MOAT FLOW SYSTEM AROUND SUNSPOTS IN SHALLOW SUBSURFACE LAYERS

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ABSTRACT

We investigate the subsurface moat flow system around McIntosh H-type symmetrical sunspots and compare it to the flow system within supergranular cells. Representatives of both types of flows are constructed by means of the statistical averaging of flow maps obtained by time–distance helioseismic inversions. We find that moat flows around H-type sunspots replace supergranular flows but there are two principal differences between the two phenomena: the moat flow is asymmetrical, probably due to the proper motion of sunspots with respect to the local frame of rest, while the flow in the supergranular cell is highly symmetrical. Furthermore, the whole moat is a downflow region, while the supergranule contains the upflow in the center, which turns into the downflow at about 60% of the cell radius from its center. We estimate that the mass downflow rate in the moat region is at least two times larger than the mass circulation rate within the supergranular cell.

Key words: convection – Sun: helioseismology – sunspots

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1. FLOWS AROUND SUNSPOTS

Sunspots are probably the most intensively studied topic of solar physics. The strong magnetic field, which is responsible for the appearance of sunspots and their evolution, significantly affects the pattern of convection and plasma flows in the upper layers of the solar convection zone. Sunspots mainly suppress an upward propagation of the heated plasma in their cores (umbrae) and harbor strong radial outflows in their penumbrae, usually termed the Evershed flow (Evershed 1909). The umbra is in principle stationary. Deep in its photosphere, localized small–scale (150 km) upflows of 0.6–1.4 km s\(^{-1}\) are observed inside most umbral dots, and downflows of 0.4–1.9 km s\(^{-1}\) are observed at some of their edges (Ortiz et al. 2010). The penumbra at the photospheric level is dominated by the horizontal Evershed flow with a magnitude of 2–5 km s\(^{-1}\). Vertical upflows of about 1 km s\(^{-1}\) are observed in the inner penumbra and downflows of 0.5–1 km s\(^{-1}\) in the outer penumbra. At the sunspot border, the downflows may reach 5 km s\(^{-1}\). All of these flows appear in strongly localized patches, including the well-known filamentary structure of the Evershed flow, and change with time. On azimuthal average, the flow is essentially horizontal with a small upward component (200–300 m s\(^{-1}\)) in the inner and a small downward component (400 m s\(^{-1}\)) in the outer penumbra (Franz 2011).

Even though not directly seen, penumbrae of evolved sunspots are usually surrounded by an additional outflow region, that is, a moat (Sheeley 1969). This intriguing region around sunspots seems to be present mostly around evolved and decaying spots and plays a role in transporting flux away from the spot, hence contributing to its decay. Harvey & Harvey (1973) showed that the magnetic elements carried by the moat flow have both polarities; however, the net flux appears to have the same sign as the parent spot. The total flux transported from the spot seems to correspond to the decayed magnetic flux of the spot.

The amplitude of the moat flow is usually about 500 m s\(^{-1}\). The moat seems to be present only on the side of the spots where the penumbra exists (Vargas Domínguez et al. 2008). Deng et al. (2007), however, reported a case of a moat flow persisting after the penumbra decayed. The width of the moat-flow region depends only weakly on the size of the parent spot (Sobotka & Roudier 2007). The latter authors analyzed the motions of photospheric granules in the vicinity of sunspots and found a significant asymmetry of the moats. Their areas are deformed in the east-west direction in such a way that the western part is narrower and the eastern one is broader than the average moat width. Also, flow velocities are asymmetric: lower by 10% in the western part than in the eastern one. Sobotka & Roudier (2007) explained this asymmetry by an interaction of the moat outflow with the measured westward motion of sunspots (about 100 m s\(^{-1}\)) in the local frame of rest. As the sunspot flux tube moves through the convection zone, the subsurface flows around it are deformed due to a gas viscosity, similar to the wake behind a sailing ship. There also seem to exist single cases of sunspots where the moat flow is purely symmetric (Balasas & Muglach 2010). The connection between the Evershed flow and the moat flow was studied by several authors with varying results. The modern studies (such as Löhner-Böttcher & Schlichenmaier 2013) seem to slightly prefer a physical origin of the moat flow to be distinct from the origin of the Evershed flow.

