MOTIONS IN THE CHROMOSPHERE NEAR SUNSPOTS

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[*Manuscript received March* 8, 1962]

Summary

The Evershed velocities in the chromosphere have been studied from Hα filtergrams. Inward motions are found in the region extending from the outer boundary of the penumbra out to two sunspot radii; the moving matter is not evenly distributed around the spot but flows in along channels. These have lifetimes of about 9 hr, very long as compared with the time of passage at inflow velocities of 45 km/sec. The velocity vector makes an angle of about 13° with the solar surface, suggesting that the matter is constrained to flow along lines of magnetic force. If so, the high velocities of inflow appear to be purely gravitational.

I. Introduction

St. John's (1913) observations showed that the Evershed velocity field near a sunspot varies with the strength of the line used. For weak lines, motion is observed away from the centre of the spot, for stronger lines the velocity decreases, and for very strong lines it reverses its direction. Most studies of the Evershed effect since then have been concerned with the outward motion which takes place in the photosphere. The present paper describes an investigation of the chromospheric velocities as observed on filtergrams taken in opposite wings of the Hα line.

It is found that the chromospheric velocities are very much larger than previously thought, and that there is also a downward component. The moving matter, however, is not evenly distributed around the spots but streams into the spot along channels whose lifetimes are very much longer than the time it takes for the matter to flow through them.

II. Observations

The filtergrams were obtained with a tunable $\frac{1}{8}$ Å filter (Steel, Smartt, and Giovanelli 1961) and either a 3 in. telescope (1960 observations) or a 5 in. telescope (1961 observations). The diameters of the solar images were 56 and 100 mm respectively.

In order to determine the complete velocity field of the chromosphere around the spot from sight-line velocities only, it is necessary to use a spot with cylindrical symmetry. Two such spots were observed: in August 1960 ($L=69°$; $B=+15°$; area$=300\times10^{-6}$ hemisphere), and July 1961 ($L=56°$; $B=+14°$; area$=375\times10^{-6}$ hemisphere).

The 1960 observations were made on the one spot on August 16, 17, 18, and 22 while it was moving across the solar disk. On August 16, 17, and 22, filtergrams were taken at wavelength intervals of $0\cdot1$ Å between $\pm1\cdot0$ Å from

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the centre of the Hα line. There is a clear difference between the chromospheric structures around the spot in the red and violet wings although the spatial resolution is low ($\simeq 6''$). The observations at $-0\cdot5$ Å, for example, show on the limb side of the spot a dark diffuse area while the rest of the area around the spot is bright, the intensity being about the same as that of the brighter regions outside the centre of activity. The filtergrams at $+0\cdot5$ Å show the reverse within a well-defined distance from the spot (about 2 sunspot radii from the spot's centre). The dark material on the centre side of the spot shows a resolved structure and is darker than the diffuse dark area observed at $-0\cdot5$ Å on the limb side. All photographs taken between $\pm0\cdot2$ and $\pm0\cdot8$ Å show the same behaviour. These differences between the red and violet wing filtergrams are only well defined outside the outer penumbral boundary ; they are not visible in the penumbra itself. The features described must be interpreted as due to large velocities in the dark structures directed towards the spot.

Plate 1 shows three photographs taken on August 17, 1960, at $+0\cdot5$ Å in a time interval of 5 hr. They show the changes in the dark structures on the centre side. From a sequence of such photographs taken on three consecutive days (August 16, 17, and 18, 1960) the average lifetime of these dark structures has been determined as about 9 hr ; the lifetimes of the individual structures, however, may vary between an hour and more than a day. These lifetimes are very long when compared with the time of passage as the velocities in these structures are about 45 km/sec, as will be shown later. One is evidently looking at channels along which the chromospheric matter streams into the spot, the time it takes to flow along the channel being very much shorter than the lifetime of the channel itself (about 12 min and 9 hr respectively).

