Kodaikanal Obs. Bull. (1984) 4, 11-17.

OBSERVATIONS OF THE EVERSHED EFFECT - PAST AND PRESENT

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There exist good reviews on this topic by Schröter (1967) and Maltby (1964). The purpose of the present one on this occasion is to bring out fully the pioneering work of John Evershed in all its aspects in this field and also to update the earlier reviews.

John Evershed (1909a,b,c) while analysing the sunspot spectra obtained by him at Kodaikanal for pressure determination in spots observed that the spectral lines show displacements in the penumbral region of sunspots. This was in fact a remarkable observation since spectroscopic observations of sunspots were started several years earlier, but line displacements were not detected previously in the spectra of the spot penumbrae. The first plate showing this line displacement was exposed on January 5 and 7 in 1909 - 75 years ago - on a spot at latitude 9°N and longitude 31°W of the central meridian covering a region 4650 A to 4790 A with a dispersion of 1.08 mm Å^{-1}. He attributes the unusual amount of detail visible in the spectrum as due to the "clearness and steadiness of the air at the time of the exposure". A preliminary measurement of ten of the best defined lines showed a mean displacement of 0.027 Å (or 0.86 km sec^{-1}) at the outer edges of the penumbra indicating a receding velocity on the limbward side of the spot. He found an approaching velocity of the same magnitude on that part of the penumbra closer to the centre of the disc. Continuing his investigations with 150 spectra representing seven different spots in the northern hemisphere and four in the southern he established the following results:

1. All spots whether in the southern or northern hemisphere show the same amount of line shifts when at the same distance from the centre of the disc and the sense of displacement is to the violet on the side of the penumbra towards the centre of the disc and to the red for the limbward penumbra.
2. These displacements are maximum for spots between 30° and 60° longitudes and disappear when they are within 10° of the centre.

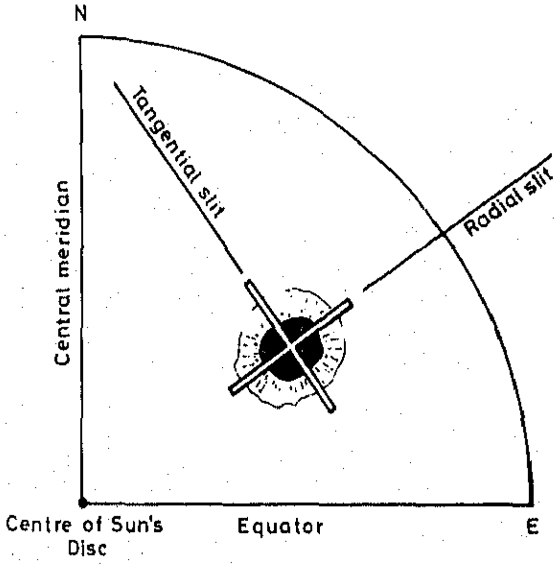

Fig.1. Radial and tangential positions of the spectrograph slit for observing Evershed flow in sunspots.

3. He found maximum line displacements for a radial slit position and no displacement for a slit normal to this position (tangential slit, Figure 1).

These observations convinced Evershed that the displacement of lines was solely due to the Doppler shift caused by the movement of the sunspot gases directed radially and horizontally outwards from the centre of the spot. This radial outflow of solar plasma from sunspots is now known as the Evershed effect. The absence of the tangential velocity ruled out any rotational motion of the gases which conflicted with the concept of motion of gas within the spot by Hale (1908). Evershed (1910) continuing his studies using absorption lines of different strengths found out that strong lines (Rowland Intensity 5-6) show lower velocities (~1.5 km/sec^{-1}) while faint lines (Rowland Intensity 0-1) show higher velocities (2-3 km sec^{-1}). He also established the monotonic increase of radial velocity from the umbral boundary with a maximum near the outer boundary of the penumbra. Although his earlier studies (1909a,b) showed that the motion abruptly ceases near the periphery of the penumbra, his subsequent observations (1916) gave evidence of the extension of the motion almost 8000 km beyond the penumbral boundary. From his observations using the CaII H & K lines, he showed that there is an inward flow of matter in the spot with a velocity of ~1.8 km sec^{-1}. Evershed also detected tangential component of the velocity of ~3.6 km sec^{-1} in five of the spots he studied and the direction of rotation was counter clockwise for some spots while clockwise for others.

