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Large-scale Flow and Transport of Magnetic Flux in the Solar Convection Zone

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Abstract. Horizontal large-scale velocity field describes horizontal displacement of the photospheric magnetic flux in zonal and meridian directions. The flow systems of solar plasma, constructed according to the velocity field, create the large-scale cellular-like patterns with up-flow in the center and the down-flow on the boundaries. Distribution of the large-scale horizontal eddies (with characteristic scale length from 350 to 490 Mm) was found in the broad equatorial zone, limited by 60° latitude circles on both hemispheres. The zonal averages of the zonal and meridian velocities, and the total horizontal velocity for each Carrington rotation during the activity cycles no. 21 and 22 varies during the 11-yr activity cycle. Plot of RMS values of total horizontal velocity is shifted about 1·6 years before the similarly shaped variation of the magnetic flux.

Key words. Sun—large-scale flow—cyclic variations.

The large-scale flows, characterizing the intermediate scale between the small-scale and solar rotation are expected from the theoretical considerations, but still the knowledge of such flows is very meagre. The main problem of large-scale velocity field measurements consists in the low velocity values of the order from 50 to 100 ms^{-1},blended by at least one order higher values of small-scale flows and also by the velocities of solar oscillations and rotation.

Movement of the large-scale magnetic flux is a well known characteristic of the magnetic field evolution in solar photosphere. In the past Wilcox & Howard (1970), Snodgrass (1983), Stenflo (1989) and Latuschko (1996) used the distribution of the background magnetic flux as “tracer” for measurements of horizontal velocity. The lifetime of large-scale magnetic phenomena is much longer than one Carrington Rotation Period (CRP, 27.275 days). We used CRP as the elementary time step of our data and the analysis was carried out during a time interval covering two 11-yr cycles of solar activity.

Surface distribution of magnetic flux is considered as a continuous scalar field. Displacements in zonal and meridional directions are measured by the local correlation technique (November 1986). The horizontal velocity field is inferred relative to the Carrington reference system in 2701 homogeneously distributed points in the photosphere from differences of pairs of the consecutive synoptic charts (Ambrož 2000). The large-scale velocity field is a continuously varying quantity in both orthogonal directions and in time. The velocity field structure differs during the whole period of activity cycle from the axially symmetric zonal velocity. It is significantly heterogeneous for different points in the photosphere. The solar equator defines a dominant plane for the north-south symmetry of the vector structures.

Semiempirical simulation of the horizontal flow in the photosphere is made by the "cork" procedure. The free testing particles, driven by inferred horizontal velocity are displaced in the solar photosphere during the time. The particle trajectories illustrate the streamlines of stationary flow. The flow structure, integrated between two consecutive Carrington rotations is the simplest picture of the large-scale flow in the solar photosphere. The nearly zonal flow was indicated in the circumpolar regions, polewards from 60° parallels on both hemispheres. Equatorwards from such limits large-scale eddies are observed (Ambrož 1987). The frequency of occurrence and the vorticity is temporally variable. Dominant vortices rotate on the northern hemisphere in the counterclockwise sense and their rotation on the southern hemisphere is opposite. The vorticity structure is much more developed during the period of maxima of the solar activity cycle. The flow structure changes slowly during a few CRPs and a temporal evolution of eddies was observed. The short-lived eddies (during one CRP) are frequent. The great, well developed eddies have a few phases of formation. The initial phase covers formation of eddy or integration of two or more small eddies respectively. The main phase is characterized by formation of one great eddy. During the decaying phase, one can observe the fragmentation of the main eddy into smaller vorticity phenomena. Finally, in the last step, the whole phenomenon disappears. Such a process is realized during 3 to 6 CRPs. On the synoptic chart during one CRP we usually see only one eddy, but also observed were five main eddies in different stages of their evolution.

