. Convergent flows deep in the convection zone contribute to the mechanical stability of the spot. Sheeley (1972) and Meyer et al. (1974) suggested that the moat outflow is similar to a supergranular convection with the sunspot at the centre of the cell. However, according to posterior measurements, moats live longer and speeds in them are faster compared to supergranules.

An alternative explanation is provided by numerical simulations of compressible convection around magnetic flux tubes. Hurlburt & Rucklidge (2000) suggest that plasma cooling in the vicinity of a cold flux tube causes downflows around the

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20077552

tube, creating a convective "collar" with convergent flows near the surface – in the opposite direction to the model by Meyer et al. (1974). This is in a good agreement with observed flows around pores, which are dominated by inward motions within about 1500 km of the edge of a pore (Sobotka et al. 1999). In case of sunspots with a penumbra, Hurlburt & Rucklidge (2000) suggest that the convective "collar" is hidden below a shallow penumbra and that the moat outflow is a manifestation of an outer cell that surrounds the "collar" and has the opposite direction of the plasma circulation than in the "collar". This means that an upflow is present below the penumbra and a surface outflow extends far beyond the penumbral border.

In this paper we utilize time series of images acquired by the Transition Region and Coronal Explorer (TRACE) to study the morphology and dynamics of sunspot moats at two different heights in the solar atmosphere. The moats are defined by means of the horizontal motions of photospheric and transition-region structures.

2. Data processing and analysis

From the TRACE data base (`http://trace.lmsal.com/trace_cat.html`), we extracted time series of white light (i.e. integrated UV and visible continua) and UV 1600 Å broad-band images of sunspots observed in the years 2000–2004. The average length of the time series is 70 min and individual frames in the series are separated by 0.5–1 min. The TRACE plate scale is $0\farcs5$ per pixel and the theoretical spatial resolution is $1''$. The characteristics of TRACE white-light and 1600 Å passbands are described by Handy et al. (1999). The first passband probes low photospheric layers, while the second one contains a mixture of a UV continuum originating in upper photosphere near the temperature minimum (Fossum & Carlsson 2005) and of C IV emission lines (1548 and 1551 Å) from the transition region, formed in magnetic features (Handy et al. 1998).

We analysed time series of 32 sunspots in white light, 26 of which were observed simultaneously in the 1600 Å passband. To study the temporal changes of moats, we utilized multiple white-light observations of 11 spots (3–4 time series for each), spanning approximately a half-day period. All sunspots were located in the central part of the solar disc to avoid geometrical distortion. They were selected to represent a broad range of morphological types and evolutionary phases, ignoring the presence and development of moats to obtain an unbiased sample. The sunspots were divided into two groups, growing *young* spots before reaching the maximum area (14 in white light and 12 in 1600 Å) and *old* spots in the maximum or decay phase of evolution (18 in white light and 14 in 1600 Å). The evolutionary phase was determined from the solar data base BASS 2000 (`http://bass2000.obspm.fr/search_struct.php`).

The frames in the series were aligned, so that the sunspots were static in the field of view, and a Fourier 3D k–ω filter was applied to remove 5-min oscillations that could bias the horizontal velocities. Horizontal motions of granules and other features were measured using the Local Correlation Tracking technique (LCT, November & Simon 1988). This method has an advantage in detecting dominant motions of all features in region of interest and can give good results if applied carefully with a knowledge of its weak points (e.g. setting the correct values of correlation shifts). We used the modifications of routines written by Molowny-Horas & Yi (1994). The FWHM of the Gaussian correlation window was set to $3''$ (6 pixels), sufficiently small to track granular motions. The computed velocities were averaged over the duration of each series, i.e., about 70 min. This time averaging is quite strong but necessary to remove the noise appearing in consequence of the small correlation window. For this reason, velocity magnitudes can be underestimated. As a result we obtained maps of horizontal velocities with field of view $3'12'' \times 3'12''$.

Our definition of the moat region is based on horizontal velocities of granules (white light) or C IV emission and UV continuum features (1600 Å). We use two criteria: (1) The speed must be higher than an empirically estimated threshold 250 m s^{-1} and (2) the deviation of velocity vector from the radial direction with respect to the spot centre must be less than $\pm 30°$. When the moat is defined, we measure its area and asymmetry, velocities inside and outside it, and azimuthal asymmetry of velocity magnitudes. Using average velocities in quiet regions distant from a sunspot as a reference, we also measure the proper motion of the sunspot with respect to quiet granulation.

