Recent evidence for convection in sunspot penumbræ

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Abstract

Whereas penumbral models during the last 15 years have appeared successful in explaining Evershed flows and magnetic field inclination variations in terms of flux tubes, the lack of connection between these models and a convective process to explain the penumbral radiative heat flux has been disturbing. We report on recent observational and theoretical evidence that challenge these flux tube interpretations and instead suggest overturning convection as the origin of the penumbral filamentary structure.

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1. Introduction

Despite considerable progress during the last decade, a theoretical framework that explains sunspot fine structure, dynamics, magnetic fields and energy balance in a consistent manner is only now beginning to emerge. This situation can partly be attributed to the small horizontal scales associated with sunspot fine structures and the relatively poor spatial resolution achieved with spectropolarimetric observations. In addition, realistic numerical three-dimensional (3D) magnetohydrodynamic (MHD) simulations of sunspot fine structure have only recently become possible.

During the last few years, there has been a remarkable improvement in the quality and diversity of observational data relevant to the understanding of sunspot fine structures, dynamics, magnetic fields and energy balance. In particular, high-spatial resolution observations from the Swedish 1-m Solar Telescope (SST) and Hinode reveal new sunspot structures and flow patterns at odds with prevailing interpretations in terms of flux tubes, but consistent with interpretations in terms of convection.

2. Dark cores in penumbral filaments

A fundamental problem of sunspots is to explain the mechanism responsible for the high radiative flux. The umbral bolometric flux is \(\sim 20\%\) that of the quiet sun, that of the penumbra \(\sim 75\%\). To explain the penumbra heat flux, efficient convection with vertical velocities of the order of \(1 \text{ km s}^{-1}\) are needed. Larger velocities than that are observed, but these are mostly horizontal. Furthermore, clear observational evidence for convection associated with bright upward and dark downward flows has been missing or inconclusive. Strong evidence for penumbral convection has, until recently, been essentially absent.

Important clues for understanding penumbræ come from the discovery of dark cores in bright penumbral filaments (Scharmer et al 2002), shown in figures 1 and 2. These were interpreted by Spruit and Scharmer (2006) as evidence for radially aligned and nearly field-free gaps below the penumbral photosphere. Within these gaps, convection carries the heat flux to the surface. In order to be in force-balance with the surrounding strongly magnetic gas, the gas pressure in the gaps must be higher than in the surrounding areas. This causes the elevation of the visible surface, defined by continuum optical depth \(\tau = 1\), to vary strongly across the filaments, such that we see the highest layers at the locations of the dark cores. The darkness of the cores is due to a combination of high gas pressure (low field strength) and an overall drop of temperature with height. The presence of strong fluctuations in the field strength thus gives rise to correlations between field strength and intensity where dark denotes a weak field and bright a strong field. The centres of the convective upflows appear counterintuitively as dark rather than bright structures. This magnetic field strength–brightness correlation, valid in the inner and mid-penumbra where the average field strength is high and the warping of the \(\tau = 1\) surface strong,
partly explains the lack of clear evidence for convection in penumbras in earlier investigations.

Dark cores were observed with the SST also above light bridges by Lites et al (2004). The highly resolved images of large pores with partial penumbrae, observed off disc centre, strongly suggest a 3D landscape with a $\tau = 1$ surface (Wilson depression) set by the magnetic field. In particular, the light bridges observed give the impression of mountain ridges, the peaks of which are outlined by dark cores. Three-dimensional MHD simulations of a simple light bridge structure by Nordlund shows a similar dark lane at the centre of the light bridge. This dark lane is formed by the same mechanism discussed above and is not related to convective downflows.

The relevance of the light bridge simulation in the context of dark-cored penumbral filaments is strongly supported by observations showing dark cores in light bridges connecting to dark cores in penumbral filaments (Scharmer et al 2007). Upflows at the location of light bridge dark cores have recently been found by Rimmele (2008).

