THE TOTAL PHOTOSPHERIC MOTION FIELD

E. A. GURTOVENKO

The Main Astronomical Observatory of the Ukrainian Academy of Sciences, Kiev, U.S.S.R.

(Received 1 February; in revised form 11 August, 1975)

Abstract. Brief consideration is given to the conception of the total photospheric motion field. A synthesis of the most thorough investigations is made and the radial ($V^{\text{rad}}$) and tangential ($V^{\text{tg}}$) components of the velocity amplitude of the total photospheric motion field are deduced. At depth $\log T_\Sigma = -3.0$ $V^{\text{rad}}$ and $V^{\text{tg}}$ have average values of 1.2 and 1.7 km s$^{-1}$ respectively. They increase smoothly with depth and reach their maximum values of $V^{\text{rad}} = 3.0$, $V^{\text{tg}} = 3.4$ km s$^{-1}$ at depths $\log T_\Sigma = -0.2$ and $\log T_\Sigma = +0.4$ respectively. In the deep photospheric layers both components seem to decrease with depth.

1. Introduction

Many problems in the physical analysis of the solar photosphere are closely related to the study of Fraunhofer lines whose profiles depend considerably on the photospheric motion field.

There are a vast number of investigations devoted to the study of the photospheric motion field. Various observational data and various methods have been used in these investigations. Besides, many authors approached the problem from different points of view. Therefore the results obtained so far appear to be highly heterogeneous.

Nevertheless, when analysing these results one can be confident about the following conclusions: (i) the velocity amplitude of the photospheric motion field has an average value of 2–3 km s$^{-1}$; (ii) the photospheric motion field occurs to be anisotropic: the tangential component exceeds the radial component; (iii) an overwhelming majority of recent results point to an increase of both components with depth; (iv) the large-scale (macroturbulent) and small-scale (microturbulent) components are not distinguished reliably. The microturbulent velocity deduced by the curve-of-growth method as well as found from direct studies of the equivalent widths of line profiles ranges from 0.5 to 2.0 km s$^{-1}$. The determined macroturbulent velocity component (convection and waves) is even more uncertain. The convective (granule) velocities, derived indirectly by various methods, can be assumed equal to 2–3 km s$^{-1}$ on the average. But most recent direct observations with high spatial resolution (See e.g. Canfield and Mehlertretter, 1973) point to essentially lower values for those velocities. The oscillatory velocity values range between the limits of 0.2–1.0 km s$^{-1}$.

Some confusion and vagueness in the terminology should also be noted. Actually the term ‘turbulence’ refers to the whole spatial spectrum of the photospheric motion field. The notions ‘microturbulence’ and ‘macro-turbulence’ are also not always properly used. For example, some authors denote by ‘microturbulence’ the data related to both components of the photospheric motion field, being unaware of the conception of the total photospheric motion field.

Solar Physics 45 (1975) 25–33. All Rights Reserved
Copyright © 1975 by D. Reidel Publishing Company, Dordrecht-Holland

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
It should be mentioned that the notions micro- and macro-turbulence are not generally simple. The limits of the characteristic lengths which determine these notions are different for the core and wings of each line, for weak and strong lines of the same atom, as well as generally for the lines of various elements.

It is also clear that in the real situation a range of spatial wavenumbers exists, whose characteristic lengths $L$ approximately obey the relation $\propto L \approx 1$, where $\propto$ denotes the total absorption coefficient. We propose to denote the motion field in this range of spatial wave-numbers by the term 'mesoturbulence'. The primary role of mesoturbulence in the solar photosphere was substantiated by de Jager (1959; 1972). We also refer to Shine and Oster (1973), who suggest that at least part of the microturbulence should be identified with the macroturbulent motions of acoustic and/or shock waves. Moreover Auvergne et al. (1973), in their attempt to bridge the gap between the usual micro- and macro-turbulent approximations, show that the non-thermal Doppler broadening of Fraunhofer lines can also be computed exactly, when the scale of turbulence is finite, i.e. neither strictly micro- nor macro-turbulence.

