Determinaton of the Velocity Vector Field in an Asymmetric Sunspot Based on Vector Magnetograph Measurements

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Abstract. A new method to determine the distribution of the full velocity vector in an asymmetric sunspot is presented. Measurements of the Doppler velocity and of the vector of the magnetic field are used as initial data for these calculations. The determination is subdivided into two stages: in a first step we obtain the distribution of the velocity projection onto the solar surface, and in the second step the orthogonal component of the velocity field is calculated. The resulting vector velocity field is in good agreement with the basic features of the siphon flow model of penumbral flux tubes.

1. Introduction

In order to understand the underlying physics of most phenomena observed in the solar atmosphere it is necessary to know the spatial distribution and development of the vectors of both the magnetic and velocity fields. For the magnetic field it is possible in principle to determine the full vector from photoelectric spectro-polarimetric measurements in Zeeman-sensitive lines – see, e.g., Staude et al. (1991) and Hofmann (1991). But for velocities only the line-of-sight component can be obtained directly from Doppler shift measurements.

The motions in the plane perpendicular to the line-of-sight can be estimated from the shifts of photospheric details, but these motions seem to be connected rather with the subphotospheric flows, so it is hard to use them together with the Doppler measurements for deriving the full velocity vector. A velocity field comparable to the relative motions of sunspots can also be determined from a time sequence of magnetograms (Levine & Nakagawa 1974). For a symmetric sunspot the full velocity vector can be estimated from the Doppler measurements alone (Klvaňa & Bumba 1996).
In the present paper the full velocity vector in an asymmetric sunspot is determined by a new method based on the measurement of the Doppler velocity and of the vector of the magnetic field. More detailed information on this subject can be found in a paper by Krivtsov et al. (1998).

2. Observations

Observations of the active region NOAA 6716 during the period July 06–12, 1991 were considered. Doppler velocities and magnetic field vectors were measured at the Einstein turnm Solar Observatory in Potsdam. Measurements in the spectral line Fe I 524.76 nm were used to obtain Doppler velocities and in the line Fe I 525.02 nm to derive the magnetic field vector. The corrected Stokes vectors were transformed into magnetic field vectors by means of the theoretical calibration functions of Staude (1970a, b; Staude et al. 1991).

3. The method of determining the horizontal velocity

Let the horizontal plane be the plane of the solar surface and the vertical direction be the direction orthogonal to the solar surface (the radial direction). To find out the velocity vector field the following assumptions will be used

1. The line-of-sight component of the velocity vector is given by the measured Doppler velocity.

2. The vertical component of the velocity vector is small compared to the horizontal component.

3. The horizontal component of the velocity vector is parallel to horizontal component of the magnetic field vector.

Assumption 2 is a widely accepted observational fact (see Maltby 1964, Schröter 1965, Title et al. 1993, Shine et al. 1994). Assumption 3 is suggested by observations showing that the Evershed flows are concentrated in the horizontal dark filaments with a nearly horizontal magnetic field; the inclined magnetic field in the white filaments is not correlated with the Evershed velocities (Title et al. 1993, Rimmele 1995a, Balthasar 1996).

Using the Assumptions 1–3 the horizontal component of the velocity vector can be calculated as

\[ \mathbf{v}_h = \lambda \mathbf{B}_h, \quad \lambda \overset{def}{=} \frac{v_e}{B_e - B_z \cos \vartheta}. \]  

(1)

Here \( \mathbf{v}_h, \mathbf{B}_h \) are the horizontal components of the velocity and magnetic field vectors, respectively; \( v_e \) is the known value of the Doppler (line-of-sight) velocity; \( B_e \) and \( B_z \) are the line-of-sight and the vertical projections of the magnetic field vector, respectively, and \( \vartheta \) is the angle between the line-of-sight and the vertical direction. Thus, in Eq.(1) the desired horizontal velocity vector is expressed in terms of the measured quantities.
4. Computation of the horizontal velocity distribution in the sunspot

Let us consider the measurement from July 8 as an example of the horizontal velocity computation. Figs. 1a, 1b, 1c show maps of the brightness, the Doppler velocity, and the magnetic field vector, respectively. The black (white) color on Fig. 1b corresponds to velocities from (toward) the observer. The map of the longitudinal projection of the horizontal magnetic field (the denominator of the coefficient \( \lambda \), Eq.(1)) is shown in Fig. 1d. In order to determine the velocity it is necessary to calculate the ratio of the Doppler velocity field (Fig. 1b) and the magnetic field (Fig. 1d). There are some problems in the vicinity of the line where the both quantities are close to zero — we have a ratio of two small parameters in this area. To avoid such errors a median filter \( 3 \times 3 \) has been applied to the field of the coefficients \( \lambda \). The result of the computation with the corrected \( \lambda \) coefficients is shown in Fig. 1e. The background shows the original Doppler velocities, and the arrows show the resulting horizontal velocities.

5. The method of determining the vertical velocity

The method described in Sect. 3 allows us to obtain the horizontal projection of velocity vector only. To find out the vertical velocity the equation of mass conservation assuming a steady state is used. We obtain

\[
\nu_z = -\frac{1}{C} \nabla_h \cdot \nu_h, \quad C \overset{\text{def}}{=} \frac{1}{\nu_z} \frac{\partial \nu_z}{\partial z} + \frac{\partial}{\partial z} \ln \rho
\]  

(2)

Here \( \nu_z \) is the vertical velocity; \( \nabla_h \) is the horizontal component of the \( \nabla \) operator; \( z \) is the coordinate along the vertical axis; \( \rho \) is the density. The scalar coefficient \( C \) can approximately be assumed to be a function only of the vertical coordinate \( z \); then it has a constant value for the whole map. Thus, with the use of Eq.(2) the distribution of the vertical velocity from the known distribution of the horizontal velocity can be found.

6. Computation of the vertical velocity distribution in the sunspot

The result of the vertical velocity computation is shown in Fig. 1f. The background shows the distribution of the vertical velocity, and the arrows show the distribution the horizontal velocity. From the map it follows that the vertical velocity is practically zero in the umbra, upflows are mainly localized at the umbral boundary, and downflows appear at the outer parts of the penumbra.

7. Comparison with measurements from the Ondřejov Observatory

At the Ondřejov Observatory (Czech Republic) Doppler velocities were measured in the Fe I 525.347 nm spectral line for the same active region; our aim was to look for possibilities to use Doppler measurements from the Ondřejov Observatory together with magnetic field measurements from the Einsteinturm Observatory to compute the whole velocity vector distribution in the active region. The point of minimum brightness in the averaged brightness maps was
used as the origin of the coordinate system for the maps measured in different observatories. The computations show that the use of Doppler velocity and magnetic field measurements from different observatories can give good results; the flows observed in the spectral lines Fe I 525.347 nm and Fe I 524.76 nm look very similar.

8. Discussion

We have presented a method of determining the distribution of the full velocity vector in an asymmetric sunspot. For the computation of the horizontal velocities the vertical velocities were neglected in a first step. However, after determination of the horizontal velocity field the method allows us to compute the small vertical components of the velocity. The resulting velocity vector field is in good agreement with the basic features of the siphon flow model of Montesinos & Thomas (1997). Our investigation has demonstrated that Doppler velocity data and vector magnetic field data needed for the vector velocity computations can be taken from different observatories. It would be highly desirable to repeat this analysis with data of much better spatial resolution, obtained, for example, at the vacuum solar telescopes at Tenerife.

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References

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Fig. 1. Computation of the vector velocity distribution in a sunspot. NOAA5716, 8 July 91.