3. Recent evidence for penumbral convection

Quite recently, strong evidence for penumbral convection has appeared in two independent investigations, based on Hinode and SST data. The Hinode data (Ichimoto et al 2007) consist of blue continuum images and 6302 spectra of penumbral filaments. Filaments located in the parts of the penumbra perpendicular to the sunspot symmetry axis, i.e. the line from sun centre through the centre of the spot, were analysed. The sunspot was located at approximately 30$^\circ$ from sun centre. At the locations perpendicular to the symmetry axis of the sunspot, flows that are perpendicular to the radial direction of the filaments can be observed with minimum interference from radially aligned near-horizontal (Evershed) flows. Space–time plots of the evolution of the filaments observed in the blue continuum show small-scale brightness structures that move across the filaments at a speed of 1–2 km s$^{-1}$, giving the impression of rotating or even twisting filaments. However, irrespective of the location of the spot on the solar disc, all filaments showed apparent motions of the brightness structures in the direction towards the sun centre. Ichimoto et al (2007) therefore concluded that the apparent twisting motions are neither an actual twist nor a helical motion of individual filaments. They suggest that the observations can instead be explained by a locally elevated $\tau = 1$ surface associated with hot and dense convective upflow plumes, consistent with the scenario proposed by Spruit and Scharmer (2006). The locally elevated $\tau = 1$ surface at the centre of the filaments and the 30 degree heliocentric distance of the sunspot then combine to hide the limb side of the filaments, such that only the top and centre of the filaments can be observed (Scharmer and Spruit 2006). Since the convective flows turn over horizontally with a motion that is directed away from the centre of the filament (the location of the dark core), a systematic flow that is always in the direction of the observer is seen, explaining the apparent rotational or ‘twisting’ motions of the filaments. Simultaneously recorded spectra show blue shifts confirming flow speeds measured from the moving brightness structures.

Independent evidence for convection comes from observations of a sunspot at 40 degree heliocentric distance with 6302 polarimetric filtergram data using the SST of Zakharov et al (2008). For filaments that were aligned with
a direction approximately perpendicular to the symmetry line, Zakharov et al measured local upflows of $\approx 1.1 \text{ km s}^{-1}$ associated with a magnetic field that is more horizontal and weaker than its surroundings by a factor of nearly two. Somewhat unexpectedly, these observations are interpreted in terms of convective rolls. However, this appears speculative since the inflow towards the centre of the filament, needed to complete the roll, must occur deep below the surface and is unobservable. Furthermore, penumbral filaments have lifetimes of the order of an hour or more, and to sustain radiative losses for such a long time, the convective upflow cannot be a shallow feature.

4. Conclusion

Until recently, theories of penumbra fine structure have focused on explaining Evershed flows and the large observed variations in magnetic field inclinations across penumbral filaments. At low spatial resolution, simple models of nearly horizontal flux tubes, embedded in a more vertical magnetic field have been found to be consistent with observations. Very little contact has been made between these models and the convective process needed to sustain the radiative output of sunspot penumbrae.

In sharp contrast, the ‘gappy’ penumbra model of Spruit and Scharmer (2006) explains the filamentary structure, the energy balance and the large magnetic field inclination variations in the penumbra as a result of overturning convection. Based on numerical simulations (Heinemann et al 2007), Scharmer et al (2008) concluded that the Evershed flow is in fact identical to the horizontal flow component of such convection. Recent observations from Hinode and the SST support this new interpretation of penumbral fine structure, even though there remain uncertainties as regards the details of the convective process.

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References

Heinemann T, Nordlund Å, Scharmer G B and Spruit H C 2007 Astrophys. J. 669 1390–4
Ichimoto K et al 2007 Science 318 1597
Lites B W, Scharmer G B, Berger T E and Title A M 2004 Sol. Phys. 221 65–84
Rimele T 2008 Astrophys. J. 672 684–95
Scharmer G B, Gudiksen B V, Kiselman D, Löfdahl M G and Rouppe van der Voort L H M 2002 Nature 420 151–3
Scharmer G B, Langhans K, Kiselman D and Löfdahl M G 2007 New Solar Physics with Solar-B Mission (Astronomical Society of the Pacific Conference Series vol 369) ed K Shibata, S Nagata and T Sakurai p 71
Scharmer G B, Nordlund Å and Heinemann T 2008 Astrophys. J. Lett. 677 L149–52
Scharmer G B and Spruit H C 2006 Astron. Astrophys. 460 605–15
Spruit H C and Scharmer G B 2006 Astron. Astrophys. 447 343–54
Zakharov V, Hirzberger J, Riehmüller T L, Solanki S K and Kobel P 2008 Astron. Astrophys. 488 L17–20