# DYNAMICS OF MOTIONS IN THE QUIET PHOTOSPHERE

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## ABSTRACT

We determine the vector velocity fields describing the plasma motions in the quiet solar photosphere, using the motions of the supergranular structures, obtained by the analysis of series of Doppler measurements of velocity fields of the whole solar disk. It turned out that the studied vector velocity fields can be submerged under the noise level, originating due to the strong variability of the supergranular structures during their life time.

We describe the method we used for the suppressing of such noise, and we bring the criterions used by the election of free parameters. We demonstrate examples of obtained vector velocity fields and of the resulting motions of matter on the visible photospheric surface. We discuss different factors influencing the reproductivness of obtained results. We construct a graph of the dependence of the differential rotation on the heliographic latitude from the mean vector velocity field, we got for the solar disk without expressive magnetic fields.

## 1. INTRODUCTION

Many challenging questions can be met in the field of solar physics: The differential rotation and its origin. Why do the equatorial parts of the Sun rotate faster that the planets orbit around and why the rotation of the polar regions is slowed down? How fast do sunspots move with respect to the surrounding photosphere, how do they move inside active regions and how the active regions move with respect to the surrounding quiet photosphere? What is the influence of such motions to solar activity and what is the origin of the regular changes of polarity of solar magnetic field? These questions have been asked for many times and many answers have been already suggested. Nevertheless, do these answers reflect the reality correctly?

Many papers (see Sect. 6 for references) present coefficients that describe the solar differential rotation. The scatter of their values is large, depending on the type of tracers and on other known or unknown factors. We assume that the photospheric velocity field stands behind many of such influences and, for this reason, we would like to investigate in more detail the dynamics of this velocity field.

## 2. METHODS OF VELOCITY MEASUREMENTS

Two types of motions can be observed in the solar photosphere: Motions of photospheric objects (sunspots, pores, and granulation) derived from the displacements or motions of plasma measured, for example, as Doppler shifts of spectral lines.

Taking into account the small thickness of the photospheric layer (about 1"), one has to deal mostly with horizontal motions of objects on the solar surface. In case of non-horizontal motion the observed object would leave the photosphere, i.e., it would disappear, what is not observed.

Doppler measurements of photospheric motions are very sensitive and include both vertical and horizontal components of the velocity vector, i.e., such velocity field is not purely horizontal.

For the studies of photospheric velocity fields, both types of velocity measurements are used. For example, displacements of objects (sunspots, filaments, magnetic fields) as well as Doppler measurements of plasma motions were utilized to determine the solar differential rotation [1] (see Table 1 and Fig. 3).

A common feature of all these measurements is a considerable scatter of the results. This is caused by differing methods, specific characteristics of tracked objects (for example: Proper motions of sunspots in active regions; evolutionary changes of the topology of magnetic fields; unknown transversal component of velocity in Doppler measurements), and by the intrinsic character of the differential rotation that, as we assume, is a result of integration of a complex structure of motions in all directions.

Among the suitable objects moving at the level of the solar photosphere (like sunspots and granulation) also rank supergranular structures, well seen in Doppler velocity maps.

In case that we assume that supergranular structures drift together with the moving photospheric plasma, these structures may serve as a tracer of plasma motions in the photosphere and subphotospheric layers till the bottom of supergranular cells.

Taking into account that the density of plasma changes with height in the photosphere nearly by factor of $10^{-3}$

[2], the photosphere behaves in many aspects similarly to the surface of a liquid. We expect therefore, that the motions should, in a high degree, resemble flows on a spherical surface.

## 3. VELOCITY FIELD DETERMINATION

The suggested method is used to measure the velocity field of plasma flowing in a narrow layer of the solar photosphere.

The method is based on the tracking of structures of the supergranular network. From the drifts of the structures, a velocity field is computed. The supergranular network is spread on the whole solar surface, so that it makes it possible to characterize non-magnetic and magnetic regions as well, including active regions and sunspots that interact with this network.

The images of supergranular network are obtained from Doppler velocity maps, from which the velocity components of the Carrington rotation and of five-minute oscillations are removed. The lifetime of individual supergranular cells [3] is long enough to allow tracking of their motions during several tens of hours, so that we can expect that the resulting velocity field is determined with a fairly high reliability.

