The Evershed Effect as we Understand it Today

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Following a description of the Evershed effect as observed by John Evershed in 1909 at the Kodaikanal Solar Observatory, we discuss the evolution of our scientific understanding that accompanied the development of the subject of magnetohydrodynamics (MHD). How the modern telescopic observations as well as the computational capabilities are serving to uncover the complex magnetohydrodynamic processes behind this highly dynamical phenomenon is discussed at length.

When we observe the spectrum of the Sun, we notice a number of dark lines superposed on a background of rainbow coloured spectrum. These lines, called Fraunhofer lines, are caused by matter near the surface of the sun (i.e., the photosphere) . This gaseous matter is not static, but moves, and this movement shifts the position of the dark lines (just as the pitch of a moving siren goes up or down depending on the motion). This is known as the Doppler shift of spectral lines.

The Evershed effect refers to the phenomenon of characteristic Doppler shifts of photospheric spectral absorption (Fraunhofer) lines observed over the penumbrae of sunspots, and is named so after its discoverer John Evershed. This discovery by Evershed, early in 1909, was through a high dispersion spectrograph that he designed and built at the Kodaikanal Solar Observatory. He observed several sunspots at various positions on the solar disk, up to 50 deg. on either side of the central meridian, and found that the line displacements were more pronounced in the penumbral regions of the spots located closer to the limb of the Sun.

Through a careful analysis of his observations, Evershed provided an accurate interpretation: the gas motions in sunspot penumbrae are radial outflows parallel to the solar surface. This basic result still remains so in our modern observations with vastly improved spectral and spatial resolutions. Evershed's

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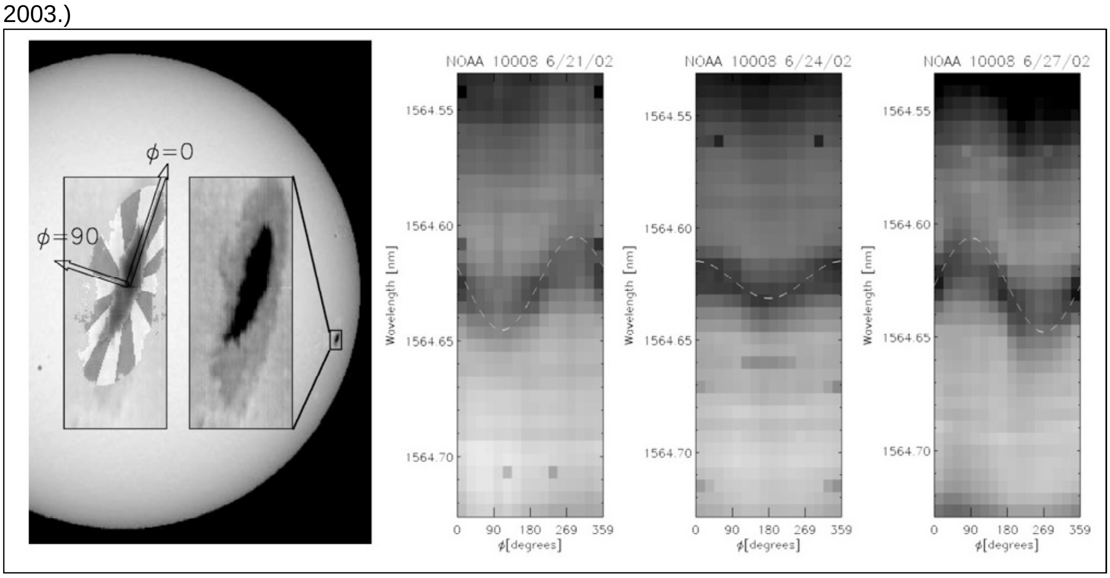
initial estimates of flow speeds were of the order of 2 km/s, and he found increasing speed as distance increased from the spot center, and no tangential compononets for flow velocity. His later results, using spectral lines formed in the chromospheric layers (located above 500–1000 km from the photosphere), indicated a radial inflow of gas at these heights; and he measured small tangential component for photospheric velocities, but considered them unreliable because of their irregular nature. A modern observation that illustrates the Evershed effect is shown in *Figure* 1.

The basic physical causes of the Evershed effect, however, are still not fully understood. This has been primarily due to the fact that the underlying physical processes are governed by magnetohydrodynamics (MHD) – the study of combined interactions of electrodynamic and hydrodynamic forces – in an astrophysical setting, studying the details of which continues to challenge our modern technological abilities in both telescopic observations and computational modelling.