The voluminous work of St. John (1913) using the 60-ft solar tower at the Mt.Wilson Observatory, of measurements of the Evershed velocities of 500 selected lines representing different elements and a large range of excitation potentials confirmed Evershed's earlier findings on faint metallic lines. For the faint lines he observed an outflow of materials from the spot into the undisturbed photosphere, whereas the strong lines (Al and Fe lines) showed no Evershed velocity. For still stronger lines (NaI D_1, D_2, and Mg b_1) and for chromospheric lines there was a reversal in the direction of motion indicating a radial flow of material into the spot (Figure 2).

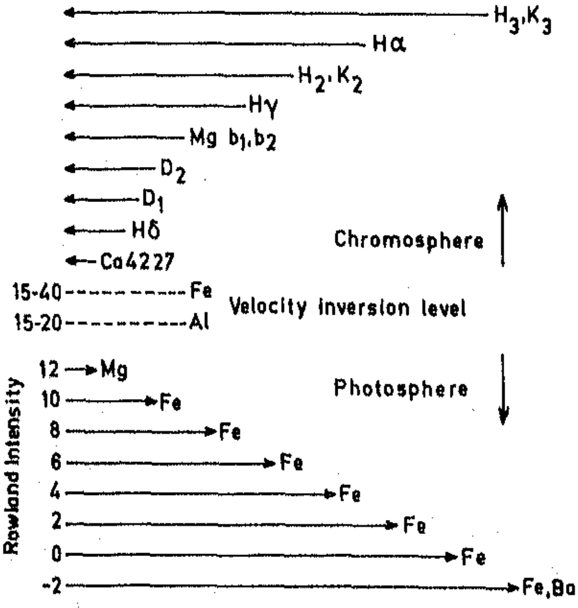

Fig.2. Schematic representation of the height dependence of the Evershed flow. The arrows towards the right represent outflow and the arrows towards the left represent an inflow of material.

This would imply that the material depletion in the umbra due to outflow at the lower levels, is replenished by inflow of material at the chromospheric level. Evershed's (1910) attempts to detect motion in the umbra using the photospheric lines showed surprisingly a descending motion of ~0.4 km sec^{-1}. Abetti's (1932) observations during the sunspot maximum of 1926-1934 showed that the radial velocity varied from 0.2 to 6 km sec^{-1} and in addition there were irregular tangential components in the range 0-5 km sec^{-1}. He also detected that the maximum velocity occurred at the umbra-penumbra boundary and not at the outer edge of the penumbra, which contradicted Evershed's findings. But Abetti's samples belonged to complex spot groups, whereas the measurements of Evershed and St. John pertained to single and rather inactive sunspots. This shows that there may be a clear distinction in the pattern of the flow between the two varieties of spots.

Michard (1951) was the first to relate the outflow velocity with the size of the spot and its magnetic field. He also established an empirical relation for the centre-to-limb variation of the velocity ($V_{r,\theta}$) in terms of the maximum radial velocity ($V_{r,o}$) and the angle (θ) between the line joining the observer and the direction normal to the solar surface by the relation,

$$V_{r,\theta} = V_{r,o} \ (1-0.8 \text{ Sin } \theta)$$

Later Schröter (1965a) obtained a similar relation

$$V_{r,\theta} = V_{r,o} \ (1-0.3 \text{ Sin } \theta)$$

This observed centre-to-limb variation confirms the height dependence of the velocity suggested by St.John (Figure 2). Kinman (1952, 1953) in his classical work on this topic derived the spatial distribution of velocities over a sunspot from the spectra obtained at the Oxford solar telescope. Assuming cylindrical symmetry about the spot centre he derived the radial, tangential and vertical velocity components from the mean sight-line velocities at many locations within the spot. His investigation covering one large and three small spots showed that the maximum radial velocity attained, increased linearly with umbral size, but the time to reach this maximum velocity was independent of the size of the umbra. The interesting point is that the radial velocity component V_r showed an increase from $\sim$ 1km sec^{-1} at the edge of the umbra and reached a maximum value of $\sim$2 km sec^{-1} at the middle of the penumbra and finally reached zero in the photosphere well outside the spot. But according to Brekke and Maltby (1963) the radial velocities end abruptly at the outer boundary of the penumbra. Schröter's spectra confirm Maltby's findings, but all these as we shall see soon depend to a very large extent on the spatial resolution employed for the observations. The spot velocity fields derived by Holmes (1961) for two spots - one large and another small - using the non Zeeman line Fe I 5576.1 Å showed a maximum radial velocity at the edge of the penumbra with an extended flow reaching zero well beyond, in the photosphere. But the maximum velocity for the large spot was only $\sim$ 0.6 km sec^{-1} as against the velocity of 3.5 km sec^{-1} expected from Kinman's linear relation connecting maximum velocity and spotsize. Also for the large spot, the velocity reaches out far into the photosphere before it becomes indistinguishable. From the measurements of the radial, tangential and vertical velocity components for a spot at six disc positions, Servajean (1961) showed that the maximum radial velocity in spots increased with increments in μ (= Cos θ) values. His interpretation is that the higher layers have lesser radial velocity in spots as compared to the deeper layers. Holmes (1963) also detected a similar variation in the U_{max} as the spot approached the limb, but interpreted this as the effect of scattered light in the telescope which becomes important as the spot is foreshortened at the limb.