The above considerations point to the necessity of determining the characteristics of the total photospheric motion field. The general solution of this task has not yet been achieved. But the task can be solved approximately. In particular, the classical notions of micro- and macro-turbulence help a great deal. Actually these notions divide all ranges of spatial $K$-numbers ($0<K<\infty$) into two parts; and one can treat the average velocity amplitudes $V_{\text{mic}}, V_{\text{mac}}$ and velocity distribution functions $\varphi_{\text{mic}}, \varphi_{\text{mac}}$ for these two parts of the total photospheric motion field. Let us assume that $\varphi_{\text{mic}}$ and $\varphi_{\text{mac}}$ are gaussians. The gaussian (or nearly gaussian) distribution of macro-turbulent velocities were justified by Evans and Michard (1962), Edmonds (1967), and Cha and White (1973). In all previous investigations it was implicitly assumed that the distribution function of the microturbulent velocities is gaussian. But it is, known however, that this assumption may not be correct (de Jager, 1974). Moreover the recent results by Rutten et al. (1974) show that the velocity distribution of the total photospheric motion field is not purely gaussian, i.e. a part of that field must have non-gaussian velocity distribution. Thus, the assumption above appears to be an approximation which is probably fairly close to the real situation. Under that assumption the velocity amplitude $V$ of the total photospheric motion field can be expressed by a simple formula

$$V^2 = V_{\text{mic}}^2 + V_{\text{mac}}^2. \tag{1}$$

Moreover the velocity amplitude can be deduced unambiguously from observations of weak Fraunhofer lines (Kondrashova and Gurtovenko, 1974). We refer also to the example of an unfavourable non-gaussian distribution which had been considered by Olson (1966). In his study the macroturbulence was represented by a two-stream convective model. Nevertheless even in this case the macroturbulence imitates the micro-turbulence with velocities which are equal to the stream velocities of the convective model. Thus one can conclude that the notions micro- and macro-turbulence almost lose their sense in respect to weak Fraunhofer lines; and the total velocity amplitude
remains the only characteristic of the photospheric motion field which can be deduced from the profiles of those lines. (Second-order effects of the line asymmetry seem difficult to treat).

2. The Determination of the Velocity Amplitude of the Total Photospheric Motion Field

Below we give a brief synthesis of the most thorough, and mainly recent, investigations which can show the dependence of the total velocity amplitude on depth as well as on direction in the solar photosphere.

(1) Schmalberger (1963) derived by trial and error the total velocity amplitude, using nine weak lines of Fe I, Fe II, Ni I and Ti I. The unpublished photospheric model by Swihart and Fishel was used in the calculations. Schmalberger’s results have been confirmed later by Mutschlecnner (1965).

(2) Holweger (1967) analysed the velocity amplitude by investigating central intensities of many Fraunhofer lines of various elements. In his calculations he used the photospheric model deduced by him in the same study. The final results on the velocity field were deduced by studying Fe I, Ti I, Si I and Cr I lines which turned out to be almost uninfluenced by hyperfine and isotopic effects. The radial and tangential components of the velocity field obtained were represented by Holweger (not quite correctly) as microturbulence. The author himself asserts that his microturbulent velocities are overestimated, and adopted macroturbulent velocities of $V_{\text{rad}}^\text{mac} = 0.2$ km s$^{-1}$, $V_{\text{mg}}^\text{mac} = 0.3$ km s$^{-1}$ which seem underestimated. In addition we comment on the following papers. Canfield (1969) in his study shows, that center-to-limb profiles of weak Ce II lines are explained well, when the Holweger’s microturbulence model is used in the computations. On the other hand, Falchi (1970) in her study of equivalent widths of nine metal lines, as well as Garz et al. (1969) in their study of the abundance through the equivalent widths of Fe I lines, both came to the conclusion that for the best fit between observations and calculations, Holweger’s velocity amplitude should be reduced by 0.7 km s$^{-1}$. The above consideration justifies the conclusion that Holweger’s data actually represent the total velocity amplitude.

(3) Mallia (1968) studied the profiles of weak CH, C$_2$, MgH, O I, Sc II and Si I Fraunhofer lines by trial and error. In his calculations he used the three-stream photospheric model by Elste. The stream velocities in that model are equal to 2.5–3.0 km s$^{-1}$ at the depth $\log \tau_5 = 0.2$. They decrease smoothly with height and are equal to zero at $\log \tau_5 = -1.0$. Using these convective velocities and observations at the centre of the disk, Mallia found a ‘best-fit’ radial velocity amplitude. The best-fit tangential component of the velocity field was found by using the deduced radial velocities and the observations near the limb.

