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Models and observations of sunspot penumbrae

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The mysteries of sunspot penumbrae have been under an intense scrutiny for the past 10 years. During this time, some models have been proposed and refuted, while the surviving ones had to be modified, adapted and evolved to explain the ever-increasing array of observational constraints. In this contribution I will review two of the present models, emphasizing their contributions to this field, but also pinpointing some of their inadequacies to explain a number of recent observations at very high spatial resolution (0.32″). To help explaining these new observations I propose some modifications to each of those models. These modifications bring those two seemingly opposite models closer together into a general picture that agrees well with recent 3D magneto-hydrodynamic simulations.

sunspots, magnetic fields, spectropolarimetry, magnetohydrodynamics

1 Embedded flux-tubes and Field-free gap models

In its most basic manifestation the structure of the penumbral magnetic field can be described as being *uncombed* (i.e. composed of two distinct interlaced components). The first component, *spines*, is characterized by a strong ($B \sim 1700$ Gauss) and inclined ($\gamma \sim 45°$)1) magnetic field. Because of the similarities it shares with the umbral magnetic field, this component is often thought to be an extension of it. The second component, *instraspines*, appears interlocked in between spines and is characterized by a weaker and more horizontal ($B \sim 1200$ Gauss, $\gamma \sim 90°$) magnetic field. This spine-intraspine structuring is already seen at 1 arcsec resolution[1]. The most successful models to explain the uncombed penumbral structure are the embedded flux-tube and the field-free gap models.

The idea of penumbral flux tubes is an early concept gathered when the first stratospheric balloons took continuum images of sunspots at 1 arcsec in the late 50's and early 60's2)[2] revealing in detail the filamentary structure of the penumbra. However, it was not until Solanki & Montavon[3] that penumbral flux-tubes were first invoked to explain the uncombed structure of the penumbral magnetic field. In this model, penumbral intraspines are assumed to be composed by at least one horizontal magnetic flux-tube. The Evershed flow is assumed to be channeled along these radially aligned flux-tubes, which are embedded in a surrounding atmosphere with a less inclined and generally stronger magnetic field (i.e. spines).

The Field-free gap model (hereafter referred to as *gappy penumbra*) was possibly first proposed

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1) Here γ refers to the inclination of the magnetic field with respect to the vertical direction on the solar surface
2) There is a very brief reference to *tubes* in Danielson

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by Choudhuri[4] to explain the connection between umbral dots and penumbral bright grains. It was later employed to explain the uncombed nature of the penumbral magnetic field[5]. In this picture, field-free plasma rising from the beneath the sunspot would pierce into the sunspot magnetic field from below, creating a region right above the field-free gap where the magnetic field is horizontal and weaker (intraspine) than in the gap's surroundings, where the field is stronger and less inclined (spines).

2 The Evershed flow

Within the frame of the flux-tube models the Evershed flow is usually explained in terms of a siphon flow channeled along a thin flux-tube[6]. This concept was developed in detail for steady[7] and dynamic[8,9] flux tubes. Simulations based on siphon flows help to explain supercritical and supersonic Evershed velocities[10], formation of shock fronts[11], proper motions of penumbral grains[12,13], and moving magnetic features as a continuation of the Evershed effect in the sunspot canopy[14−19].

The gappy penumbral model, as initially proposed[4,20], does not identify the origin of Evershed effect. Within the field-free gap there are convective flow motions (upflows at the gaps' center and downflows on the edges), but these are unable to explain the radially outwards Evershed flows observed in the deep photosphere. It has been proposed[20] that the hot plasma inside the gap could heat the atmosphere above it, where the horizontal field lies, producing a local version of the mechanism introduced by Schlichenmaier et al.[20] to drive the Evershed flow.