Attempts to explain the observed properties of the moat flow were seen in the literature shortly after the discovery, when the observers pointed to the resemblance of the moat flow and supergranular flows. Supergranulation is a mid-scale convection-like velocity pattern with cells having a typical size of ~30 Mm and a lifetime of around one day (e.g., Hirzberger et al. 2008; Roudier et al. 2014) covering all the solar surface. Indeed, the predominantly horizontal outflow velocity field within supergranules with a peak flow of around 500 m s\(^{-1}\) is reminiscent of the outflow in the moat. Studies showed that the moat flow was usually faster than an average supergranular flow and moats also lived longer (for several days) than the ordinary supergranules. Therefore, it was Meyer et al. (1974) who first suggested that the moat flow was essentially a supergranular flow with a sunspot in the middle of the cell.

The flow system around sunspots was also a target for modelers. The two-dimensional simulations by Hurlburt & Rucklidge (2000) showed a model where the flux tube responsible for the
confinement of the sunspot umbra is first surrounded by an inflow region, which in the case of an evolved sunspot is hidden below the penumbra, and hence not seen by surface observations. Further away, a large outflow region appears, observable as the moat flow in the surface layers. The moat-like flow is also present in state-of-the-art simulations, such as those of Rempel et al. (2009a, 2009b) and Rempel (2011), where outflows dominate the flow structure at all depths.

The moat flow as a distinct flow structure could not go unnoticed by helioseismologists. Gizon et al. (2000) used an iterative deconvolution of the surface gravity \( f \) mode travel times and found that the properties of the moat flow averaged over the depth of \( \sim 1 \) Mm are similar to those observed at the surface. Subsequent flow inversions around a cylindrically symmetric sunspot NOAA 9787 (Gizon et al. 2009) showed that the outflow from the spot is present to depths of at least 4.5 Mm and becomes stronger with depth. Featherstone et al. (2011) only confirmed these conclusions by saying that the outflow region extends to depths of at least 10 Mm, but also suggested that the outflow region had two components: a surface moat flow and a deeper part reaching the peak at a depth of around 5 Mm.

Therefore, it would seem that the structure and origin of the moat flow around sunspots is well understood. However, there is one piece of the puzzle missing: even though the moat flow is generally considered to be mostly horizontal, it certainly must have some vertical component. Supergranular flows are also mostly horizontal, and yet there is an important weak (but measurable) vertical component with an upflow of around 4 m s\(^{-1}\) (Duvall & Birch 2010) in the center of the cell and a downflow in the network lanes. The vertical component of the moat flow is poorly addressed by observations. Löhner-Böttcher & Schlütermaier (2013) concluded that the vertical components of both the Evershed and surface moat flows are small and that they cannot even address the sign of the vertical component. Due to the lack of observational evidence, the vertical component of the flow around sunspots is one of the targets of our study. It seems that currently only state-of-the-art time–distance helioseismology is able to provide firm estimates of the weak vertical flows in the upper solar convection zone.

2. LINEAR INVERSIONS FOR TIME–DISTANCE HELIOSEISMOLOGY IN A NUTSHELL

The investigated flows are measured using a time–distance helioseismology (Duvall et al. 1993). This method comprises a set of tools used to measure and analyze the travel times of solar waves traveling through the solar convection envelope. The propagation of the waves is affected by the perturbed plasma parameters, which act as scatterers to the wave field. An important scatterer leaving a large imprint in the difference travel times (the difference of the measured travel time of waves traveling in opposite directions) is plasma streaming, which we want to study.

The standard time–distance helioseismic pipeline consists of the following consecutive steps. First, the spatio-temporal datacube is prepared using the tracking and mapping pipeline. This datacube is spatio-temporally filtered to retain only waves of interest, and subsequently the travel times are measured from cross-correlations of the filtered signal at two places. These travel times are finally inverted for flows assuming a linear relation between the flow vector and the measured travel time.