3. Results

An example of velocity maps with identified moats is shown in Fig. 1. Horizontal motions away from sunspots are observed in both white-light and 1600 Å passbands, which means in the low photosphere, as well as around the temperature minimum and in the transition region. Moat areas are marked by white colour in the figure and white circles delimit the regions of interest. A visual inspection of all velocity maps reveals that moats, or at least their parts, are detected in white-light as well as in 1600 Å passbands around *all* sunspots, both old and young, so that they are not only associated with decaying spots. A similar conclusion has already been made by Brickhouse & Labonte (1988). Further, moats have mostly asymmetric, sectored shapes. This is a well-known fact, but general characteristics of the asymmetry based on a sufficiently large sample of moats have not been studied until now. We do that in Sect. 3.2. The asymmetry is independent of the position on the solar disc, so that we can exclude a projection effect. In 56% of the cases, concerning mostly young spots, the moats are probably influenced by the other spots, pores, and dispersed magnetic fields in the neighbourhood.

3.1. Moat areas and average velocities

Comparing moat areas A_m with areas of sunspots A_s in white light, we find that, on average, $A_\mathrm{m}/A_\mathrm{s} \simeq 1$ for young and 2 for old spots. Old spots have larger moats, probably because the convective flows around them are better developed. The correlation between moat areas observed in the 1600 Å passband and those in white light is very high, with a correlation coefficient of 0.88. This means that the size of a moat is practically independent of the height in the atmosphere.

We define the maximum moat radius $R_\mathrm{max} = \sqrt{(A_\mathrm{max} + A_\mathrm{s})/\pi}$ as an effective outer radius of a hypothetical moat with area A_max obtained by azimuthal extrapolation of the area of the best-developed moat sector to all directions. We find that in white light the relation between the maximum moat radius and the effective radius of the spot $r_\mathrm{s} = \sqrt{A_\mathrm{s}/\pi}$ is approximately linear:

$$R_\mathrm{max} = 9\farcs8 + 1.1\, r_\mathrm{s} \quad \text{for young spots,} \tag{1}$$

$$R_\mathrm{max} = 15\farcs5 + 1.1\, r_\mathrm{s} \quad \text{for old spots.} \tag{2}$$

This is illustrated in Fig. 2, where the scatter plot of measurements and the corresponding linear fits are displayed. We can

