OBSERVATIONS OF THE HORIZONTAL VELOCITY FIELD SURROUNDING SUNSPOTS

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Abstract. During the summer and fall of 1971, Doppler spectroheliograms were obtained for several sunspots located near the solar limb. These observations confirm a previous result based on the study of only a few sunspots that in the plage-free photosphere surrounding sunspots the spatially-averaged horizontal flow tends to be outward at 0.5–1.0 km s\(^{-1}\) for distances typically 10000–20000 km beyond the outer boundary of the penumbra. It is suggested that these material motions are the means by which small-scale fragments of magnetic flux are carried away from sunspots.

1. Introduction

During the last few years, observations with magnetographs and spectroheliographs have revealed that in annular regions surrounding sunspots, magnetic fields and their associated faculae move laterally outward on the solar surface at speeds on the order of 1 km s\(^{-1}\) (Sheeley, 1969, 1971; Vrabec, 1971; Harvey et al., 1971; Harvey and Harvey, 1972). If the magnetic fields are ‘frozen’ into the solar material as is often assumed, then one might suppose that the observed proper motions indicate the presence of a horizontal flow of material. Such material motions would be expected if sunspots tend to be located at the centers of supergranules or if the Evershed velocity extends well into the extra-penumbra photosphere. An exploration of the two-dimensional velocity field in and around sunspots (Sheeley and Bhatnagar, 1971) revealed evidence for a horizontal outflow extending roughly 10000 km into the extra-penumbral photosphere. However, the presence of a confusing fine structure in this velocity field together with the limited number of sunspots observed indicated that observations of more sunspots were needed to clarify the properties of the horizontal outflow. This seemed particularly important in view of different properties associated with different sunspots such as their stage of development and their surrounding magnetic field configuration. This paper describes observations of several more large, well-developed sunspots located at heliocentric angles of roughly 60° where horizontal velocities may present significant line-of-sight components, but at the same time where spatial foreshortening is not prohibitive.

2. Observations

Time-lapse sequences of spectroheliograms were obtained simultaneously in the violet and red wings of the Zeeman-insensitive Fe i \(\lambda 5434\) line at the rate of 20 s/}

* Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
frame. These films were photographically subtracted to form Doppler spectroheliograms of the total line-of-sight component of velocity. Next, pairs of Doppler spectroheliograms separated by 2.5 min were photographically added to eliminate the component of velocity field that oscillates with a 5 min period. A single frame so obtained is referred to as a spectroheliogram of the slowly-varying component of velocity field. Such spectroheliograms were obtained on several days during the summer and fall of 1971, with the 82 cm main image and the 37 cm east auxiliary image at the McMath Solar Telescope on Kitt Peak. When possible, a CN $\lambda 3883$ spectroheliogram indicating the magnetic field pattern surrounding the sunspot was obtained immediately after the Doppler run for comparison with the slowly-varying velocity field. Although this supplementary information was helpful, it was not essential because at a heliocentric angle of 60° the facula fields were visible on spectroheliograms of the $\lambda 5434$ average-wing intensity obtained by photographically adding the violet- and red-wing spectroheliograms.

Figure 1 illustrates the kind of results that have been obtained when the spectroheliograph exit slits were placed symmetrically on the linear parts of the profile $\pm 0.07$ Å from the $\lambda 5434$ line core. The upper photograph shows the slowly-varying component of velocity field with darker-than-average features corresponding to line-of-sight velocity components directed toward the observer and lighter-than-average features corresponding to components directed away from the observer. The closed curve has been drawn to indicate the location of the outer boundary of the sunspot penumbra. It is clear from this figure that although a complicated fine structure is present, the spatially-averaged line-of-sight component of velocity is approaching on the centerward side of the sunspot and receding on the limbward side to a considerable distance beyond the outer boundary of the penumbra. A comparison with the CN $\lambda 3883$ spectroheliogram in the lower photograph shows that on the centerward side of the sunspot the large-scale velocity of approach extends across the annular region from the outer edge of the penumbra to the place where the facula network first takes form. Since this sunspot is located at the relatively high heliocentric angle of 60°, these large-scale line-of-sight velocities probably correspond to horizontal motions. With this interpretation, Figure 1 shows that outward horizontal motions extend 10000–20000 km beyond the penumbral boundary.

Table I summarizes the measurements of the horizontal extra-penumbral outflow for the sunspot region in Figure 1 as well as for five other sunspot regions observed during 1970 and 1971. This table shows that the spatially-averaged horizontal velocity extends approximately 10000–20000 km beyond the outer penumbral boundaries of five of the six sunspots on both their limbward and centerward sides. The remaining sunspot shows an outflow extending 12000 km beyond its centerward penumbra, and shows only marginal evidence for an outflow beyond its limbward penumbra. In this latter case, the observing conditions were very poor so that relatively little weight should be placed on this observation.