In this study, we only analyze the difference travel times measured using the surface gravity \( f \) mode of solar oscillations, utilizing the center-to-annulus and center-to-quadrant geometries (Duvall et al. 1997) with radii of the annuli from 5 to 20 pixels in steps of 1 pixel and with a pixel size of 1.46 Mm (henceforth “travel times”). The travel times are fitted from the measured cross-correlation using the Gizon & Birch (2004) linearized approach, the wave sensitivity kernels are computed using the Born approximation (Birch & Gizon 2007), consistent with the travel-time measurements, and the travel-time noise covariance matrix is measured by fitting from a large set of travel-time maps (Gizon & Birch 2004).

The inversion is performed utilizing the Multichannel Optically Localised Averaging approach (MC-SOLA; Jackiewicz et al. 2012) using a code validated using synthetic data (Śvanda et al. 2011). The vector flow inversion, differing only slightly, was used by Śvanda et al. (2013), where the whole time–distance pipeline was validated against the direct surface-flow measurement from granule tracking. Our flow estimates are thus representative of the near sub-surface flow at depths of 0–3 Mm, with random-noise levels of 30 m s\(^{-1}\) for the horizontal components and 4 m s\(^{-1}\) for the vertical components assuming travel-time averaging over 24 hr. The effective resolution of the flow map is set by the horizontal extent of the averaging kernel (Figure 1), which is also returned from the inversion. The horizontal full width at half-maximum of the averaging kernel is 10 Mm. From Figure 1, one immediately notes two facts: the horizontal shape of the averaging kernel for the horizontal flow component is slightly elliptical, while for the vertical component it is perfectly round, and the cross-talk contributions are negligible.

We would like to stress that we are not comparing the inferences about the moat flow obtained by methods utilizing direct surface measurements with our time–distance results. That is because the time–distance inferences represent the real solar flow smoothed by the averaging kernel. This effect usually smears out any details in the flow, which exist on scales smaller than the appropriate extent of the averaging kernel. For the same reason, our time–distance inferences do not represent the surface plasma flow, but an average over the depth of 0–3 Mm where the gravity center of the averaging kernel lies at a depth of 1.0 Mm. One has to keep that in mind when discussing the time–distance inferences in the context of other works and studies that speak about purely surface inferences.

3. ENSEMBLE AVERAGING

We processed 38 months of high-cadence (one frame each 45 s) full-disk Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) Dopplergrams covering the period from 2010 May 1 to 2013 June 30. On each day, we tracked the central-meridian region and mapped it using Postel projection with a pixel size of 1.46 Mm utilizing a standard tracking tool. The tracking and mapping resulted in a large set of datacubes that were filtered to retain only the signal of the \( f \) mode and inverted for all three components of the flow independently. For each day, we obtained one map for the vector flows in the central-meridian region, roughly between \( \pm 70^\circ \) in latitude and \( \pm 30^\circ \) in longitude from the disk center.

The magnetic field acts as an additional scatterer to the seismic waves, generally leading to a reduction of an acoustic
power in the magnetized regions (e.g., Braun & Lindsey 1999). To mitigate this problem, we normalized the measured cross-correlation at each point by its maximum value (similarly to Couvidat et al. 2012). This approach allows us to correct for wave absorption in regions occupied by a weak dispersed magnetic field. Such an approach does not improve the situation in the regions of strong field where the physics of the interaction of waves with the magnetic field is also not known well. Therefore, we do not consider the inferred flow in sunspots to be trustworthy (for discussion see Gizon et al. 2009) and do not discuss these regions further.

Due to the large noise level, we chose not to study individual representatives of moats around sunspots and compare them to individual supergranular cells; instead, we proceed using a statistical approach by forming the average representatives of both features using the ensemble averaging approach.

3.1. Sunspots

In order to simplify our analysis, we chose to investigate the moat flows only around axially symmetrical type-H sunspots (McIntosh 1990). Furthermore, we put the following constraints on the spots belonging to the sample: the spot must be isolated with no other spot within a distance of 10 heliographic degrees, at the time of observation the spot should not be located farther than 20 heliographic degrees from the central meridian, and its latitudinal distance from the disk center should be less than 30°. The selection was done by hand in the first step, closely cooperating with NASA’s www.solarmonitor.org; the accurate positions were then fine-tuned automatically from HMI intensitygrams by finding the gravity centers of the sunspots.