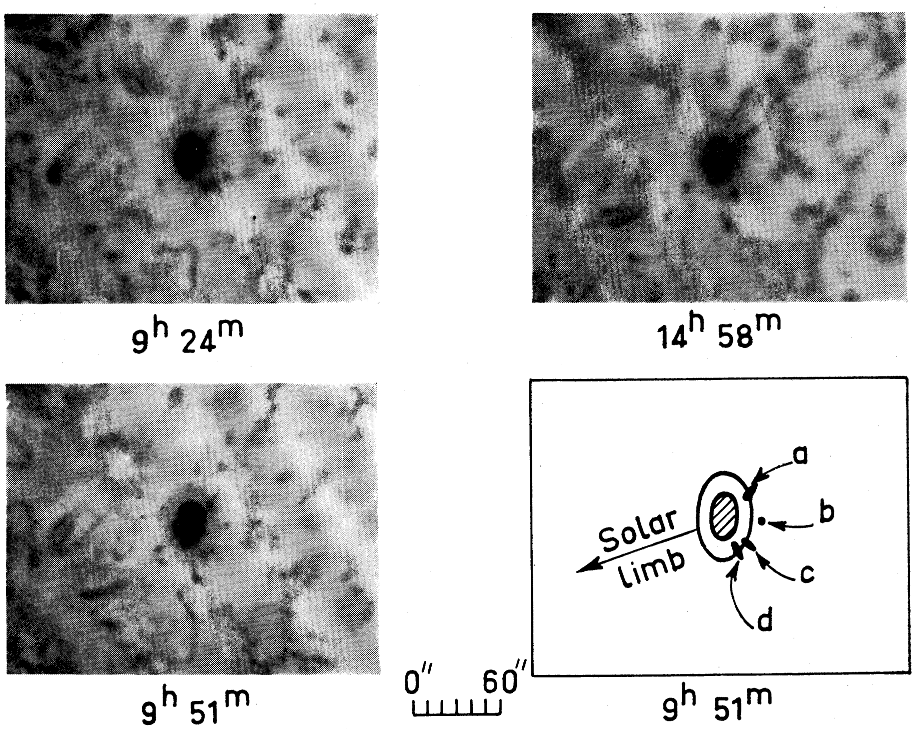
The 1961 observations were made at H$\alpha\pm0\cdot5$ Å only. They show features similar to those in the 1960 photographs, but in addition they resolve the limbside structure of the spot at $-0\cdot5$ Å. Plate 2 illustrates these filtergrams. The differences between the two filtergrams are again very small in the penumbra, as is clearly illustrated in the third photograph of Plate 2, which shows the ratio of the intensities at $\pm0\cdot5$ Å obtained by photographic subtraction as described by Giovanelli and Jefferies (1961). The motions stop abruptly at the penumbral boundary. Inside the penumbra the Doppler shifts are less than $0\cdot010$ Å ($0\cdot5$ km/sec) ; Leighton (1962) recently obtained similar results.*

III. Reduction

The velocity field is assumed to be cylindrically symmetrical around the spot's axis. The determination of the actual velocities requires photometry, though the direction of motion can be obtained from visual examination of the photographs.

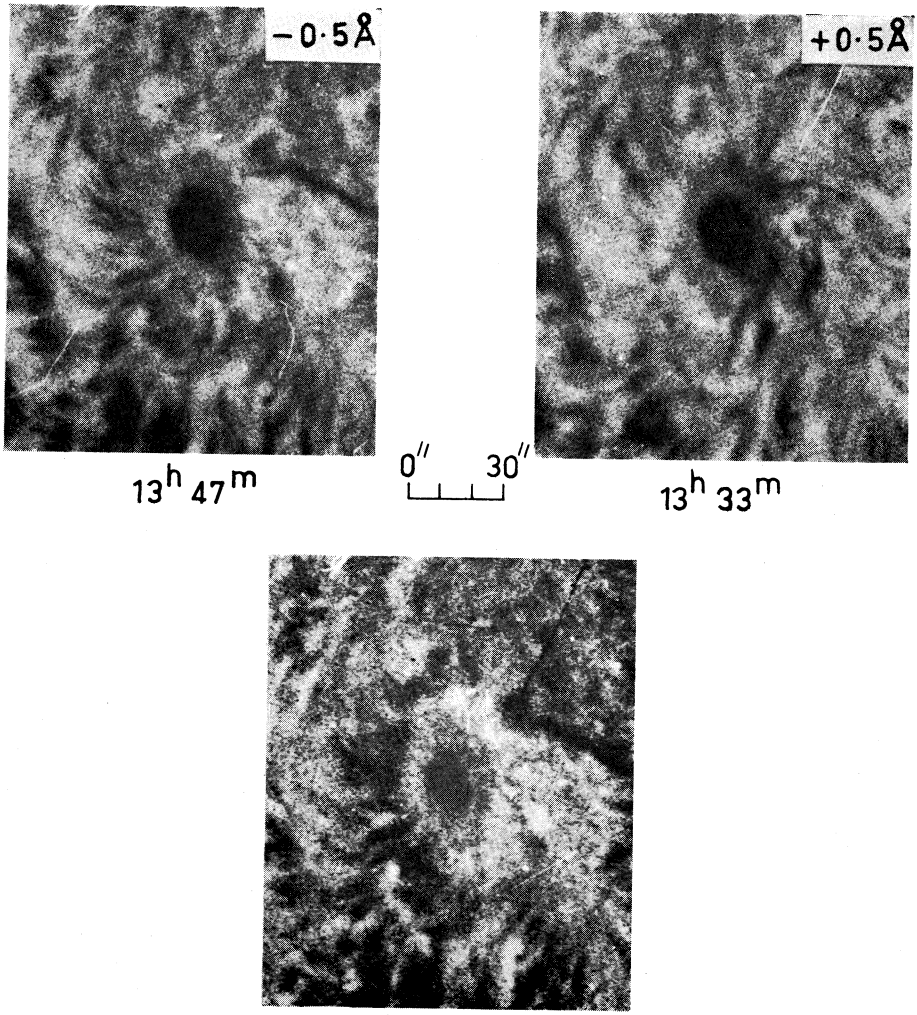
* The motions studied are rather similar to those of the sunspot prominences of type IIIa as described, e.g. by Pettit (1936, 1943) and Ellison (1944). Type IIIa prominences, however, are different in size ($>80''$), are very rare (only visible near about 1% of the spots) and occur mainly over sunspot groups. The structures studied in this paper could well be called " dwarf prominences of type IIIa " ; however, apart from being smaller, they are very common near all types of sunspots.