3 Spectropolarimetric observations

Both the flux-tube and gappy-penumbra models feature one of the key ingredients to explain the polarization profiles observed in the penumbra at $\simeq 1$ arcsec resolution: the uncombed structure of the magnetic field (see sec. 1). The other requirement is the presence of a strong ($\gtrsim 5$ km·s^{-1}) radial outflow in the weaker and horizontal component of the magnetic field. This is readily included in the flux-tube model (see sec. 2), and consequently this model is able to explain the anomalous polarization signatures observed in sunspot penumbrae (e.g. multi-lobed and highly asymmetric Stokes V profiles). This includes the Stokes profiles in the visible Fe I 630 nm[21], near-infrared Fe I 1.56 μm[11,22−25], Ti 2.2 μm spectral lines[26] and even simultaneous observations in different wavelength ranges[27−29]. It is also possible to explain the azimuthal variation of the net circular polarization[30−33], as well at is center-to-limb variation[3,32,34] in different spectral lines.

So far, the gappy penumbral model has not been used to explain the polarization signals in the sunspot penumbra. Without further modifications, such an attempt will face severe difficulties since this model does not include a radial outflow in the horizontal magnetic field above the field-free gap. Having a horizontal flow along the field-free gap (instead or in addition to the convective flow) produces net circular polarization[35], but it has not been demonstrated that it possesses the correct sign nor that its azimuthal variation matches the observations. It also seems unlikely that multi-lobed Stokes profiles can be produced with such a flow configuration.

4 Dark-cored penumbral filaments and penumbral heating

The high average brightness of the penumbra (about 70 % of the quiet Sun) imposes strong constraints as to which mechanism is responsible for its heating[36]. Within the horizontal flux-tube model, the energy source invoked is the Evershed flow itself, which appears in the inner penumbra (where the flux-tubes are slightly tilted upwards) as a hot upflow that develops inside the flux tube and quickly becomes horizontal. This hot upflow heats the filament as it moves radially outwards. Numerical estimates have shown that the radiatively cooling time is very short, producing bright filaments that are much shorter than observed[37]. Schlichenmaier & Solanki[38] postulate that long and bright filaments can be explained if a new hot upflow appears right after the previous one cools down and sinks as a downflow. However, the smooth variations of the inclination observed along filaments at very high spatial resolution seem to rule out this possibility[39,40]. This problem has been revisited recently[41] generalizing the calculations done by Schlichenmaier et al.[37] to three dimensions, thick flux-tubes[1)1], and embedded in a magnetized atmosphere with a more realistic temperature stratification. It has been possible to reproduce considerably longer bright filaments, so that the Evershed flow remains as a possible heating source. In this work they have also explained, in terms of opacity effects, the dark lanes observed by Scharmer et al.[42] at the core of penumbral filaments. The required densities and temperatures are in agreement with those necessary to keep a thick flux-tube in magnetohydrostatic equilibrium with the surrounding magnetic atmosphere[43,44].

Contrary to the problems faced by the horizontal flux-tube model, the gappy penumbral model allows for a very efficient heating mechanism. Similar to granulation, convective flows inside the field-free gaps could provide the energy to maintain the penumbral brightness. The continuous upflow along the full length of the filament carries much more energy than the localized (mainly in the inner penumbra) upflows at the flux-tubes' inner footpoints. Furthermore, the hot upflow at the center of the gap would create a density enhancement at its top. This locally raises the continuum level where the plasma is cooler, thus producing a central dark lane. Although no calculations have been carried out to confirm either effect, this appears to be a plausible scenario.

5 Magnetic field inclination

Results from the study of the observed polarization signals in the penumbra have revealed that the magnetic field vector of the component carrying the Evershed flow (intraspines) is tilted slightly upwards in the inner penumbra: $\gamma \sim 70^{\circ}$, whereas it is directed downwards in the outer penumbra. $\gamma \sim 110^{\circ}$. This is seen both at low[11,21,23] and high spatial resolution[39,45].

This would represent no major obstacle if it was not for the fact that these regions are often as large as $\sim 2-4$ Mm radially. A flux-tube in the inner penumbra pointing $\sim 70^{\circ}$ with respect to the vertical would rise more than 700 km along that distance, quickly escaping from the layers where spectral lines are formed[46].

