ON THE DETERMINATION OF HELIOGRAPHIC POSITIONS 
AND ROTATION VELOCITIES OF SUNSPOTS

II. Systematic Effects Caused by the Wilson Depression*

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Abstract. Using sunspot positions of small sunspots observed at Debrecen and Locarno as well as positions of recurrent sunspots taken from the Greenwich Photoheliographic Results (1940–1976) the influence of the Wilson depression on the rotation velocities was investigated. It was found that the Wilson depression can be determined by minimizing errors of the rotation velocities or minimizing the differences of rotation velocities determined from disk passages and central meridian passages. The Wilson depressions found were between 765 km and 2500 km for the first sample while they were between 0 km and several 1000 km for the second sample. The averaged Wilson depression for the second sample is between 500 km and 965 km depending on the reduction method. A dependence of the Wilson depression on the age of the spots investigated seems not to exist.

1. Introduction

When analyzing the heliographic positions and rotation velocities of some small but stable sunspots observed at different observatories systematic differences were found by Wöhl (1983, in the following cited as Paper I): The rotation velocities differed by up to 0.26 deg day$^{-1}$ and the spots showed higher mean rotation velocities in the disk centre as compared to the limb region by 0.13 deg day$^{-1}$ and 0.26 deg day$^{-1}$ for two observatories.

Similar results were already reported in the following papers:

(1) Arévalo et al. (1982) found an increase of the equatorial rotation velocity of sunspots by 0.11 deg day$^{-1}$ when reducing the cut-off longitude of the spots from $\pm 90$ deg to $\pm 40$ deg in longitude. They used Greenwich Photoheliographic Results.

(2) Tuominen and Kyröläinen (1981) report about displacements of recurrent sunspots towards the limb or the disk centre depending on the cycle. They used also data from the Greenwich Photoheliographic Results.

(3) Balthasar et al. (1982) compared the rotation velocities of stable recurrent sunspots with two methods: (a) from positions during the disk passages and (b) from two central meridian passages. For different classes of spots faster rotation velocities by 0.03 deg day$^{-1}$ and 0.05 deg day$^{-1}$ were found from the method b).

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Following a suggestion of Schröter (1981, private communication) we investigate in this paper the possible explanation of the above findings by the Wilson depression of sunspot umbrae.

2. Data Used

The positions of the sunspots Mt. Wilson No. 20646, 20658, and 20883 determined at the Debrecen Heliophysical Observatory and the Locarno Observatory in June and September 1979, which were investigated in Paper I were used again.

In addition the positions of stable, recurrent sunspots from the Greenwich Photoheliographic Results 1940 until 1976 were used. A part of these spots was already investigated by Balthasar et al. (1982), but the new sample contained all positions available out to the solar limb. Again only those spots were selected, which showed at least two consecutive passages of type H or J with at least eight positions per passage. This sample again was divided in two classes:

Class 1: 20 spots with only two passages, and
Class 2: 35 groups with more than two passages and including not only groups of type H or J.

3. Reductions and Results

3.1. Debrecen and Locarno Data

For the spots observed at Debrecen and Locarno linear regression lines for the positions depending on the time were computed. Then a correction of the longitudes depending on the depth \( W \) of the Wilson depression was applied and a new regression analysis performed, which resulted in most cases in a smaller error of the fit, if a depth of some

<table>
<thead>
<tr>
<th>Mt. Wilson No.</th>
<th>Uncorrected data</th>
<th>Corrected data</th>
<th>Equivalent solar disk radius correction (arc sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rotation velocity (deg day(^{-1}))</td>
<td>Error (deg day(^{-1}))</td>
<td>Depth ( W ) (km)</td>
</tr>
<tr>
<td>20646 Debrecen</td>
<td>13.125</td>
<td>± 0.00654</td>
<td>1390</td>
</tr>
<tr>
<td>Locarno</td>
<td>13.015</td>
<td>± 0.03162</td>
<td>2502</td>
</tr>
<tr>
<td>20658 Debrecen</td>
<td>12.986</td>
<td>± 0.00684</td>
<td>765</td>
</tr>
<tr>
<td>Locarno</td>
<td>12.913</td>
<td>± 0.02443</td>
<td>−</td>
</tr>
<tr>
<td>20883 Debrecen</td>
<td>12.701</td>
<td>± 0.01231</td>
<td>2502</td>
</tr>
<tr>
<td>Locarno</td>
<td>12.598</td>
<td>± 0.01571</td>
<td>9800</td>
</tr>
</tbody>
</table>

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100 km was adopted. In the case of the spot Mt. Wilson No. 20658 observed at Locarno the error was increased in any case while for the other fits a minimum of the error could be found. The appropriate values of \( W \) together with the rotation velocities determined and the errors are given in Table I. In addition the corrections needed for the solar disk image radii are given to explain the same changes of the rotation velocities and their errors.