MOTIONS IN THE CHROMOSPHERE NEAR SUNSPOTS



Filtergrams taken August 17, 1960, at $+0\cdot5$ Å showing the changes in the dark high-velocity structures near a sunspot. The drawing indicates the points used in Section III.

MOTIONS IN THE CHROMOSPHERE NEAR SUNSPOTS



Filtergrams taken July 10, 1961, at ±0·5 Å showing the motions in the chromosphere near a sunspot. The solar limb is on the left. The bottom photograph is obtained by photographic subtraction, and shows the absence of motion in the penumbra.

(*a*) *Direction of the Velocity Vector*

There are two positions along the spot's circumference where the differences between the red and violet filtergrams disappear, i.e. where there is a zero sight-line velocity. The angles between the sunspot radii through these points and the direction away from the centre of the Sun are called Φ_1 and Φ_2 (Φ positive if measured clockwise, see Fig. 1); Φ_1 and Φ_2 determine the direction of the velocity vector. With v_r, the radial component of the velocity, positive away

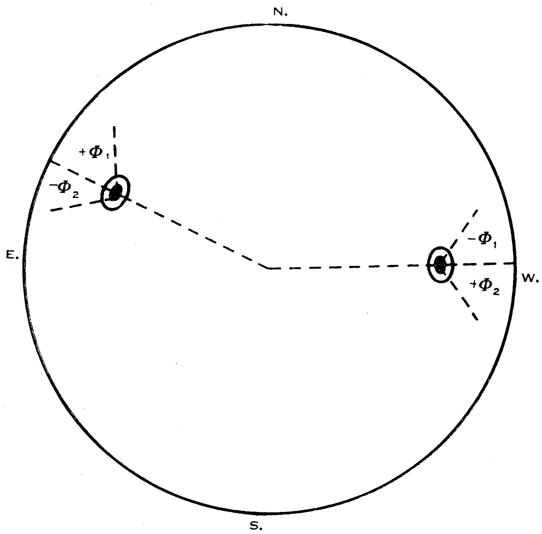


Fig. 1

from the spot, v_h, the vertical component, positive when upwards, and v_φ, the tangential component, positive when clockwise if viewed from the Earth, the direction of the velocity vector is given by

$$
\begin{aligned}
v_h/v_r &= +\tan\theta\cos\tfrac{1}{2}(\varphi_1-\varphi_2)\sec\tfrac{1}{2}(\varphi_1+\varphi_2),\\
v_\varphi/v_r &= -\tan\tfrac{1}{2}(\varphi_1+\varphi_2),\\
\tan\varphi &= \cos\theta\tan\Phi,
\end{aligned}
$$

with θ, as usual, the angle between the line of sight and the normal to the Sun's surface.