The gappy penumbral model does not suffer from this shortcoming in the inner penumbra, since the vertical component of the magnetic field does not totally vanish on top of the gap. This yields magnetic fields slightly tilted upwards there, while the gap beneath can remain horizontal, thus remaining close to the line-forming layers. However, this peculiarity of the gappy penumbral model poses problems in the outer penumbra, where inclinations of $\sim 110^{\circ}$ with respect to the vertical are also observed over radially extended regions. This would imply a field-free gap that sinks more than 700 km in just 2–3 Mm, thus escaping from the line-forming layers. The situation is aggravated because this model predicts inclinations close to 90° only on a very small region right above the gap. In fact, near $\tau_5 = 0.1 - 0.01$ the inclinations values are closer to $70 - 80^{\circ}$, forcing the gap to sink even further to explain the observed inclinations.

Note that the magnetic field inside flux-tubes can be twisted and thus it can posses inclinations larger than 90° while the tube's axis remains horizontal[44]. Therefore flux-tube models do not suffer from this problem in the outer penumbra.

6 A unifying picture from 3D MHD simulations

Very recently, the first 3D MHD simulations of a sunspot have been presented[47,48]. So far these simulations have been restricted to grey radiative transfer and a moderate grid separation (20–30 km). Despite these shortcomings they have been able to reproduce a number of features that resemble the penumbral structure as seen from continuum images: 2–3 Mm long penumbral filaments featuring dark-cores and lifetimes of about 1 h.

Figure 1 shows the properties of the magnetic field and velocity vectors in a vertical slice across

1) With a radius larger than the pressure scale-height in the Photosphere (about 100 km)