High Resolution Observations

Among these mention must be made of observations by Holmes (1961, 1963), Bhatnagar (1964) and Schröter (1965a,b) who used dispersions in the range 5.0 to 8.0 mm/Å for the study of the Evershed phenomena.

Bhatnagar (1964) measured the sight-line velocities on a spot during its successive passage across the disc for various positions on the disc (ranging from μ = 0.35 - 0.95) using non-Zeeman lines (Ni I 4912 Å, Fe I 5576 Å and Fe I 5691 Å). He used the Kodaikanal 120 foot focal length solar tower telescope which has an image scale of 5.5 arc sec mm^{-1} and the associated 60 foot spectrograph at dispersions of ~ 8 mm $Å^{-1}$. The radial velocities derived by him from the line-of-sight velocities assuming cylindrical symmetry, steeply rose from the umbral border reaching a maximum value of 1.5 - 2.0 km sec^{-1} near mid penumbra and then declined gradually to almost zero far out in the photosphere. Ni I 4912 Å and Fe I 5691 Å showed similar velocities whereas Fe I 5576 Å had systematically lower velocities by about 30-35%. The velocities in all the three line progressively decreased from the centre to the limb, a fact that was noticed by Michard (1951) and Servajean (1961) earlier. This is more pronounced for observations made close to the limb (Holmes, 1963). The straight line fit to the plot of the velocities for different μ positions show that the slopes for the two weak lines 4912 Å and 5691 Å are nearly the same, while the slope is flatter for the strong line 5576 Å. This makes one feel that the velocity dependence with height in the atmosphere may be real, although the scattered light would contaminate the estimation of velocities to a certain extent. Another interesting point in Bhatnagar's velocity measure is that they pertain to the successive passages of the same spot and the fact emerges that the radial velocities are higher in the fully developed phase than in the early phase of growth of the spot.

The existence and the numerical value of the tangential velocities are debatable points. There are as many observations in the literature showing the presence of the tangential velocities as there are pointing to their absence. Evershed (1909c, 1910) detected tangential components of 0.25 to 0.35 km sec^{-1}. However in his later measurements (1916) he found no evidence for a regular tangential component, although irregular velocities were present at times. Kinman (1952) believed that the tangential component was random in nature and in general was within the errors of measurement although at some locations within the spot the value was as much as -0.5 ± 0.2 km sec^{-1}. But his neglect of the tangential component in the interpretation of his later measurements (1953) appears prejudicial. Abetti's (1932) measurements on 26 spots show irregular tangential component with values varying from 0 to 5 km sec^{-1}. Measurements of Servajean (1961) and Bhatnagar (1964) are indecisive and the errors in the latter's measurements are rather large, making a realistic conclusion on the tangential components not possible. Systematic and precise measurements with high spatial and spectral resolution are called for to settle this question.

The use of high spatial resolution and spectral resolution not only made the velocity measurements more precise and error free, but also brought out the microscopic structure of the Evershed flow as motions in the penumbral filaments as well as the phenomenon of asymmetry of spectral lines in the penumbral regions. Bumba (1960) using the high dispersion spectrograph of the Crimean