Actually all Mallia’s results, except the radial component at the depth $\log \tau_5 > -1.0$, represent the velocity amplitude of the total motion field. At depths $\log \tau_5 > -1.0$ the radial component of the total amplitude can be calculated by Formula 1 where $V_{\text{mac}}$ should be taken as equal to the adopted stream velocities at the relevant depths.
(4) Gonci and Roddier (1971) studied by trial and error the precise center-to-limb observations of \( \lambda 4607 \) \text{Sr I} line. The BCA photospheric model was used in the computations.

The results obtained should in principle represent the velocity amplitude of the total photospheric motion field. In order to explain the observed line asymmetry the authors assumed stream velocities of \(-0.2 \) km s\(^{-1}\) and \(+0.7 \) km s\(^{-1}\). These stream velocities are not likely to represent the real convective macroturbulent velocities.

(5) Kondrashova and Gurtovenko (1974) studied the profiles of 20 weak and moderately weak Fraunhofer lines. They derived the total velocity amplitude by trial and error. They used the BCA photospheric model in their calculations.

(6) Gurtovenko analysed about 80 weak Fraunhofer lines which are not influenced by hyperfine and isotopic effects and are formed at various depths in the photosphere (1975a). He computed the average depths of formation of all lines. For the computed optical depths the line profiles were analysed, accounting for the damping effect. As a result the Doppler half-widths were obtained for each line. Finally the total velocity amplitudes, derived from the Doppler half-widths, were plotted against the relevant optical depths. The HSRA photospheric model was used in the study.

(7) Gurtovenko (1975b) studied the profiles of 27 weak \text{Fe I}, \text{Ti I} and \text{Ni I} lines that are not influenced by hyperfine and isotopic effects. The best-fit total velocity amplitude was derived by trial and error for every observed line and for various positions on the solar disk. The HSRA photospheric model was used in the calculations.

(8) Withbroe (1967) derived the microturbulent velocity amplitude by studying the equivalent widths of a number of \text{CH} lines observed at various positions on the solar disk. By using the obtained microturbulent velocities, he analysed the profile of the \( \lambda 4248.944 \) line and found the best-fit macroturbulent velocities. Elste's model 10 was used in the study.

(9) Lites made a combined analysis of 18 strong \text{Fe I} lines (1973). Among other results were the best-fit micro- and macroturbulent velocity amplitudes within a large range of photospheric and cromospheric depths. The calculations were based on the HSRA model.

The results listed above are shown in Figures 1 and 2. Mallia's radial component for the depths \( \log \tau_5 < -1.0 \) was taken from his Table VIII. That component was calculated at depths \( \log \tau_5 > -1.0 \) with \( (V^2)^{\text{rad}} = \zeta^{2\text{rad}} + V^{2\text{conv}} \), where \( \zeta^{\text{rad}} \) and \( V^{\text{conv}} \) denote respectively the radial component from Table VIII, and the adopted convective velocities. In the range of depths \(-1.0 < \log \tau_5 < 0.2\), the latter increased smoothly with depth, from 0 to 3 km s\(^{-1}\).

Holweger's results are given according to his Table II. His macroturbulent velocities \( V^{\text{mac}}_{\text{rad}} = 0.2 \) km s\(^{-1}\), \( V^{\text{mac}}_{\text{rad}} = 0.3 \) km s\(^{-1}\)) were not taken into account, as they do not appreciably change the main results.

From Gonci and Roddier's study we have used the data presented in their Figure 6. The moduli of their stream velocities have been averaged \( V_{\text{aver}} = 0.5 \) km s\(^{-1}\). Both components of the total velocity amplitude \( V \) were calculated with \( V^2 = \zeta^2 + V^2_{\text{aver}} \), where \( \zeta \) denotes their turbulent velocities in the streams, and \( V_{\text{aver}} = \text{const} = 0.5 \) km s\(^{-1}\).
s⁻¹. Gonzi and Roddier's results do not change appreciably if one neglects their stream velocities $V_{\text{aver}}$.

From Withbroe's and Lites' results we took their micro- and macroturbulent velocities. Both components of the total velocity amplitude were calculated by our Formula 1. The other data are shown in their original form.

Fig. 1. The radial component of the total velocity field according to results from various authors: 1 - Schmalberger, 2 - Holweger, 3 - Mallia, 4 - Gonzi and Roddier, 5 - Kondrashova and Gurtovenko, 6 - Gurtovenko (1975a), 7 - Gurtovenko (1975b), 8 - Withbroe, 9 - Lites (see references).