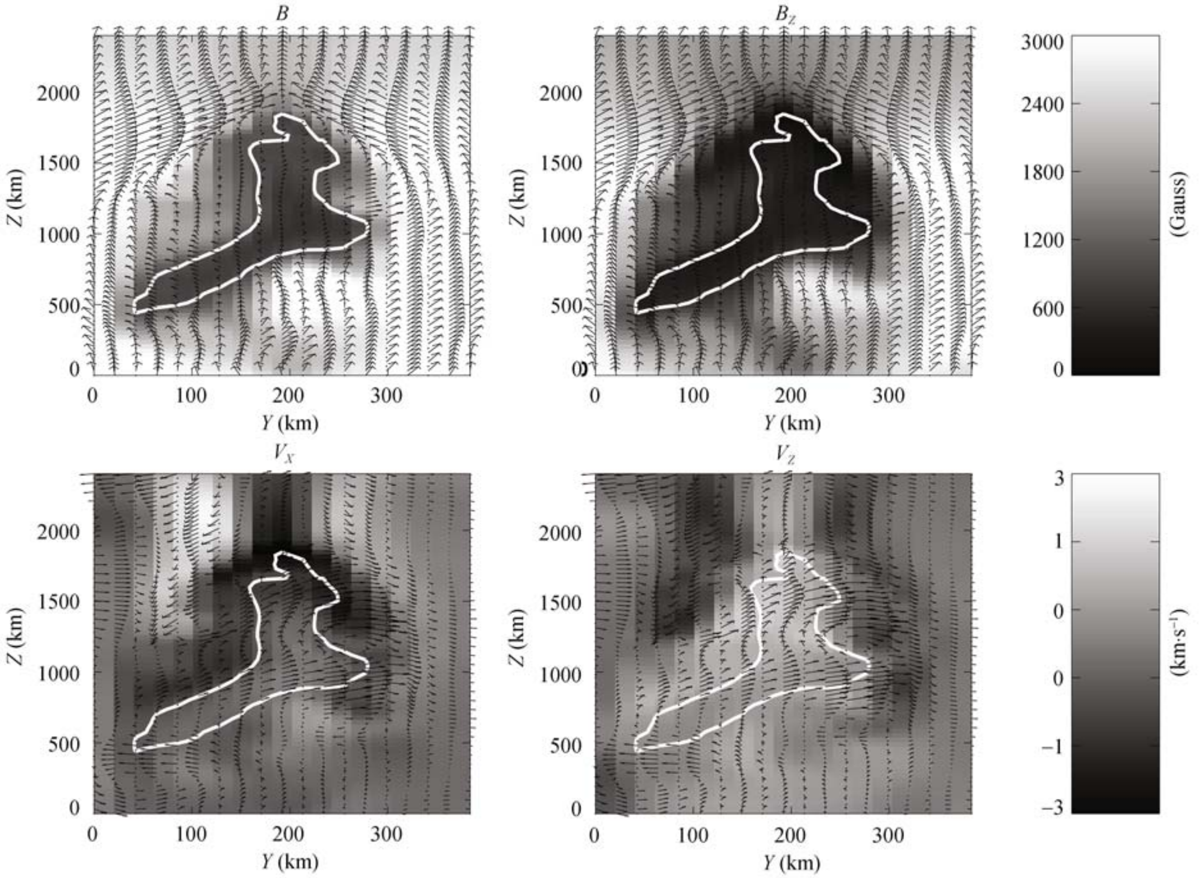

Figure 1 Vertical slice across a penumbral filament from a snapshot in Rempel et al.'s simulations. The X-axis corresponds to the radial direction along the penumbra. *Upper-left*: total magnetic field. *Upper-right*: vertical component of the magnetic field B_z. The white contour encloses the region where the total field strength is smaller than 1000 Gauss. The mean magnetic field inside this area is about 850 Gauss. The arrows show the magnetic field vector in the YZ-plane. *Lower-left*: radial component of the velocity V_x (radial direction in the penumbra). *Lower-right*: vertical component of the velocity V_z. The arrow field shows the velocity field in the YZ-plane.

one of the simulated filaments by Rempel et al.[48]. In this figure V_x will be referred to as radial velocity or Evershed flow. The subsurface structure of these filaments reveals plumes of weak and horizontal field below the visible surface of the penumbra[1)2]. The plumes carry an upflow at its center that turns over near the $\tau_5 = 1$ level and feeds downflows along the sides of the plume. These results share common points with both the flux-tube model and the gappy penumbral model. The magnetic field inside the plume is highly inclined due to the expulsion of the vertical component of the magnetic field due to convective motions. However these motions have little effect on the horizontal component of the field. The smaller magnetic field inside the plume yields a larger gas pressure inside than raises the $\tau_5 = 1$ level compared to the outside (see Figure 9 in ref. [47]).

1. The plumes' typical vertical extension ($\sim$ 1 Mm) is much larger than its horizontal extension ($\sim$ 300 km). This does not support the concept of a *round* flux-tube, although vertically elongated flux-tubes are still possible. This possibility is interesting because makes the flux-tube more stable against the action of the external field[43]. However, this same effect rules out the possibility of

1) Inside the plume, the magnetic field is not totally horizontal (inclined about $\gamma \simeq 60-70^\circ$). Together with the fact that the simulated penumbra is a factor of 2–3 smaller than typically observed, this makes these simulations mostly representative of the inner penumbra.

detecting the lower boundary of the flux-tube[21].

2. Plumes do not reach the bottom of the simulation box ($\sim$ 6 Mm), nor they originate in the convection zone, but rather they form within the surrounding field. This supports the concept of embedded flux-tube as opposed to a field-free gap piercing from beneath the sunspot.

3. The plumes contain a horizontal field of about 750–900 Gauss. This is inconsistent with the concept of a *field-free* gap[49]. However, numerical simulations with higher resolution (lower magnetic diffusivity and viscosity) tend to yield smaller magnetic fields.

4. Plumes sustain a convective flow pattern (Figure 1; lower panels) in terms of a hot upflow across its center and cool downflows along the plumes' edges. These convective motions in the deep layers are in agreement with the predictions of the gappy penumbral model[49,50]. This is also supported by a number of recent observations[51−53], although other observations at disk center with better spatial and spectral resolution do not find them[54].

5. Because the field is not totally horizontal inside the plume, the downflows have a component towards the umbra that presents itself as an inverse Evershed flow. At the top of the plume the flow turns horizontal (V_x peaks) deflected by the highly inclined magnetic field there and producing a flow pattern near τ_5 that resembles the Evershed flow. No indications of siphon flows are found.