## 4. THE DATA

We utilize for our work full-disk Doppler measurements in the spectral line Ni I 676.8 nm, obtained with the MDI instrument onboard SOHO. The temporal resolution of the raw measurements is 1 minute and the image size is 1024 x 1024 pixels. Three uninterrupted time series of dopplergrams are available to us: 1996: May 24 – July 24, 1997: April 14 – July 13, and 1998: January 9 – April 10. In the present work we use the observations taken on May 26, 1996, when the Sun was completely quiet and no strong magnetic fields were present on the disk.

## 5. DATA REDUCTION

### 5.1 Temporal filtration of raw dopplergrams

The one-minute cadence of the raw dopplergrams made it possible to apply a suitable filtration in order to decrease the number of frames and to remove high spatial frequencies including the manifestations of five-minute oscillations. We used the method of weighted averaging [4, 5] to filter the data. To obtain one reduced frame, a sequence of 31 raw dopplergrams was used. The weight of an individual raw dopplergram depends on its position in the sequence (see [4] for details). This filter suppresses the amplitude of the five-minute oscillations by factor of about 500. The effect of this filter is by an order stronger compared to the case of a simple averaging over a period of 60 minutes [4].

Small displacements of supergranular structures in the raw dopplergrams caused by the solar rotation in the intervals 1 – 31 minutes were compensated by means of a reverse rotation of the Carrington coordinate system.

To meet the condition for the correct sampling of the signal, the reduced frames obtained by the integration of 31 raw frames (in the period of 31 minutes) are calculated and stored each 15 minutes. That means that 96 reduced full-disk frames describe the 24-hour evolution of the Doppler velocity field.

### 5.2 Correction for solar rotation

The Doppler velocity pattern of supergranulation is contaminated by the line-of sight component of solar rotation. This component can be approximated by a projection $V_c$ of the Carrington's rotational velocity vector to the direction toward the observer. According to [6]:

$$V_c = -V_0 \sin\alpha \cos\delta \cos B_0 , \qquad (1)$$

where α is the heliographic longitude of the observed point, measured from the central meridian, δ is the heliographic latitude of the point, $B_0$ the inclination of the solar axis, and $V_0$ =1,8557 km/s is the rotational speed on the perimeter, derived from the synodic period of rotation of the Carrington's coordinate system. Subtracting $V_c$ from the reduced dopplergrams, we obtain a clearly visible supergranular structure on the solar disk.

## 6. CALCULATION OF THE VELOCITY FIELD

The field of horizontal velocities is obtained by applying the Local Correlation Tracking (LCT) technique [7] to the series of all reduced dopplergrams, after making the corrections mentioned in Sect. 5. The algorithm correlates locally (with a window of 17 x 17 pixels) the structures in the processed and reference images and computes, with sub-pixel accuracy, vectors of displacements in all points of the processed frame.

The processed frame may not necessarily follow the reference frame immediately but it can have an optional time lag after it. Increasing the lag, we obtain larger geometrical shifts of supergranular structures and, consequently, an improvement of the signal-to noise ratio in the resulting displacement map. This time lag we call a correlation interval *KI*. For two subsequent frames, *KI* = 1 and the time lag is 15 minutes.

Our analysis of the reproducibility of obtained velocity fields shows that, in our case, for small *KI* (*KI* < 3) the sensitivity of the method is low and the searched velocity fields are below the noise level. On the other hand, large *KI* (*KI* >5) leads to instabilities in the tracking due to mismatched structures in the processed and reference frames. We use *KI* = 4 for the present analysis.