Altogether, we identified 104 spots fulfilling these constraints. The sizes of the spots in the sample vary; the mean distance from the spot’s center to the outer penumbral boundary determined from corresponding HMI intensitygrams is 9.9 ± 3.6 Mm. To account for the different sizes of sunspots in the ensemble, we normalized the inverted flow maps so that the outer penumbral boundary coincided for all spots. This normalization was achieved by the interpolation of the flow maps onto a new coordinate grid where a small correction was added or subtracted to the radial coordinate so that the outer penumbral boundary lay at a distance of 10 Mm from the gravity center of each spot.

Figure 1. Time–distance inversion averaging kernels. The upper set of panels represents the display of the kernel of the horizontal components of the flow ($v_x$ in this case), while the lower set of panels is for the vertical flow component. The solid white line contours 50% of the kernel maximum.
indicates the average location of neighboring supergranules. The largest arrow indicates a horizontal flow of 400 m s$^{-1}$.

Such a transformation conserves the distances in the radial direction but slightly distorts the distances in the tangential direction. It was shown by Sobotka & Roudier (2007) that the width of the moat depends only weakly on the size of the parental spot, and given its average width (around 10 Mm) the distortions caused by our normalization are negligible. The transformed maps of flows were averaged about the positions of the gravity centers of the respective HMI intensity images. When assuming that each sunspot flow map contains an independent realization of the random noise component, the estimate for the error levels in each point is then 2.9 m s$^{-1}$ for the horizontal and 0.4 m s$^{-1}$ for the vertical component. These values are fully consistent with root-mean-square values of the quiet-Sun portions of the averaged flow map.

### 3.2. Supergranules

As a control set, we constructed a flow map of an average quiet-Sun supergranule. As a proxy for the identification of supergranules, we used center-to-annulus travel-time maps for distances of 5–7 pixels (7–10 Mm), which were sensitive to a weak vertical flow and also to a divergence of the horizontal flow. Hence, the supergranules were identified by searching the map for compact regions of large positive divergence (hence the negative travel time) surrounded by a region of negative divergence (hence positive travel time). The segmentation of individual supergranular cells was performed using a watershed algorithm (Beucher & Meyer 1992).

In a continuous space, the watershed algorithm recognizes individual basins belonging to regional minima $m_i$ of the function $f(x)$ as sets of points having coordinates $x \in \mathbb{R}^2$ fulfilling the condition

$$f(m_i) + T_f(m_i, x) < f(m_j) + T_f(m_j, x)$$  \hspace{1cm} (1)

for all regional minima $m_j$, $j \neq i$, where $T_f(p, q)$ is the topographic distance of points $p$ and $q$, defined as

$$T_f(p, q) = \inf_{\gamma} \int_{\gamma} |f(\gamma(s))| ds,$$  \hspace{1cm} (2)

where $\gamma(s)$ is a parametric curve connecting points $p$ and $q$. In the case of supergranules, the function $f$ is the travel-time value at coordinate $x$. In our case, we only consider local minima with travel-time value less than zero, thus excluding minima which are very unlikely to be a supergranular center. By implementing this algorithm for a discrete set of points in the travel-time map, we were able to assign a set of points to each selected regional minima (all minima with a positive plasma outflow).

The large number of travel-time maps allowed us to uniquely identify 222,976 supergranular cells. All three-component flow maps obtained by the inversion were averaged about these supergranular cells. Again, assuming the independence of the random noise realization, the random error levels are practically negligible (formally less than a few cm s$^{-1}$).

### 4. COMPARISON OF FLOW PATTERNS

From our comparison of statistically significant samples, it turned out that the moat flows around symmetric H-type spots and the outflows within the supergranular cells are similar (see Figure 2). There are, however, two principal differences.