3.2. Greenwich data

While a constant Wilson depression was assumed in the first reduction, the center-to-limb variation of the depression was taken into account in the second reduction: using the umbra model \( M_3 \) of Stellmacher and Wiehr (1975) and the LTE Program of H. Schleicher the center-to-limb variation of the continuum level at 5000 Å (about the center of the observing wavelength region) was determined. A difference of about 80 km from the center to \( \cos \Theta = 0.2 \) was found. In the following the parameter \( W \) for the Wilson depression is given for the center of the solar disk, but it is taken with the above mentioned correction for positions outside the disk center.

Similar to the reductions described in 3.1 the errors of linear regressions were minimized by varying the parameter \( W \). In addition the differences to the rotation velocities determined from central meridian passages were minimized. As a matter of fact averages of daily rotation values and linear regressions were computed. The results for all appropriate spots taken together are given in Table II. When computing individual Wilson depressions and then averaging the results mean values of 1184 km for class 1

<table>
<thead>
<tr>
<th>Sample (number of spots)</th>
<th>Wilson depression from minima of rotation velocity errors</th>
<th>from minima of differences to velocities from central meridian passages</th>
<th>Averaged types of the spots (see text)</th>
</tr>
</thead>
<tbody>
<tr>
<td>class 1 + 2 (156)</td>
<td>700 800</td>
<td>500 700</td>
<td></td>
</tr>
<tr>
<td>class 1 (40)</td>
<td>700 700</td>
<td>1000 1000</td>
<td></td>
</tr>
<tr>
<td>1\textsuperscript{st} passage (20)</td>
<td>800 750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2\textsuperscript{nd} passage (20)</td>
<td>200 750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>class 2 (116)</td>
<td>700 700</td>
<td>400 650</td>
<td></td>
</tr>
<tr>
<td>1\textsuperscript{st} passage (35)</td>
<td>700 800</td>
<td>0 100</td>
<td></td>
</tr>
<tr>
<td>2\textsuperscript{nd} passage (35)</td>
<td>500 600</td>
<td>600 450</td>
<td></td>
</tr>
<tr>
<td>3\textsuperscript{rd} passage (29)</td>
<td>400 400</td>
<td>1000 1000</td>
<td></td>
</tr>
<tr>
<td>4\textsuperscript{th} passage (13)</td>
<td>1250 1250</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
and 658 km for class 2, respectively, were found. The errors of the means were 419 km and 268 km, respectively.

From model computations taking spots with constant rotation velocities but with statistical errors for the daily positions and a fixed Wilson depression of 500 km it was found, that the depression could be determined by the described methods within small errors. It seems that the real depressions are systematically smaller by about 10 to 20% than the determined ones. This effect is caused by the position errors introduced.

In addition the dependence of the Wilson depression on the age of the spots was investigated. The results are given in Table II, with decimal numbers for the usual spot symbols (A \leq 1, \ldots, H \geq 8, J \geq 9). An average type of less than 8 means that there are bipolar groups in the sample, it means not, that we deal with E-groups if it is e.g. 5.1.

4. Discussions and Conclusions

As already indicated in the introduction, it is obvious, that the Wilson depression influences the observed positions of sunspots on the solar disk. The averaged values of the depression, which can be found from the analysis described above are in fairly good agreement with those from simple estimations of the magnetic pressure inside of umbrae of large spots and other observing methods (e.g. Mattig, 1969).

Since the new method gives the possibility to analyse special samples, it was found that the correct depth of the depression could only be obtained, if single undisturbed sunspots were investigated and their positions were determined from the centers of the umbrae and not from surrounding details or light-bridges. This is in agreement with an investigation performed by Koch (1983).

The changes of the solar image radii, which would be necessary to explain the same effects are too big to be real (see Table I). In addition it would be hard to understand, why they had to be assumed in almost all cases in the direction of smaller radii, independent of the observing method. Nevertheless cases of wrong solar image radii are important as already indicated in paper I and will be discussed in more details in another paper. For future reductions of rotation velocities of sunspots we believe that the Wilson depression can be taken into account and will reduce errors of determined positions.

The results given in Table II do not show a clear dependence of the Wilson depression on the age of the spots.

Acknowledgements

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*Greenwich Photoheliographic Results* : 1940–1976, Royal Greenwich Observatory.