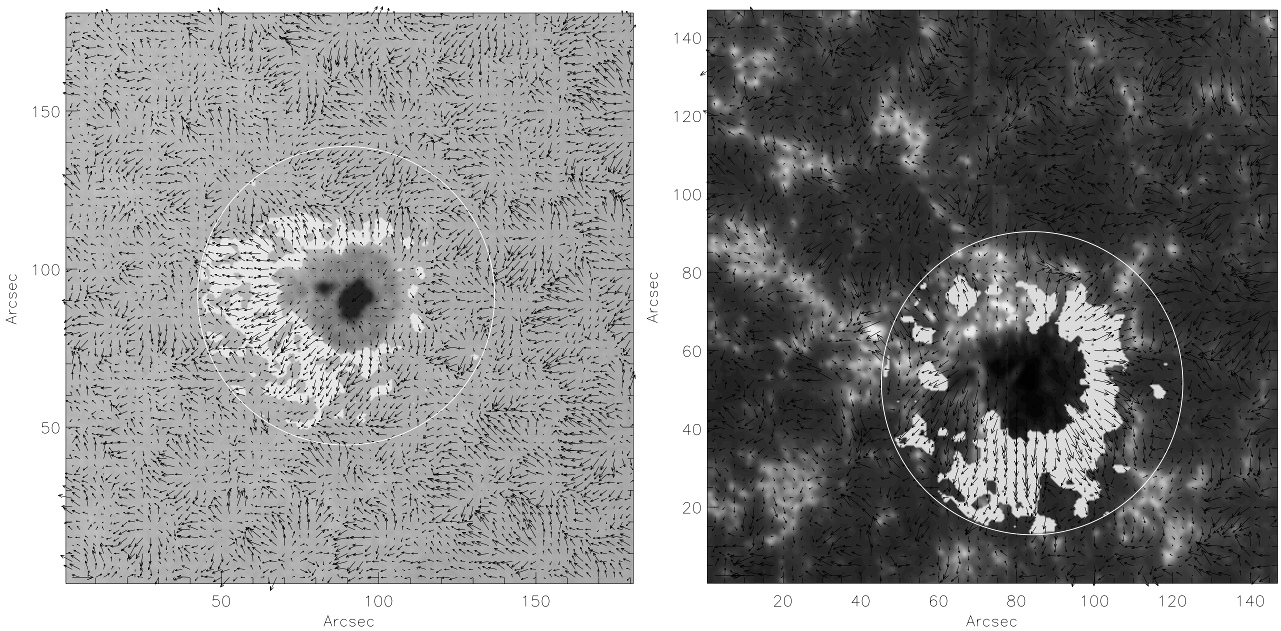

Fig. 1. Horizontal velocity maps around the old spot NOAA 9339, computed for white light (*left*) and 1600 Å (*right*). Moat regions are white. Length of the horizontal arrow in the bottom-left corner corresponds to 1 km s^{-1}. White circles indicate the regions of interest. Orientation: east is left and north top.

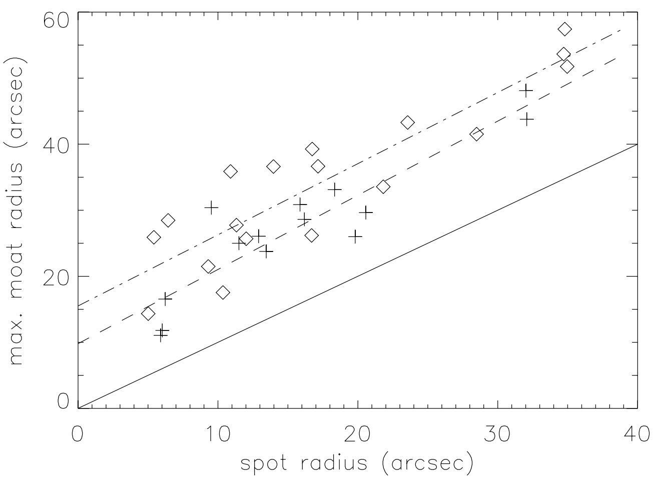

Fig. 2. Maximum moat radius (see text) versus sunspot radius. Young spots are marked by "+" and old spots by "◇". Linear fits are shown separately for young spots (dashed line) and old ones (dash-dot). The solid line corresponds to values $R_{\max} = r_{\mathrm{s}}$.

see that the maximum moat width $R_{\max} - r_{\mathrm{s}}$ does not practically change with the spot radius – linear coefficients in (1) and (2) are equal to 1.1 – but depends on the evolutionary phase: it is approximately equal to 10″ for young and 16″ for old spots. These values are comparable to the typical radius of a supergranule (14″–20″).

Horizontal velocities were measured in regions of interest (an example in Fig. 1), separately inside and outside the moats. Our results make it possible, for the first time, to compare velocities around young and old spots at two different atmospheric heights represented by the white-light and 1600 Å passbands. Average values are summarized in Table 1, together with standard deviations that characterise the dispersion of speeds around individual sunspots. We can see that, inside the moat, speeds of granules in white light are higher around old spots than around young ones. This might indicate that the sub-photospheric convective flows are slightly faster in the case of old spots. In the 1600 Å passband, speeds in the moat are generally higher than in white light. The velocity magnitudes of 400 m s^{-1} inside the moat are below the lower limit of the usual range 500–700 m s^{-1} (see Sect. 1), which can be explained by the time-averaging effect introduced by the LCT method. Velocities outside the moat are substantially lower than inside. They are more reduced in the vicinity of young spots, possibly due to a dispersed magnetic field in developing active regions.

Table 1. Average horizontal velocities [m s^{-1}].

Position	Passband	Young spots	Old spots
Inside moat	white light	380 ± 30	410 ± 30
	1600 Å	450 ± 70	450 ± 40
Outside moat	white light	200 ± 40	240 ± 40
	1600 Å	200 ± 40	210 ± 50

3.2. Moat asymmetry

Moat areas and horizontal velocities measured in different azimuths relative to the sunspot centre are not equal. To study the asymmetries quantitatively, we divided the moat region into 18 sectors of 20°, where 0° is oriented to the east and 90° to the south. The moat area and velocity were measured separately in each sector.