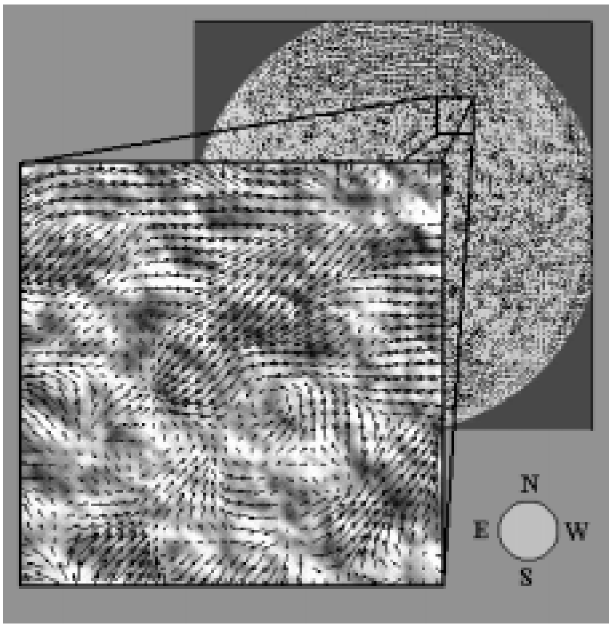

*Fig.1: Local horizontal velocity field in the solar photosphere. The underlying image in the enlarged subfield shows the dopplergram of supergranular network.*

The calculated vector velocity field in the thin layer of the solar photosphere, that is, the velocity vectors tangential to the solar surface, is displayed in Fig.1. This local velocity field reflects the motions of morphological structures on the solar disk, including the motions inside supergranules. The field shown in Fig.1, however, is too fine to see global velocity structures that, among others, characterize the differential rotation.

The global velocity field can be obtained by filtering spatially the data of Fig.1 using a boxcar of 40 x 40 pixels. After the filtration (Fig.2), the velocity vectors are ordered in a form of large cells that are well consistent with the conception of the solar differential rotation.

The velocity field shown in Fig.2 describes the difference between the Carrington's rotational speed of the rigid body and the real rotational speed of the solar plasma. We can see that the solar rotation, compared to the equatorial one, is slower in high heliographic latitudes. In latitudes of about 18 degrees, both speeds are approximately equal (the difference is zero) and in the equatorial zone the plasma rotates faster.

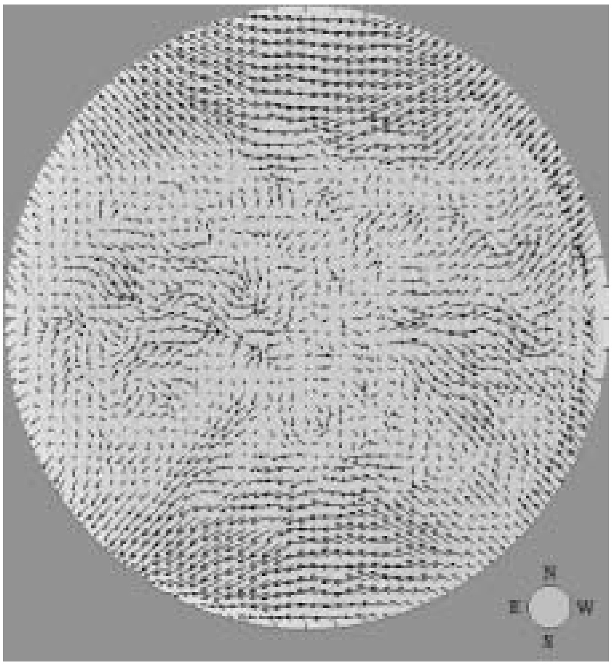

*Fig.2: Global velocity field obtained as a spatial filtration of the full-disk velocity field shown in Fig.1.*

Table 1 summarizes the values of coefficients *A, B, C* of the sidereal differential rotation. Its angular velocity ω is given by:

$$\omega = A + B\sin^2\delta + C\sin^4\delta \qquad (2)$$

In Fig.3 we plot various curves of the differential rotation calculated according to Table 1. Our result [OR] was obtained by zonal averaging of velocities over the solar disk. The differences between the values of the averages and the curve that fit them indicate that the differential rotation is a result of a summation of many different runs of velocity versus latitude. In fact, the differential rotation is a simplified global description of a complex system of zonal and meridional flows [8].