The angles Φ_1 and Φ_2 have been found by visual comparison of the red and violet wing filtergrams. The visual determination of the points around the spot's circumference where there is no difference between the two wings is not much less accurate but much easier than a photometric determination. For the 1960 observations all the filtergrams between $\pm 0\cdot 2$ and $\pm 0\cdot 8$ Å were used; the 1961 observations were available only for $\pm 0\cdot 5$ Å. In the earlier group, no changes could be detected for points at different distances from the centre of Hα. Table 1 presents the data obtained for the spots and their averages (the August 22, 1960, data were difficult to measure and hence their lower weight). There is a downward movement, the direction of motion making an angle of some 13° with

TABLE 1

DETERMINATION OF THE DIRECTION OF THE VELOCITY VECTOR NEAR A SUNSPOT

Date	Position	Sin θ	Φ_1	Φ_2	v_h/v_r	v_φ/v_r	Weight
16.viii.1960	$L=69°$ $B=+15°$	0·64	+79°	—76°	+0·23	+0·03	2
17.viii.1960	$L=69°$ $B=+15°$	0·48	+82°	—75°	+0·12	+0·07	2
22.viii.1960	$L=69°$ $B=+15°$	0·59	—93°	+65°	+0·17	—0·23	1
10. vii.1961	$L=56°$ $B=+14°$	0·74	—90°	+63°	+0·36	—0·24	2
				Average :	+0·23	—0·08	
				Standard deviation :	±0·06	±0·09	

the solar surface. The observations provide no evidence of a significant tangential component ; this is in accordance with the value derived from Coriolis force considerations (see e.g. de Jager 1959) which give $v_\varphi/v_r \approx 2 \times 10^{-4}$ for the radial velocities concerned.

(b) The Magnitude of the Velocities

To determine the actual velocities, the average intensity I_λ^* of the dark spots indicated by *a*, *b*, *c*, and *d* in Plate 1 has been measured with respect to the intensity I_λ of their surroundings. This has been done for wavelengths between ±1·0 Å, 0·1 Å apart, and at ±1·5 Å and ±2·0 Å from Hα. The values of

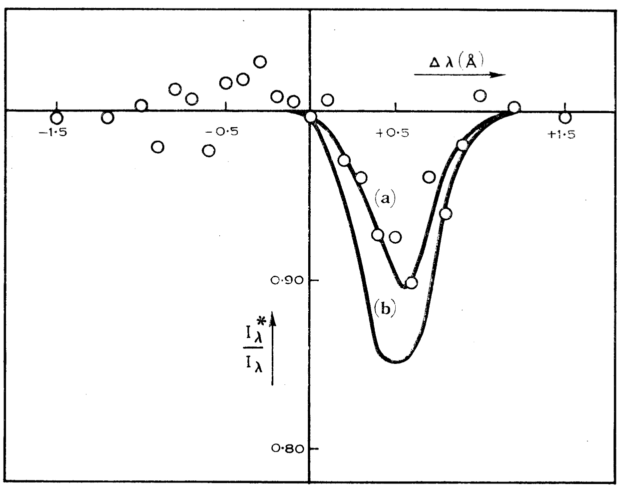


Fig. 2.—Contrast of the dark channels with respect to the background radiation, (*a*) uncorrected and (*b*) corrected for parasitic light.

I_λ^*/I_λ are shown in Figure 2 ; curve (*a*) is taken as their average, while curve (*b*) shows the intensity ratio after correction for the parasitic light from the filter (16% of the continuum intensity independent of the wavelength setting of the filter for the wavelength interval concerned).

The curve is roughly symmetrical around H$\alpha+0\cdot52$ Å, which should correspond to the Doppler shift $\Delta\lambda_v$ were there no emission by the cloud itself. However, since the cloud is a self-emitting and scattering medium, the intensity I^*_λ takes the form

$$I^*_\lambda = I_\lambda f(\Delta) + F(\Delta), \tag{1}$$

where $\Delta=\Delta\lambda-\Delta\lambda_v$, $\Delta\lambda$ being the distance from the Hα line centre. The first term in equation (1) represents the light transmitted by the cloud; $f(\Delta)$ is a symmetrical function around $\Delta\lambda_v$ and is equal to $\exp-\tau_\lambda$, where τ_λ is the optical depth of the cloud. The second term $F(\Delta)$ represents the self-emission and the scattering of the cloud; with non-coherent scattering, $F(\Delta)$ is also symmetrical