1. While the outflow region within the average supergranular cell is very symmetric about the center of the cell (that claim is true even when a lesser number of supergranules, comparable to the number of sunspots used here, is averaged), the moat outflow region displays a clear asymmetry in the east-west direction (Figure 3). Such an asymmetry was already found by Sobotka & Roudier (2007)—see Section 1. They compared average areas of 20° wide sectors of moats around well-developed spots. The sector directed to the east had an area larger by a factor of four to five than that directed to the west. Our data are consistent with this finding: the moat outflow extends from the penumbral boundary by 16 Mm to the east, which is about twice the extent of 7 Mm to the west (Figure 4). According to Sobotka & Roudier (2007), the moat outflow is distorted, due to a viscosity of the gas, by the proper motion of sunspots to the west. The mass conservation in both the distorted radial outflow and a nearly symmetrical downflow is kept due to the asymmetry in the tangential component of the flow. The radial outflow is redirected (by the sunspot’s proper motion) around the spot, first to the north and south and then eastward. This is seen in both the radial and tangential components of the flow (for illustration, see Figure 5). A slight asymmetry is also seen in the vertical component of the moat flow, however, it is not as pronounced as in the case...
Figure 3. Comparison of the flow components around an average H-type sunspot (two concentric black circles) and an average supergranule for reference. Maps of (a) radial, (b) tangential, and (c) vertical flow components around an average H-type spot and corresponding maps of (d) radial, (e) tangential, and (f) vertical flow components in the average supergranule show a clear distortion of the horizontal moat outflow due to the westward proper motion of the sunspot with respect to the local frame of rest (a). The moat shows up clearly as a downflow region (c). The tangential component is positive in the counter-clockwise direction. The sector-like structure of the tangential component of the horizontal flow in the average supergranule (e) is an artifact caused by the slightly elliptical shape of the inversion averaging kernel in the horizontal domain.

(A color version of this figure is available in the online journal.)

Figure 4. Polar-coordinates plots of Figures 3(a)–(c) to show better the asymmetry of the horizontal components of the moat outflow. Contrary to the radial and tangential (positive = counter-clockwise) components, the vertical component does not show any remarkable asymmetry, except a slightly enhanced downflow to the south and to the north of the spot. The shaded region indicates the strong-field regime where the time–distance inferences are not trustworthy.

(A color version of this figure is available in the online journal.)

of the radial and tangential components of the horizontal flow. Note that all the discussed figures are plotted in the local frame of rest, in which the sunspot drifts westwards and the visualization of the flow field differs from the natural comoving frame. Unfortunately, it is not possible to easily transform between the two frames, as the drifting speed is unknown and cannot be determined reliably because the only observable that characterizes the environment at the studied depth is the flow field. A very rough estimate can be made by decomposing the flow field into the symmetrical and non-symmetrical parts, where the non-symmetrical part at the sunspot location represents the drifting speed. Using such a procedure, we estimate the drifting speed to be 120 m s$^{-1}$. Even though such a number is in excellent agreement with the drifting speed for the old, large sunspots found by Sobotka & Roudier (2007), we do not consider our determination to be very reliable given the assumptions made.

2. Azimuthally averaged radial profiles of the horizontal and vertical velocity components (Figure 6) and a cartoon displaying a simplified model of the velocity vectors in the moat and the neighboring supergranule (Figure 7) show that within the supergranular cell, there is an upflow near its center which turns into a downflow around 60% cell radius from the cell center. The moat is a pure downflow region with slight asymmetry, extending from the penumbral boundary by about 12 Mm where it is adjacent to downflows at the borders of neighboring supergranules. The maximum azimuthally averaged downflow speed in the moat is 1.5 m s$^{-1}$, larger by a factor of 1.3 than that at the supergranular border. The out- and downflow in the moat region should be compensated by an upflow in the region of the sunspot, which is not detectable by the present helioseismic methods and may serve as a possible mechanism enhancing the moat downflow.