The azimuthal distribution of the moat area, averaged for young and old sunspots, is displayed in the left panel of Fig. 3. We find that in white light, moats are clearly asymmetrical in the east-west direction. While the eastern part of the moat region is large, the western part is very small and sometimes even missing (see the example in Fig. 1). This area's asymmetry is particularly strong for old spots with well-developed moats. The situation is different in the 1600 Å passband. Moats around young spots do

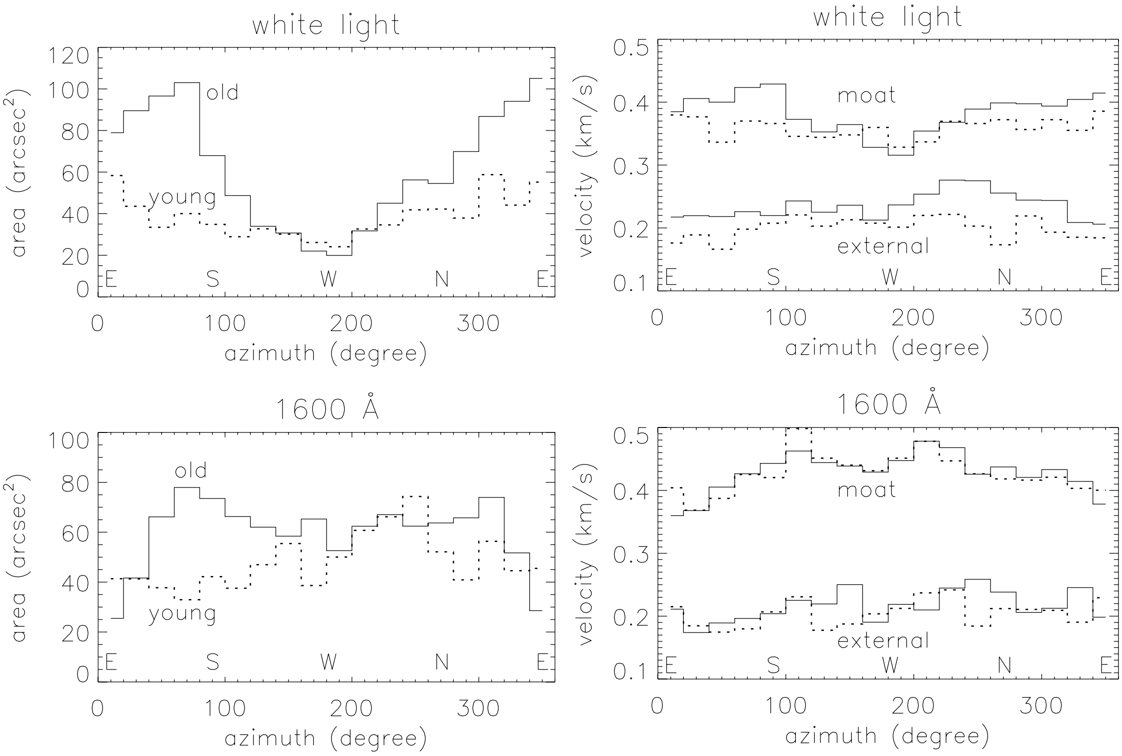

Fig. 3. *Left*: average azimuthal distribution of the moat area. *Right*: average azimuthal distribution of velocities inside moats and outside *(external)*. Solid line – old spots, dotted line – young spots.

not show the east-west asymmetry, and those around old spots have reduced eastern parts, in contrast to the white-light case.

The azimuthal distribution of velocity magnitudes, averaged for young and old sunspots, is shown in the right panel of Fig. 3. In addition to the moat velocities, "external" speeds outside moat regions are plotted for comparison. These speeds do not show any east-west asymmetry. However, we find that the moat velocities in white light are asymmetric, being higher by about 40 m s^{-1} (young spots) and 70 m s^{-1} (old spots) in the eastern sectors than in the western ones. In the 1600 Å passband, the asymmetry is reverse that in white light, with a minimum in the east and a maximum in the west, both for young and old spots. The difference between the maxima and minima is approximately 100 m s^{-1}.

We can conclude that the east-west asymmetry of velocity magnitudes is consistent with the asymmetry of areas: at low photospheric layers (white light), both areas and speeds are larger in the eastern parts of moats, while higher in the atmosphere (1600 Å), the areas are larger (at least for old spots) and horizontal motions are faster in the western parts.

From the flow maps, for each spot we can determine its proper motion (drift) with respect to the quiet photosphere. Since the reference frame of the image series is always connected to the sunspot, the proper motion is equal, with an opposite sign, to the average motion of granules in quiet areas distant from the spot. Average drift velocities from east to west are shown in Table 2, together with numbers of sunspots. Leading and following parts of spot groups are considered separately. One old following spot was excluded from the sample because of a residual error in the alignment of images. The north-south drift velocities are very close to zero. In spite of a considerable dispersion of individual velocities ($\sigma \simeq 60$ m s^{-1}), we see that young spots, both leading and following, drift to the west with a speed of approximately 100 m s^{-1}. Old leading spots drift with a similar speed, while old following spots are practically without motion. This results in a separation of leading and following parts of developed sunspot groups. These kinds of motions were derived e.g. by Gilman & Howard (1985) and van Driel-Gesztelyi & Petrovay (1990) from positional observations of sunspots.