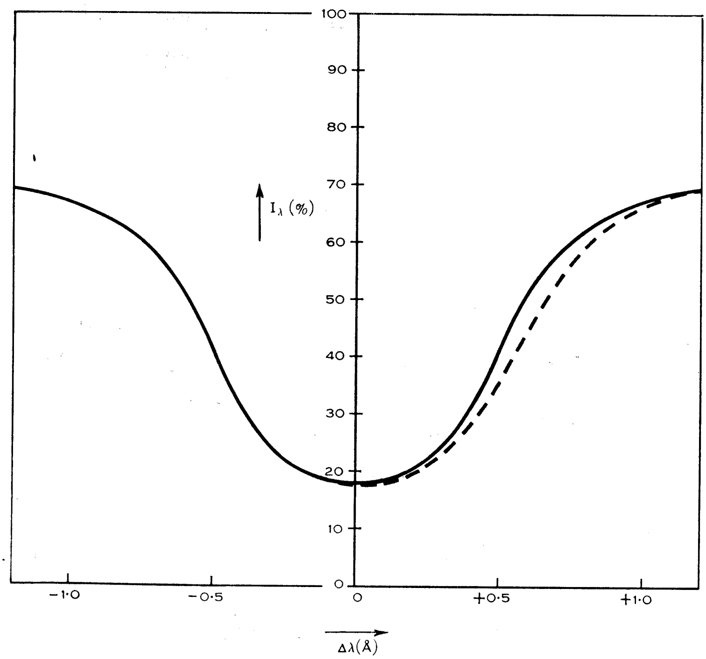


Fig. 3.—Profile of Hα in the dark, high-velocity spots.

around $\Delta\lambda_v$. Equation (1) shows that I^*_λ/I_λ is not symmetrical around $\Delta\lambda_v$ unless $F(\Delta)=0$, whence it can be seen that the preliminary Doppler shift of $0\cdot52$ Å as determined above is an overestimate. However, the difference is small for any reasonable values of $F(\Delta)$, and for further calculations $\Delta\lambda_v$ is taken to be $0\cdot50$ Å.

With the values $v_h/v_r=+0\cdot23$ and $v_\varphi=0$, as already derived, the sight-line velocity v_s may be calculated in terms of v_r for the four points measured. The average over the four points is $v_s=0\cdot51v_r$, whence $v_r=46$ km/sec. From this, $v_h=10$ km/sec and $v=\sqrt{(v_h^2+v_r^2)}=47$ km/sec. This velocity is very much larger than that obtained by measurements of the line shifts, e.g. by St. John (1913), 3 km/sec, and by Severny (1960), 2 km/sec, in the Hβ line. Figure 3 shows the profile of Hα as it would appear in the dark high-velocity regions from the present measurements and in the region outside them. Although the dark matter has a very high velocity, the velocity measured from the line displacement would be only 3 km/sec. This value may even decrease if the open spaces between the dark channels are included, as in the case of low resolution spectrograms.

Although Severny (1960) measured these diluted velocities, his conclusion that the motions are along magnetic lines of force remains unaffected. The existence of the downward motion in the present measurements suggests this also. If the matter must flow under the action of gravity along the magnetic lines of force, the equation of motion is $\mathrm{d}v/\mathrm{d}t = g_{\parallel} - \mathrm{grad}\, p_{\parallel}$, where the subscript "$_{\parallel}$" refers to the components along the lines of force, e.g. $g_{\parallel} = g \sin 13°$. If the pressure gradient is small with respect to $g_{\parallel}$, one can write $\mathrm{d}v/\mathrm{d}t = g \sin 13°$, or $v = 113\sqrt{s}$ cm/sec, where s represents the distance (in cm) already travelled by the matter. Taking this as 20″, the distance from the spot penumbra where the velocity becomes zero, one obtains $v = 43$ km/sec. This is in good agreement with the measured velocity, which also refers to points on the border of the penumbra. It seems, therefore, that gravitational forces are responsible for the motions described in this paper, and that the pressure gradients are small with respect to $g_{\parallel}$ near a sunspot.

IV. Conclusion

The observations described here confirm the existence of a flow of chromospheric matter into sunspots, a flow which extends outwards from the centre of the spot up to two sunspot radii. This is different from the outward motions in the photosphere, which seem to be predominantly horizontal.* The existence of a downward velocity suggests the motion to be along lines of magnetic force. The measured velocities of 40 to 50 km/sec are just those expected if matter flows along these lines of force under the influence of gravity.

V. Acknowledgments

The author wishes to thank Mr. D. G. Norton for his assistance with the observations, and Dr. R. G. Giovanelli for his help during the preparation of this paper.

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* The small vertical component downward with respect to the photosphere, found by Kinman (1953) and Servajean (1961) to be respectively 0·5 and 0·3 km/sec, can well be ascribed to the general upward motion in the photosphere of about 0·3 km/sec suggested by the discrepancy in the Einstein red shift (Adam 1958). This discrepancy will probably be absent, or in any case different, in the penumbra.