Column 6 of Table I gives the spatially-averaged horizontal outflow velocities for the six sunspots. The velocities were obtained from photographic densities using the
30,000 KM

Fig. 1. A comparison of the patterns of velocity and magnetic field (as indicated by CN intensity) in the neighborhood of a sunspot: (a) slowly-varying component of line-of-sight velocity; lighter-than-average features are receding and darker-than-average features are approaching the observer. (b) spectroheliogram of the CN λ3883 intensity field taken about 45 min after the velocity spectroheliogram. The sunspot has a heliocentric position angle of 60° and the west limb is to the right. The closed curve in Figure 1 (a) indicates the location of the penumbral boundary of the sunspot.

average line profile for calibration (Leighton et al., 1962). For the five cases in which an appreciable outflow occurred on both centerward and limbward sides of the sunspot, the velocity in column 6 refers to the average of the two values obtained. For the other sunspot, column 6 gives the value of the only outflow observed. This Table shows a tendency for the magnitude of the spatially-averaged horizontal outflow in the extra-penumbral photosphere to lie in the range 0.5–1.0 km s$^{-1}$.

3. Discussion

In this study, it has become clear that the properties of the Evershed velocity are vastly different from those of the horizontal outflow of material in the extra-penumbral photosphere. First, the strong Evershed velocity is confined to dark, spoke-like
<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Sunspot diameter (km)</th>
<th>Extra-penumbra extension (km)</th>
<th>Average outflow velocity (km s$^{-1}$) $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 19, 1970 (1)</td>
<td>56° SW</td>
<td>30000</td>
<td>12000</td>
<td>0.4</td>
</tr>
<tr>
<td>Aug. 19, 1970 (2)</td>
<td>60° SW</td>
<td>20000</td>
<td>10000</td>
<td>0.5</td>
</tr>
<tr>
<td>Aug. 13, 1971</td>
<td>60° SW</td>
<td>25000</td>
<td>14000</td>
<td>0.6</td>
</tr>
<tr>
<td>Sept. 25, 1971</td>
<td>66° SE</td>
<td>42000</td>
<td>19000</td>
<td>0.8</td>
</tr>
<tr>
<td>Oct. 4, 1971</td>
<td>60° SW</td>
<td>41000</td>
<td>10000</td>
<td>0.5</td>
</tr>
<tr>
<td>Nov. 1, 1971</td>
<td>66° SE</td>
<td>30000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Corrected for foreshortening assuming that the velocities are purely horizontal

$^b$ Corrected for foreshortening assuming that the velocities are purely horizontal.
features that constitute the ragged outer boundary of the penumbra, whereas the extra-penumbral velocity, of course, occurs outside the penumbra. Second, the magnitude of the Evershed velocity is much greater than that of the extra-penumbral outflow. Typical values of the Evershed velocity range from $4 \text{ km s}^{-1}$ to $6 \text{ km s}^{-1}$, whereas the magnitude of the spatially-averaged, horizontal, extra-penumbral outflow lies in the range $0.5$--$1.0 \text{ km s}^{-1}$. The extra-penumbral velocity appears distinguishable from the supergranulation, and in this sense the present observations indicate a tendency for sunspots to occur at the center of supergranules, as Simon and Leighton (1964) once speculated.

Thus, one is led to the conclusion that the supergranulation currents are responsible for the observed motions of small-scale magnetic field horizontally outward from sunspots. Although these large cells of horizontally moving material are distributed more or less uniformly over the entire solar surface (Leighton et al., 1962), systematic horizontal motions of magnetic fields are observed only surrounding sunspots (and where new flux first appears). This suggests that only here are the sources of magnetic flux in the centers of supergranules. Apparently everywhere else these strong magnetic fields have already been transported to the supergranulation boundaries. Consequently, on most of the solar surface one observes only the small-scale random displacements perhaps reflecting the influence of the ordinary granulation, and the slowly-varying displacements possibly reflecting gradual changes of the supergranulation velocity pattern itself.

The origin of the small-scale outward proper motions of magnetic fields remains a mystery. One might suppose that these fields are fragmented away from the outer boundary of a sunspot penumbra, become predominantly vertically oriented, and are subsequently carried horizontally outward in the moving material. If enough flux of a given polarity survives the trip to the supergranulation boundary, it will pile up there to form the beginning of the photospheric network. Although one might logically suppose that the vertical component of the fragmented fields would have the same magnetic polarity as the sunspot itself, a significant fraction are observed to have the opposite polarity. Since the ones that do have the opposite polarity originate at the outer boundary of the penumbra and not within the penumbra itself, one might at first speculate that horizontal fields in the outer part of the penumbra occasionally turn vertically downward at the penumbral boundary to produce these fields of opposite polarity. However, it is observed that even when sunspots have decayed to the point that they no longer have penumbra, not only do the outward proper motions and horizontal material motions still occur, but both magnetic polarities are still involved (Harvey and Harvey, 1972). Thus, a more likely explanation may be that sunspots indicate the general area where magnetic flux is being released from below the surface, and that the fields of 'opposite polarity' simply represent some of this flux.

* A very important observational consequence of these widely different horizontal velocities is that to detect the Evershed velocity near the limb, the spectroheliograph exit slits must be positioned much farther into the line wings than is suitable for measuring the extra-penumbral velocity.
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References