Fig. 2. The tangential component of the total velocity field. The labels are the same as in Figure 1.
3. Discussion

Figures 1 and 2 show that the results of various authors are in fairly good agreement. That agreement happens to be best in the middle part of the considered range of optical depths. This is not an unexpected result, because exactly the middle part of that range appears to be the average depth of formation of the weak (mainly metal) lines which have been used by the various authors in their investigations. The sensitivity of the line profiles to the motion field decreases considerably beyond the depth of line formations. That is why the differences between the various data increase essentially towards both ends of the considered range of optical depths.

We believe that the differences between the various results in Figures 1 and 2 are mainly due to different observational data as well as to the different methods used by various authors. The use of various photospheric models influences the results also; but in our opinion that influence seems to be secondary in character.

The results of Figures 1 and 2 can apparently be considered as a set of measurements which are influenced by accidental errors. In order to average these measurements one must attach the proper mathematical weight to each measurement. This is a difficult task indeed. We do not believe that one can even do it properly. But we have at least tried to determine these weights not entirely arbitrarily.

The essential advantages of Holweger’s study consist in the large amount of observational data used, and in the thorough analysis of his data. In the study by Gurvenko (1975b) only weak Fraunhofer lines, that are not influenced by hyperfine and isotopic effects, have been used. Moreover, these lines were observed with a double pass spectrometer. We attached to Holweger’s and Gurvenko’s (1975b) results the weight 3.

In Schmalberger’s investigations only nine lines have been used. In the paper by Kondrashova and Gurvenko not only weak but also some moderate lines were studied. The original investigation by Gurvenko (1975a) seems to be fairly reliable but the results are given only in a small range of optical depths. A weight 2 was attached to these three investigations.

In Mialia’s study the convective macroturbulent velocities had been adopted before the analysis of the line profiles was performed. Despite Gonczi and Roggier’s precise observations of the 4607 Sr i line, their results may be somewhat incorrect because the line itself is moderately strong, and its possible hyperfine and isotopic structure was not discussed. In Withbroe’s investigations the dependence of the velocity amplitude upon depth was not studied properly. Furthermore, his results were given in a small range of optical depths. The observations and the analysis of the Fe i lines by Lites appear to be very reliable. But the velocity amplitude in the photosphere could not be obtained reliably, because the weak Fraunhofer lines were not analysed in his study. The author himself regards his turbulence model, in the layers below the temperature minimum, as a preliminary one. In our review of the above considerations, the weights of the last four results were put equal to unity.

With the adopted weights the plots in Figures 1 and 2 were averaged by standard
methods. The averaging was performed over steps $\Delta \log \tau_5 = 0.25$ and within the depth range $-3.0 < \log \tau_5 < +0.5$. The results are given in Table I and Figure 3. In Figure 3 the smoothed curves of $V^{tg}$ and $V^{rad}$ are drawn also.

It appears that besides the well known increase of both components with depth, the maxima of $V^{rad}$ at $\log \tau_5 \approx +0.3$, and $V^{tg}$ at $\log \tau_5 \approx -0.2$ are fairly certain. A tendency of the radial component to increase with height at the depth $\log \tau_5 = -3.0$