Table 2. Average east-to-west drift velocities of sunspots with respect to quiet granulation [m s^{-1}]. Numbers of spots are in parenthesis.

Sunspots	Young	Old
Leading	110 (9)	120 (13)
Following	90 (5)	40 (4)

Let us look for a relation between the east-west asymmetry of moat areas/velocities and the proper motion of sunspots in the photosphere. We characterise the asymmetry by the normalised difference of areas $(A_{\rm e} - A_{\rm w})/(A_{\rm e} + A_{\rm w})$ integrated over 8 eastern (e) and 8 western (w) sectors of the moat or by the normalised difference in average velocities $(v_{\rm e} - v_{\rm w})/(v_{\rm e} + v_{\rm w})$ in these sectors. No correlation was found between the proper motion and the asymmetry of moat velocities. Also the moat area asymmetry observed in the 1600 Å passband is independent of the proper motion. In Fig. 4 we show a scatter plot of the moat area asymmetry of young and old sunspots in white light versus the proper motion speed. Positive values correspond to dominant eastern sectors in the moat and to proper motion directed westward. There is no relation seen in the case of young spots with less-developed moats and with a narrow range of drift velocities. However, for old sunspots we detect a weak positive correlation with a coefficient of 0.6. The east-west asymmetry of white-light moat areas around old spots tends to increase with the increasing speed of the sunspot westward drift. Therefore we suggest that there is a physical relation between the sunspot proper

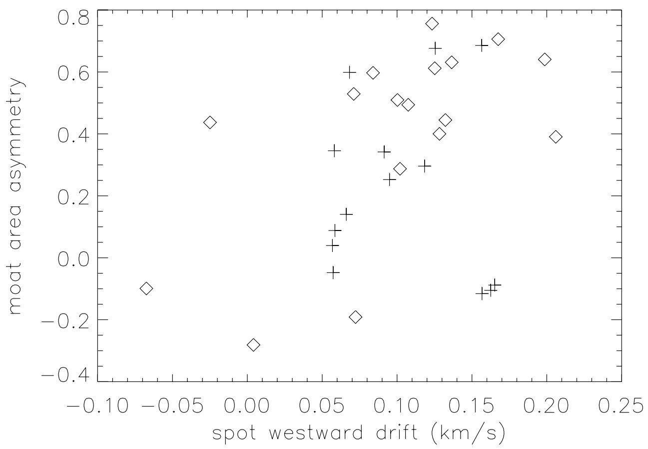

Fig. 4. Area asymmetries of moats in white light (see text) versus velocities of sunspot proper motion. Young spots are marked by "+" and old spots by "◇".

motion relative to quiet granulation and the shape of the moat at the photospheric level.

3.3. Temporal evolution of moats

In several cases, TRACE white-light observations of sunspots with sufficiently high frame cadence lasted, with some gaps, for about one day. In the available data we found 11 (6 young and 5 old) sunspots observed for periods from 8 to 17 h, typically 13 h. Within these periods, we selected 3–4 series of white-light frames for each spot, approximately 70-min long, and obtained maps of horizontal velocities of granules to study the evolution of moat areas, velocities, and asymmetries on the half-day time scale.

We characterise the temporal changes of areas and velocities by relative changes per hour: $\Delta A_\mathrm{m}/\bar{A}_\mathrm{m}$ or $\Delta v_\mathrm{m}/\bar{v}_\mathrm{m}$, where ΔA_m, Δv_m are variations in moat area and velocity per hour and $\bar{A}_\mathrm{m}$, $\bar{v}_\mathrm{m}$ are time-averaged values. The moat areas did not show any substantial changes on the half-day time scale. Eight spots (6 young and 2 old) had relative area fluctuations with amplitudes typically 0.013 h^{-1} without any clear trend. The moat area increase of 0.02 h^{-1} was found in the case of 2 old spots. One spot in the phase of final decay (the sunspot area was diminishing by 0.057 h^{-1}) decreased its moat area with a rate of 0.034 h^{-1}. Even smaller relative changes were found for velocities: the amplitudes were generally below 0.007 h^{-1}, only the decaying spot showed a decrease of 0.009 h^{-1}.