Figure 1*. *A modern observation of Evershed effect by M Penn et al (Ap. J. Letters, Vol.590, p.L119, 2003) using the US National Solar Observatory's Kitt Peak Vacuum Telescope. Left panel: The background image, taken at a wavelength of 869 nm, shows the disk position of a sunspot observed on June 29, 2002. The two inset images show continuum maps at 2231 nm, with the penumbral bins and spot azimuth directions shown in the left inset. Right panels: Doppler shifts of CN line at 1564.625 nm as a function of azimuth angle around the sunspot during 3 days. The spot positions were 0.65 (east), 0.27, and 0.66 (west) solar radii from disk center on June 21, 24, and 27, respectively. The line absorption can be seen at a variety of wavelengths ranging from zero outflow speed up to about 9 km/sec. The dashed lines show the typical horizontal speed of 6 km/sec corrected for projection effects. (Credit: M Penn *et al.*, *Ap. J. Letters*, **Vol.590,** p.L119, 2003.)



Evershed's discovery surfaced early in an exciting era of spectroscopic techniques to study the Sun and other celestial objects, at the turn of the last century, and as such predated, by three to four decades, the development of the actual means to describe the phenomenon in its right context, namely, the subject of magnetohydrodynamics. As we look back, with our current appreciation of the ubiquitous presence of magnetohydrodynamical phenomena in the Universe, Evershed's observations clearly stand out as the earliest successful ones of such a phenomenon in action in a celestial setting.

The immediate scientific impact of Everhsed's discovery pertained to another momentous event in astrophysics, viz., the detection of a magnetic field in sunspots by George Ellery Hale a year earlier in 1908 at his Mt.Wilson Observatory, California. This was the first ever discovery of an extraterrestrial magnetic field, and was motivated by the prevailing speculations that sunspots were giant vortices and that all rotating heavenly bodies harbored a magnetic field. Hale considered his detection of magnetic field in sunspots, in turn, as an indication of swirling flow of ionized gas, which could have generated the magnetic field locally.

However, as Evershed himself pointed out in his discovery paper in 1909 [1] his observations of radial outflow of gas made the circular flow hypothesis untenable. It was not until the early 1930's that the local generation of axisymmetric magnetic field, such as those in sunspots, due to axisymmentric motions were shown to be impossible by Cowling through theoretical calculations (Cowling's anti-dynamo theorem [2]), and in particular, he suggested sunspots as pre-existing tubes of magnetic flux breaking through the surface.

Immediate follow-up research on Evershed effect, naturally, was through intense observational examinations, most notably at Mt.Wilson Observatory. More observational programs followed gradually all over the world, and in general, observational studies have gone on almost continuously over the past century. Modern high resolution observations, starting from the 1990's, from various groups all over the world, have served to spatially resolve the flow and magnetic structures which have the following dominant properties: flow occurs mainly in the dark penumbral filaments where the field is more nearly horizontal than average, and the inner penumbral heads of horizontal flow structures have concentrated but bright upflows, which feed the horizontal flows.

A modern high-resolution observation from the Japanese space mission HINODE is shown in *Figure* 2: the left panel is a white light continuum image and the right panel is a Dopplergram, which is a map of line of sight (LOS) velocities – dark shade represents flow towards and the bright shade flow away from the observer.

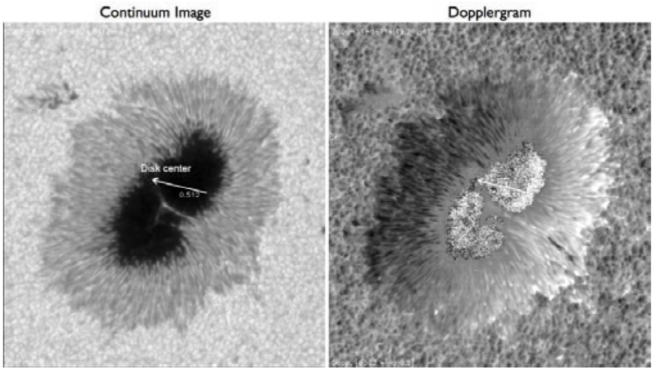


Figure 2. A high-resolution observation of a sunspot from the Japanese space mission HINODE. Left panel: White light continuum image of the sunspot. Right panel: Dopplergram – a map of Doppler shifts converted to line of sight (LOS) velocities – of the same sunspot derived from the spectral line Fe I (630.2 nm); dark shade represents flow towards and the bright shade flow away from the observer. (Credit: Kiyoshi Ichimoto (Kyoto Univ.) and SOT/HINODE Team.)