Observatory detected the strong asymmetry in the line profiles within the penumbra which accompanies the Evershed flow. Servajean (1961) studied the changes in the line asymmetries for different spot positions on the solar disc. Bumba termed this phenomenon the 'line flag' whereas Holmes (1963) who also studied the asymmetry called it the 'line flare'. It is interesting to note that Evershed (1916) detected in his low dispersion spectra that the spectral lines develop a 'diffuse wing' in the direction of the Evershed displacement near the outer boundary of the penumbra. Similar diffuse asymmetric widening was also detected in the spot spectra at the McMath-Hulbert Observatory (1956). But its real significance was brought out only by the work of Bumba and Servajean. Under very favourable seeing conditions, Bumba was even able to resolve the broadening into a satellite line but Servajean, Holmes or Bhatnagar do not find any indications of such a satellite line in their spectra. Bhatnagar (1964) in his photometric study has investigated the dependence of the asymmetry on the strength of the line, on the locations of the slit on the spot and on the spot's position on the disc. The asymmetry grows in magnitude from the edge of the penumbra and reaches maximum values around the middle of the penumbra. The asymmetry has the same sense as the Evershed flow for the three lines he used (4912 Å, 5576 Å and 5691 Å) and probably therefore is independent of the strength of the line. Also, the maximum asymmetry is a function of the spot's position on the disc, such that the spot near the disc centre has an asymmetry maximum smaller than for spots near the limb. Again stronger lines show less of asymmetry than the weaker lines. Bumba finds that the flagging in D_1 and D_2 lines of Na I is opposite to the direction of the Evershed displacement and the direction of flag near the core of these lines is opposite to that in the wings. Servajean (1961) has suggested that the asymmetry is a manifestation of the different velocities corresponding to the different strata in the line forming layers, whereas according to Bumba (1963) the upstreaming of material at the umbral-penumbral boundary which bends and becomes horizontal in the penumbra cause the asymmetry. The asymmetry can also result when the outward moving material in the bright fibrils of the penumbra cause a blue wavelength shift which is not balanced by the inflowing matter in the dark fibrils of the penumbra (Schröter 1965b). Such an asymmetry would give a C-shape to the bisector of the line profile. The C-shape and its change for different μ positions have been investigated in great details by Schröter (1965a) using the Freiburg spot spectra employing the equidensitometry technique. The potentialities of this technique in bringing out the finest details in the spectra are well illustrated in his paper. His (Schröter 1965a) figure 6 shows that the displacement is small in the line core, and the asymmetry reaches a maximum value at a distance of 0.8 times the radius of the spot from the spot centre. The centre to limb variations of the Evershed velocities at a fixed location from the centre of the spot shows that the velocities increase towards the limb reaching a maximum at $\mu \simeq 0.4$. He also studied the variation of the asymmetry using the line Fe I 5123 Å within the penumbra. The core of the line shows small displacements which increases away from the core and again falls less steeply at the wings. According to him, the sunspot spectra obtained at high spatial resolution show not only line asymmetry but resolve into strong satellites (as seen by Bumba), which appears diffuse at the photosphere - penumbra boundary and rather sharp on the other side of the line centre.

The Evershed flow in the photosphere chromosphere interface region was investigated by Bones and Maltby (1978) from the velocities in the core and in the wings of the Mg b_1 line using high resolution spectra. The measured velocities (~ 1.8 km/sec) follow the pattern already known from earlier studies. Another front from which the motions in sunspots were investigated was by using high spatial resolution photographs of sunspots. From the time sequence photographs of the Princeton stratoscope project Schröter (1962) was able to detect the systematic motions of the bright knots in the bright penumbral filaments. These knots which form part of the filaments move outward from the centre of the spot with a mean velocity of ~ 2km sec^{-1}. He also detected material motion in the opposite direction in the dark channels that lie in between the bright filaments. There could be little doubt that these proper motions of the bright knots represent the Evershed flow that we see in the spectra of spots. Some of Bhatnagar's spectra (1964) show continuum brightness fluctuations in the penumbral regions that represent the motions of the bright knots. Maltby's (1975) results on the velocities in the chromosphere derived from H_α filtergrams obtained on either wings at $\Delta\lambda \pm 0.25$ Å, ± 0.5 Å and ± 0.75 Å with a resolution of 1/8 A provide a three dimensional picture of the Evershed flow and its variation with time. The flow which is concentrated in channels is directed towards the umbra. These velocity channels occur mostly in regions occupied by the dark fibrils, whereas the flow channels with velocity directed away from the spot appear bright as in the continuum (Schröter, 1962). One interesting point is that the apparent length of the flow channels differ at different heights - they are long in the chromosphere (~ 16 arc sec) and shorter at the lower levels (~ 7 arc sec). The flow channels which are in the form of loops alter with a characteristic time of about 10 minutes which possibly also represents the characteristic time of perturbations of the flow channels.