To quantitatively measure the temporal variations in the moat shape, we calculated a time correlation between moat areas in the 20° sectors that divide the moat azimuthally (see Sect. 3.2). For 4 of 5 old sunspots the correlation coefficient was above 0.7 and for 3 of 6 young spots above 0.6. In the rest of the cases, the moat shape was influenced by neighbouring spots and pores (3 young spots) or by disturbing patterns of diverging horizontal motions of granules inside the moat area (1 old spot). We can conclude that the moat shape and asymmetry do not change substantially during the half-day period.

4. Discussion and conclusions

We utilized LCT flow maps calculated from series of TRACE white-light and 1600 Å images to detect moats around 32 sunspots in different phases of evolution. The moats were defined on the basis of horizontal velocities of granules in white light and of moving magnetic features (MMFs) observed in the C IV emission, which are dominant structures seen around sunspots in 1600 Å. This way we obtained information from two different heights – the low photosphere and the transition region. In moat regions, horizontal motions away from sunspots are observed at both heights. On the other hand, the Evershed flow in the penumbra is directed outwards the umbra in the photosphere but inwards in the chromosphere and transition region (inverse Evershed flow). In this case, MMFs in the transition region move in the opposite direction to the inverse Evershed flow. This is in principle possible, because the inverse Evershed flow is concentrated in narrow channels in the superpenumbra (Maltby 1975) and MMFs may move outside of these channels.

We detect moats around both young (growing) and old (stable and decaying) sunspots. Moat areas in the white-light and 1600 Å passbands are well-correlated, so that they are practically independent of the height in the atmosphere. Old spots have larger moats with granular motions that are faster by 30 m s^{-1} than in the case of young spots. The maximum moat width in white light, defined in Sect. 3.1, depends on the evolutionary phase, but it is almost independent of the spot radius. Its value (10″ for young and 16″ for old spots) is comparable to the typical radius of supergranules. This result contradicts Brickhouse & Labonte (1988), who claimed that the moat radius scales with the spot radius by a factor of 1.8 (unlike 1.1 in this work). The discrepancy can be partially explained by the fact that Brickhouse & Labonte used various methods in addition to granular motions to measure moat radii: Doppler shifts, magnetic tracers, and facular motions, which, together with a reduced spatial resolution, can give larger moat sizes.

We find that moat regions are mostly asymmetric in the east-west direction. This asymmetry is more visible in the case of old spots, where moats are better developed. In white light, moats are elongated toward the east, while in the 1600 Å passband the eastern parts of moats are less developed. This means that the area asymmetries are opposite in the low photosphere and in the transition region. The same is valid for moat velocities. In white light, the velocities of granules are higher in the east than in the west. Horizontal velocities observed in 1600 Å have an opposite east-west asymmetry and are higher on average (450 m s^{-1}) than those measured in white light (400 m s^{-1}). We find that moats are stable in size, shape, and average velocity on a time scale of 12 h.

Proper motions of sunspots with respect to quiet granulation were measured. Young spots and old leading spots drift to the west with a speed of approximately 100 m s^{-1}, while old following spots are almost static. We find that, in the case of old sunspots, the moat area asymmetry in white light increases with increasing speed of proper motion. This fact, together with the detected east-west asymmetry in velocities, points to a possible physical relation between the proper motion and the moat properties. If we admit that the moat shape in white light, determined by granular motions, is related to sub-photospheric convective flows around the spot, we may speculate that these flows are deformed by the spot's westward motion through the convection zone, resulting in reduced width of the moat cell in the west and enhanced in the east. In the 1600 Å passband, moats are mostly defined by MMFs, connected rather with the sunspot than with the sub-photospheric convective cells in its neighbourhood. Therefore, the moat shapes and velocities observed in 1600 Å are not influenced by sub-photospheric convection. The opposite east-west asymmetry might be tentatively explained by a westward bend of magnetic flux tubes that form MMFs in the transition region.

Acknowledgements. We express our thanks to the TRACE team and to the solar database BASS 2000 for kind use of their data. We also thank N. Meunier for a useful discussion. M.S. appreciates the hospitality of the Paul Sabatier University in Toulouse. This work was supported by the grant IAA 3003404 of the Grant Agency of the Academy of Sciences of the Czech Republic (AS CR), by the Research Plan AVOZ 10030501 of AS CR, and by the European Solar Magnetism Network (contract HRPN-CT-2002-00313).

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