The study of flow structure shows the discrete character of the flow systems. The free "cork" testing particles are initially homogeneously distributed in solar photosphere. After time interval of one or more CRPs, the testing particles are redistributed due to the inhomogeneous velocity structure. The cellular-like phenomena are formed with a characteristic dimension of about 40° in longitude. They contain positive and negative values, distributed into large-scale regions. The positive and negative regions form large-scale patterns, covering the whole photosphere. The structure of such divergence patterns contains the non-axially symmetric component. The accumulation of testing particles correlates well with the negative horizontal divergence regions.

According to the assumption about the 3D divergence-free flow of the incomepressible medium, the positive regions may indicate the large-scale up-flow, whereas the negative regions correspond with the down-flowing plasma. The character of the empirically simulated flow evokes an image of large-scale flow phenomena with a possible relationship with the large-scale convection in the deep layers of solar convection zone. The structure of convection cell is characterized by possible up-flow in the central part and by down-flow on the peripheries with more or less horizontal eddy flow between the vertical flow regions.

The horizontal divergence chart, calculated from the inferred velocity field, is projected on the sphere and shown in Fig. 1. The white regions in the left column contain the positive divergence values, the negative horizontal divergence relates with the dark regions. Both regions create the separate and cellular-like patterns on the solar surface with mean characteristic dimension about 420 ± 70 Mm. The shape and the position of the cellular patterns vary in time.

Figure 1. Composition of the horizontal divergence map derived from displacement of the magnetic flux distribution during one CRP (left), the streamlines during two CRP (center) and the end points of the "cork" trajectories after three CRP (right) when nearly "immediate" stationary velocity field was used for simulation of the transport during sufficiently long time. The velocities are inferred for the time interval from CR 1866 to CR 1867 in the year 1993. The ends of streamlines correlate well with black (negative) areas in the left picture. The white regions show the positive values of the horizontal divergence. The shadow areas relate with horizontal divergence free regions with nearly parallel streamlines.

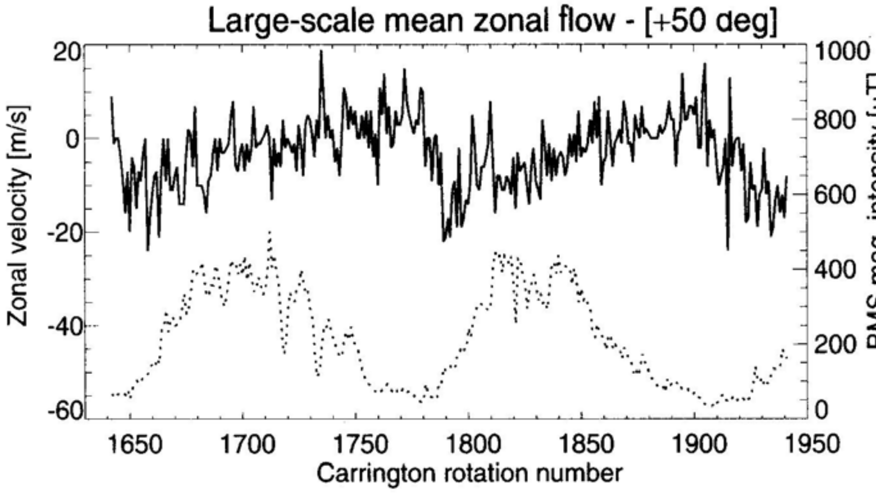

Figure 2. Plot of the time dependent mean zonal velocity (full line and scale on the left). The plot drawn by dotted line corresponds with the mean absolute value of the magnetic flux, corresponding with the scale on the right (for details see in text).

The mean horizontal velocities in Fig. 2 were calculated from each synoptic chart in the latitude belt from 50°N to 50°S for all longitudes. The investigated time interval covers the period of two cycles of solar activity, starting from CR1642 to CR1943. On the plot is zonal velocity compared with absolute value of magnetic flux. Both curves anti-correlate and the time lag of minimum-maximum is about 22 CRPs. The RMS horizontal velocity values were also correlated with magnetic flux. The RMS zonal velocity maximum is in the increasing part of the 11-yr solar activity cycle. The velocity curve is also shifted 21 CRPs (about 1.6 years) before the curve of the magnetic field. The cross correlation coefficients in extremes are -0.47 and 0.34, respectively.

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