Finally, I shall mention about the high spatial resolution two dimensional observations of Sheeley and Bhatnagar (1971) and of Sheeley (1972) which have provided a final answer to some of the questions relating to the Evershed flow. For example the question where the Evershed flow terminates has been a subject of much dispute since the time of its discovery. They derived a series of Dopplergrams from a time lapse sequence of spectroheliograms obtained on either wings of the Zeeman insensitive line Fe I 5434 A. These velocity field pictures showed clearly that the Evershed flow confines itself to the dark spoke like filaments that end in the rugged outer boundary of the penumbra and the magnitude of the Evershed velocity is ~ 4-6 km sec^{-1}. Besides this, they also noticed an extra penumbral horizontal flow with speeds of 0.5 - 1.0 km sec^{-1} which extended to 10,000 - 20,000 km beyond the penumbral boundary. Comparison of these Dopplergrams with the CN 3883 Å spectroheliograms showed that this extra penumbral flow terminated at the facular network. This high spatial resolution study established that the extra penumbral flow is indistinguishable from the well known supergranular flow and is distinctly different from the Evershed flow.

In conclusion I shall list the salient points which require immediate attention and study.

I. The relation between the Evershed velocities and the size of the spot and the magnetic field configuration associated with it should be firmly established.

II. We do not know how the motions are related to the evolutionary aspects of the spots? At what phase of the growth of the sunspots does the flow start? How are velocities related to the age of the spot?

III. The problem of tangential velocities should be settled.

IV. According to Galloway's model of the Evershed flow, the flow is in the form of pulses. It would be interesting to check for any periodicities or the pulse nature of the flow.

V. How are the line asymmetries caused?

VI. What is the nature of the velocity pattern in bipolar spots?

Answers to these questions from studies at high spatial and spectral resolution should help us to understand fully the macroscopic structure of the Evershed phenomenon which even to this day remains as enigmatic as it was 75 years ago.

References

Abetti, G., 1932, Mem. Soc. Astr. Ital. **6**, 353.

Bhatnagar, A., 1964, Ph.D. Thesis, Kodaikanal, Unpublished.

Bones, J., and Maltby, P., 1978, Solar Phys. **57**, 65.

Brekke, K., and Maltby, P., 1963, Ann. Astrophys. **26**, 383.

Bumba, V., 1960, Izv. Krym. Astrofiz. Obs. **23**, 253.

Bumba, V., 1963, Bull. Astron. Inst. Czech. **14**, 137.

Evershed, J., 1909a, Mon. Not. Roy. Astron. Soc. **69**, 454.

Evershed, J., 1909b, Kodaikanal Obs. Bull. **2**, No.15, 63.

Evershed, J., 1909c, Mem. Kodaikanal Obs. **1**, Part I.

Evershed, J., 1910, Mon. Not. Roy. Astron. Soc. **70**, 217.

Evershed, J., 1916, Kodaikanal Obs. Bull. **3**, No.51, 167.

Hale, G.E., 1908, Astrophys. J. **28**, 314.

Holmes, J., 1961, Mon. Not. Roy. Astron. Soc. **122**, 301.

Holmes, J., 1963, Mon. Not. Roy. Astron. Soc. **126**, 155.

Kinman, T.D., 1952, Mon. Not. Roy. Astron. Soc. **112**, 425.

Kinman, T.D., 1953, Mon. Not. Roy. Astron. Soc. **113**, 613.

Maltby, P., 1964, Astrophys. Norveg, **8**, 205.

Maltby, P., 1975, Solar Phys. **43**, 91.

McMath, R.R., Mohler, O.C., Pierce, A.K., and Goldberg, L., 1956, Astrophys. J. **124**, 1.

Michard, R., 1951, Ann. Astrophys. **14**, 101.

Schröter, E.H., 1962, Z. Astrophys. **56**, 183.

Schröter, E.H., 1965a, z. Astrophys. **62**, 228.

Schröter, E.H., 1965b, Z. Astrophys. 62, 256.

Schröter, E.H., 1967 In Solar Physics, ed. John N. Xanthakis; Interscience Pub. p.325.

Servajean, R., 1961, Ann. Astrophys. **24**, 1.

Sheeley, N.R., and Bhatnagar, A., 1971, Solar Phys. **19**, 338.

Sheeley, N.R., 1972, Solar Phys. **25**, 98.

St. John, C.E., 1913, Astrophys. J. 37, 322.

DISCUSSION:

GOKHALE: Has anyone looked for short time scale variations in Evershed velocity?

SIVARAMAN: In the model of Galloway he shows that Evershed phenomenon is in the form of pulses. It would be worthwhile to obtain time lapse spectra and search for any temporal periodicities.