MHD and Evershed Effect

Understanding the phenomenon of sunspots seeded the initial development of the subject of MHD, which followed promptly the discoveries of Hale and Evershed at the turn of the last century. MHD describes how the electrodynamics of an ionised gas subject to an external magnetic field couple to its bulk hydrodynamic motion. That this coupling could generate a transverse wave, known as the Alfven wave, propagating along the magnetic field was first predicted by Hannes Alfven in 1942 [3]. The above Nobel Prize-winning work (1970) of Alfven was, in fact, out of his attempts to explain the migrations of sunspots towards the solar equator.

Though his attempts to explain the sunspot motions turned out to be incorrect, Alfven's theoretical work paved the way for the formal development of MHD as a major scientific discipline with wider applications to astrophysical phenomena. Though it involves the marriage of two well understood classical disciplines, MHD has been notorious for presenting highly complex dynamical phenomena, especially in astrophysical settings. Sunspots are prime examples of such complexities, but are also considered as excellent proving ground for MHD because they can be studied in such a wealth of details owing to our close proximity to our star, the Sun.

The two key physical effects in MHD, viz. (i) the dynamo action that makes good of fluid motions to generate and amplify magnetic fields, and (ii) the modification of fluid motions and energy transport by the generated field, are thought to be basic to all the varied MHD phenomena observed in the Universe. As referred to earlier, ideas on the presence of dynamo action in heavenly bodies were speculated much earlier and were the motivating factor for Hale in his discovery of magnetic field in sunspots. Soon after Cowling's (1934) anti-dynamo theorem made Larmor's (1919) proposal [4] that sunspots were sites of homogeneous fluid dynamos as an unlikely scenario, attention turned to explaining their thermal (darkness) structure as a consequence of strong magnetic field – the latter of the above two basic MHD effects.

Biermann [5] suggested in 1941 that the magnetic field, due to its force on moving charges, could exert a net body force on the motion of gas across field lines and, if strong enough, could largely stop the convective of flow energy leading to the darkness of sunspots. Cowling [6] in 1953 furthered the ideas of Biermann. Theoretical interpretations of the Evershed effect, however, started relatively late in 1955 when Sweet found an origin in convectively driven motions [7]. Since then, there have been several different theories based on magneto-convective mechanisms to explain the Evershed flow, most notable ones being: (i) a linear theory of convective rolls in horizontal magnetic field proposed by Danielson (1961) [8] and its non-linear modification by Galloway (1975) [9] to drive a radial outflow, (ii) Busse's theory in 1987 [10] of three dimensional convection in inclined magnetic field, where Reynolds stresses drive a Evershed flow, and (iii) interchange convection of Jahn and Schmidt [11] in 1994 and Schlichenmaier *et al* [12] in 1998 where a dynamical evolution of thin magnetic flux tubes produces the Evershed flow.

A major theoretical attempt involving a non-convective origin for the Evershed flows is the siphon flow proposal by Meyer and Schmidt in 1968 [13] and its detailed exploration by Thomas, Montesinos *et al* [14]. Here, pressure differences between the photospheric end points of arched flux tubes spanning from the inner penumbra to the outer penumbra drive flows along the tubes. The siphon flow models of Montesinos and Thomas in 1997 have the attractive feature that they can consistently explain both the normal (outward) and the reverse (inward) Evershed flows at the photospheric and chromospheric layers, respectively.

Magneto-Convective Simulations

We are currently in a period of revived attention mostly fuelled by our increased numerical computational capabilities to simulate MHD processes. Interactions between convective motions and the magnetic field of a sunspot could easily be appreciated from observations shown in *Figure* 2: in regions outside of the sunspot, where no strong magnetic fields are present, convection goes on in the form of overturning granular cells, which have bright upflows surrounded by narrow downflow lanes; on the other hand, within the sunspot, the dark umbral region is devoid of any convective pattern while the penumbra shows radially elongated bright and dark structures indicating of a modified pattern of convection. Based on 3D nonlinear simulations of such interactions between turbulent convection and magnetic fields, a new magneto-convective picture of Evershed flows has emerged [15,16] where the convective interactions between an upward hot plume and magnetic field produce all the necessary ingredients to drive a horizontal Evershed flow as observed.