Tab.1: Sidereal differential rotation [degree/day]

| Author | A | B | C | Remark |
|---|---|---|---|---|
| [9] | 14,440 | -1,98 | -1,98 | plasma rotation |
| [10] | 14,192 | -1,70 | -2,36 | |
| [11] | 14,049 | -1,69 | -2,35 | |
| [OR] | 14,485 | -3,11 | 1,32 | |
| [12] | 14,368 | -2,69 | 0 | single sunspots |
| [13] | 14,393 | -2,95 | 0 | |
| [13] | 14,552 | -2,84 | 0 | all sunspots |
| [14] | 14,551 | -2,87 | 0 | |
| [15] | 14,09 | -0,37 | 0 | $Ca^+K_3$ regions |
| [C] | 14,184 | 0 | 0 | Carrington |

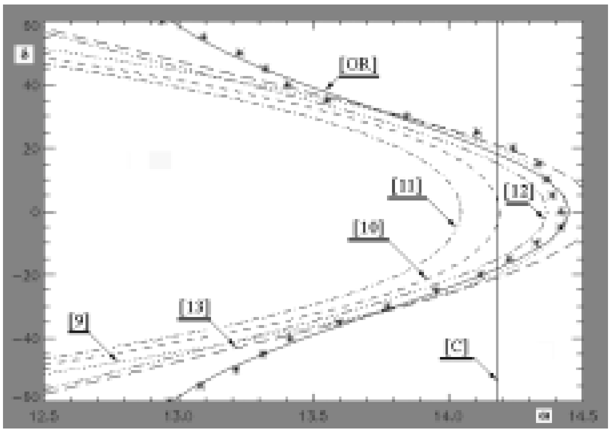

*Fig.3: Curves of differential rotation according to Tab.1. Asterisks and solid line – present work.*

## 7. REPRESENTATION BY STREAMLINES

The visualization of plasma motions by means of velocity vectors is not always readable enough. The motions can also be represented by streamlines that show the trajectories of particles carried by the calculated velocity field.

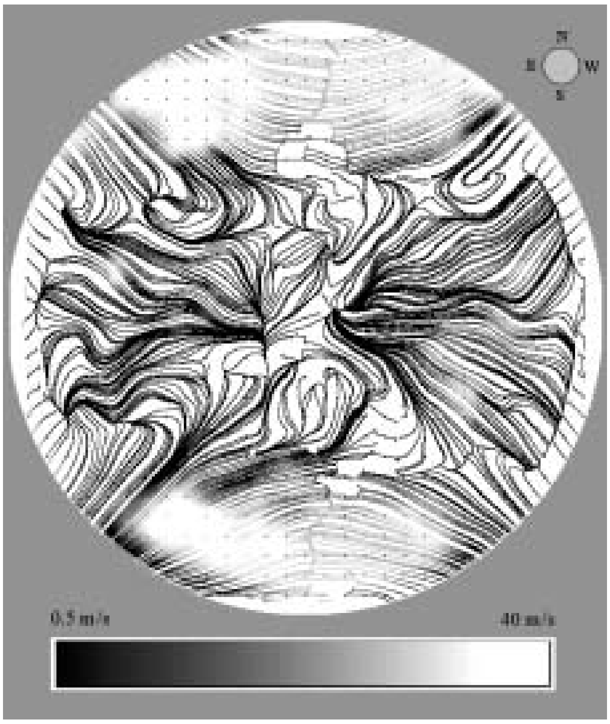

*Fig.4: Streamlines showing the directions of plasma motions in the velocity field displayed in Fig.2. The gray scale represents different velocity magnitudes.*

In Fig.4 we can see the directions and speeds of plasma flows in the photosphere, as derived from the motions of supergranular structures. From the point of view of hydrodynamics, there is an interesting segmentation of structures formed by the streamlines, which characterize the spatial distribution of velocities in the moving plasma. We suppose that these structures indicate different physical conditions in the subphotospheric plasma.

## 8. CONCLUSIONS

A research method to study plasma motions in a thin layer of the solar photosphere has been elaborated, based on the SOHO/MDI data. The plasma motion is derived from the displacements of supergranular structures, which cover the whole solar surface in quiet photosphere as well as in weak magnetic and active regions. This way, plasma motions can be studied in nearly all parts of the solar disk.

Using the described method, we have determined the solar differential rotation on May 26, 1996, and approximated it by a curve. We have confirmed that the real rotational curve is determined by local zonal flows, which differ substantially from the idealized parabolic shape of the differential-rotation curve.

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