The average distance of the surrounding supergranules from the spot center is 40 Mm, which is only slightly larger than the average distance between centers of neighboring supergranular cells (38 Mm; see Figure 2). This would favor the hypothesis
that an isolated medium-sized symmetrical sunspot and the flow system around it (the moat flow) act, on average, as a larger supergranular cell (Bumba 1965). Formation of the moat flow replacing the ordinary supergranular flow was also described in some of the early models of sunspot formation (e.g., Piddington 1976a, 1976b).

### 4.1. Mass Flow Rates

We estimated the mass flow rates within the average supergranular cell and within the moat region of the average H-type spot. We evaluated the radial cumulative mass flow rate:

$$\dot{m}(R) = \int_R^\infty dR \rho v_z,$$

where $\rho$ is the density estimated as an average of the model-S density (Christensen-Dalsgaard et al. 1996) weighted by the inversion averaging kernel, $v_z$ the vertical velocity component, and $R$ is the radial coordinate. We assume the density to be constant in the horizontal domain.

In the case of the average supergranule, $\dot{m}(R)$ reaches its maximum of $\sim 5 \times 10^5$ kg s$^{-1}$ at a distance of $\sim 12$ Mm from the cell center and then vanishes at a distance of 19 Mm, which corresponds to the supergranule boundary. From this point of view, the continuity equation holds within the supergranular cell under the assumptions. Such a result may also be interpreted differently: the plasma density within the supergranular cell does not vary much in the horizontal domain.

In the case of an average H-type sunspot, when ignoring the strong-field regions and neglecting the east-west asymmetry,
we obtain a total cumulative mass flow rate of $\dot{m}(R) \sim -10 \times 10^5 \text{kg s}^{-1}$. Since we ignored both the sunspot umbra and penumbra, this number must be considered as a lower limit. Hence, in the shallow sub-surface around the H-type sunspot, at least twice as much mass sinks than in the average supergranular cell. This downflow must be compensated by an upflow somewhere in the magnetized region of the sunspot. The structure and amplitude of such an upflow cannot be determined using the present helioseismic techniques. When assuming that a homogeneous upflow takes the shape of an annulus with a width of 500 km and a radius of 5 Mm, approximately under the boundary of the umbra, then the lower limit of such a homogeneous upflow would be 20 m s$^{-1}$. Without knowing the real structure of the flow under the umbra, we cannot do much more at this stage.

5. CONCLUDING REMARKS

Compared to surface velocity observations, the speeds obtained by helioseismic methods are usually small. Our maximum horizontal velocity of the moat outflow, 400 m s$^{-1}$, is nearly identical to the result of Sobotka & Roudier (2007). However, the magnitude of the Evershed flow is larger by an order and vertical velocities observed on the solar surface in and around penumbrae are larger by two to three orders than the subsurface downflow in the moat. (1) Current helioseismic methods are restricted to non-magnetic and weak-field regions, so that we miss the information from the penumbra. (2) All extremely fast flows on the surface, including the Evershed flow, are localized to small areas and vary in time so that they are smoothed by spatial and temporal averaging in helioseismic measurements.

The subsurface moat flow surrounding a symmetric H-type sunspot, obtained as an average of 104 sunspots, in principle, is very similar to the flow system in an average supergranule (222,976 cells averaged). The average size of a moat region is comparable to the average size of supergranules, so that the moat flows around H-type sunspots seem to replace ordinary supergranule downflows. However, the flows in the moat are asymmetrical. We expect that the westward proper motion of sunspots with respect to the local frame of rest distorts the horizontal outflow in the moat and redirects it partially back around the sunspot. This confirms the asymmetry in the horizontal motions of granules detected previously by Sobotka & Roudier (2007).

Thanks to the improved formulation of the MC-SOLA time–distance inversion, we were able for the first time to study properly the vertical velocity component, in which moats differ from supergranules. The whole moat is a downflow region with a flow amplitude (1.5 m s$^{-1}$) that is larger than the downflows at the edges of supergranules, measured in our reference sample. Our conservative estimate shows that the mass emerging in the considered part of the moat is twice the mass circulating in the near-surface layers of the average supergranule. Hence, at least the same amount of mass must emerge near the sunspot flux tube. It should be possible to compare our measurements with the state-of-the-art numerical models of sunspots.

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