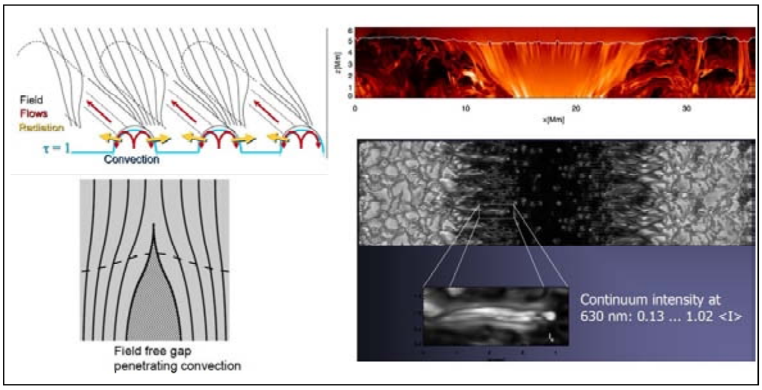


Figure 3. A 3D nonlinear magnetoconvection simulations of a sunspot with Evershed flows by M Rempel et al [16]. The left panels depict the geometry of magnetic and flow fields facilitatingthe magnetoconvection interactions as seen in the simulations, snapshots of which are in the right panels: the top right panel shows the magnetic field strength, varying from zero (dark) to about 9000 Gauss (white shade), and the bottom right panel shows a continuum intensity snapshot. Refer to the text for more details.

The results from such simulations [16] are shown in *Figure* 3. The panels in the left show the basic geometry of the magnetic field and the resulting convective flows: the inclined magnetic field in the penumbra causes a symmetry breaking which leads to elongated filaments with strong outflows along the nearly horizontal magnetic field near optical depth unity. The upflow also turns over into a motion perpendicular to the filament axis. Dark lanes (see the right panel) appear above the strongest upflows owing to the upward bulging of the surface of optical depth unity and the piling up of plasma in a cusp-shaped region at the top of the filament, above which the less inclined field outside the filament becomes laterally fairly homogeneous. The horizontal outflows are concentrated along the dark lanes. The top right panel shows the magnetic field strength, varying from zero (dark) to about 9000 Gauss (white shade), and the bottom right panel shows a continuum intensity snapshot from the simulations.

Overall, the deeper connections between fine-scaled magnetic fields and the Evershed flow fields have always been the motivating factor to go for higher spatial and spectral resolution observations, which have proved to be essential in understanding this dynamical phenomenon. A complete and fully consistent picture of Everhsed flows, with ability to match all the observed features is yet to be realized, even a 100 years after its discovery. It is likely that a more delicate and detailed picture of Evershed flows would emerge from very high spatial and spectral resolution spectropolarimetric observations planned in the near future. It is equally likely that the fast developing computational resources and algorithms could get complex enough to reproduce well the observations.

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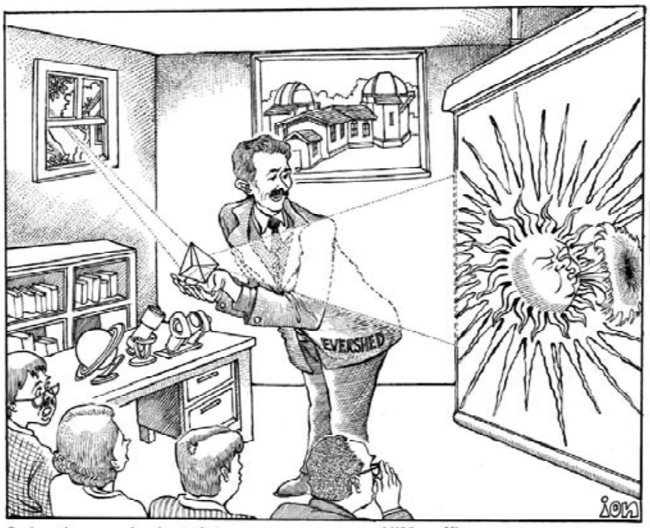

Only when we look at the spectrum, we see HIM puffing..