<table>
<thead>
<tr>
<th>$\log \tau_5$</th>
<th>$V^{rad}$ (km s$^{-1}$)</th>
<th>rms error</th>
<th>$V^{tg}$ (km s$^{-1}$)</th>
<th>rms error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-3.00$</td>
<td>1.18</td>
<td>$0.24$</td>
<td>1.69</td>
<td>$0.20$</td>
</tr>
<tr>
<td>$-2.75$</td>
<td>1.20</td>
<td>0.23</td>
<td>1.80</td>
<td>0.19</td>
</tr>
<tr>
<td>$-2.50$</td>
<td>1.24</td>
<td>0.20</td>
<td>1.91</td>
<td>0.15</td>
</tr>
<tr>
<td>$-2.25$</td>
<td>1.31</td>
<td>0.17</td>
<td>2.03</td>
<td>0.15</td>
</tr>
<tr>
<td>$-2.0$</td>
<td>1.41</td>
<td>0.15</td>
<td>2.16</td>
<td>0.16</td>
</tr>
<tr>
<td>$-1.75$</td>
<td>1.52</td>
<td>0.11</td>
<td>2.34</td>
<td>0.16</td>
</tr>
<tr>
<td>$-1.50$</td>
<td>1.63</td>
<td>0.10</td>
<td>2.65</td>
<td>0.11</td>
</tr>
<tr>
<td>$-1.25$</td>
<td>1.74</td>
<td>0.10</td>
<td>2.88</td>
<td>0.14</td>
</tr>
<tr>
<td>$-1.00$</td>
<td>1.86</td>
<td>0.13</td>
<td>3.04</td>
<td>0.15</td>
</tr>
<tr>
<td>$-0.75$</td>
<td>2.01</td>
<td>0.16</td>
<td>3.18</td>
<td>0.16</td>
</tr>
<tr>
<td>$-0.50$</td>
<td>2.24</td>
<td>0.17</td>
<td>3.30</td>
<td>0.17</td>
</tr>
<tr>
<td>$-0.25$</td>
<td>2.54</td>
<td>0.16</td>
<td>3.43</td>
<td>0.17</td>
</tr>
<tr>
<td>0</td>
<td>2.88</td>
<td>0.20</td>
<td>3.50</td>
<td>0.22</td>
</tr>
<tr>
<td>$+0.25$</td>
<td>3.02</td>
<td>0.21</td>
<td>3.16</td>
<td>0.32</td>
</tr>
<tr>
<td>$+0.50$</td>
<td>2.97</td>
<td>0.25</td>
<td>2.80</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Fig. 3. The radial and tangential components of the total photospheric motion field, deduced by averaging of the data in Figures 1 and 2. The vertical bars denote the double rms errors.
seems also apparent. These peculiarities of the photospheric motion field are not unexpected. As a matter of fact, in the high photospheric layers the macroturbulent wave motions whose velocity amplitude increases with depth are predominant. At deeper levels the macroturbulent velocities are mainly due to convection, whose velocities, according to theoretical investigations by Vitense (1953), Böhm (1963), and Wilson (1969), reach their maximum at the depths $\log \tau_5 \approx 1.2$ or even somewhat deeper in the photosphere. We refer also to an empirical study of the convective velocities by Olson (1966), who showed that these velocities ($\approx 1.9 \text{ km s}^{-1}$) reach their maximum at $\tau_5 \approx 0.5$.

The distinction between the depths of maximum values of the radial and tangential components can also be explained (at least qualitatively) by the theoretical picture of the convective cells: the horizontal outflow of matter begins after the upward velocity had stopped or essentially diminished.

The assumed run of $V^{\text{rad}}$ and $V^{\text{tg}}$ at depths $\log \tau_5 > 0.5$ is shown in Figure 3 by the dashed lines.

The knowledge of the total velocity field in the highest photospheric and in the chromospheric layers is also scanty. Canfield (1971) shows in his original study of the profiles of weak emission lines at the solar limb that the tangential component of the total velocity amplitude equals $2.0 \pm 0.2 \text{ km s}^{-1}$ in depth $-4.3 < \log \tau_5 < -2.1$. His results agree well with our average data in Figure 3, and show that the tangential component should stop diminishing at depths $\log \tau_5 < -3.0$.

The radial macroturbulent velocities of the oscillations, according to Evans and Michael (1962), amount to $\approx 1.5 \text{ km s}^{-1}$ at the height of formation of strong chromospheric lines. Thus, the radial component of the velocity amplitude should increase with height from $1.2 \text{ km s}^{-1}$ at $\log \tau_5 = -3.0$ to at least $1.5 \text{ km s}^{-1}$ at the depth $\log \tau_5 \approx -7.0$.

There are only a few investigations of the microturbulent velocities in the chromospheric layers, because they require knowledge of the deviations from LTE and of many poorly known parameters. Such investigations were made by Athay and Canfield (1969), Linsky and Avrett (1970), Lites (1973) and others. We consider as the most thorough the study by Lites, who gave both micro- and macroturbulent components at the chromospheric layers. Being included in Figure 3, his results extend the available information on the total velocity field into the chromospheric layers.

The data on the velocity amplitude of the total photospheric motion field (Table I and Figure 3 in this study) may be used directly for the computation of weak and moderately weak Fraunhofer lines.

Acknowledgements

It is a pleasure to thank Prof. Dr G. de Jager and Dr R. C. Canfield for their valuable critical comments which resulted in the improvement of this paper.
References