6. In these simulations the mechanism responsible for the energy transport and heating of the penumbra is mainly performed by the convective flow in the YZ-plane. This is in better agreement with the gappy penumbral model. However, it does not support the simulations based on thin flux-tubes, where the energy transport is produced by the hot upflowing gas in the inner penumbra that is transported along the X-axis (tube's axis).

Keeping these simulations in mind, we could bring together the gappy and embedded-flux tube model if on the one hand we consider a flux-tube (where the magnetic field is horizontal) that is highly squeezed vertically and that harbors a convective flow pattern (besides the horizontal Evershed flow along its axis). The energy transported by the convective motions would explain the heating of the penumbra (sec. 4). On the other hand, we could take a field-free gap (harboring a convective flow pattern) and fill it with a horizontal magnetic field of about 1000 Gauss and a horizontal velocity of at least 5 km$\cdot$s^{-1}. This would allow the gappy penumbral model to explain the polarization profiles observed in the penumbra (sec. 3).

7 Open questions

Despite the success of these 3D MHD simulations there are a number of issues that remain unclear. Many of them will certainly be solved as simulations become more realistic and observations of better quality become available. However, some others cast doubt as to whether these simulations represent the real magnetoconvective process occurring in the penumbra. To address these concerns and others, it is compulsory to carry our forward modeling of Stokes profiles using non-grey simulations.

A first concern has to do with the convective velocity pattern along the edges of the plumes, which yields velocities that are directed inwards instead of outwards. This inflow is yet to be discovered. Note that the inflow predicted by these simulations is not exactly the same as the flow pattern reported by Zahkarov et al.[51]. Both show downflows at the edges of the filaments ($V_z < 0$), but in Zahkarov et al. the Evershed outflow ($V_x > 0$) is superimposed (but canceled in their data by observing perpendicularly to the line of symmetry of the sunspot), whereas in the simulations is directed inwards ($V_x < 0$). Perhaps the inflow remains hidden because better spatial resolution is needed to detect it, or because it occurs below the elevated $\tau_5 = 1$ thus remaining invisible.

The same argument concerning the location of the $\tau_5 = 1$ level is often used to support the claim that plumes tend to be more field-free in simulations with higher resolution (sec. 6, item 3). If penumbral plumes are really field-free, why do we not observe regions devoid of magnetic field[55]? Again, the solution invoked is the opacity effect at the top of the plume, that rises the $\tau_5 = 1$ level to a region which is not totally field-free[55].

However, this explanation remains controversial. In umbral dot simulations[55] $\tau_5 = 1$ is formed above the plumes, whereas in simulations of penumbral filaments[47,48] $\tau_5 = 1$ is formed inside (see also Figure 3 in ref. [5]). This is due to the larger difference in the magnetic field strength between plumes and their surroundings in the umbra, which yields a larger gas pressure and thereby raising the $\tau_5 = 1$ level in umbral dots as compared to penumbral filaments. Therefore, if convective motions and field-free regions are difficult to observe in penumbral filaments, it should be even more difficult in the case of umbral dots. However, both convective motions[56,57], and almost field-free regions (down to ∼400 Gauss[57]) are indeed seen in umbral dots. The only possible explanation we are left with, is that the penumbral plumes *are not* field-free, whereas umbral plumes *are*. The reason why these simulations yield smaller fields inside penumbral plumes for higher resolution runs might be because these simulations are not representative of the mid- or outer- penumbra (where the magnetic field is almost horizontal; see footnote on page 1673), and thus convective motions are still relatively effective in getting rid of the magnetic flux inside the plume, through the expulsion of the still strong vertical component of the field.

Another very problematic issue, coming back to the observed velocities, is the ubiquitousness of the Evershed outflow. No region in the penumbra seems to be free of it, as it appears inside intraspines but also weakly in spines (Figure 14 in ref. [58], Figures 2 and 3 in ref. [59]). None of the mentioned models, including numerical simulations, can explain these observations.

More concerns with the velocity field appear as we realize that the convective flow has a similar magnitude compared with the Evershed flow ($\sim 2-3$ km·s^{-1}). This vigorous convection is clearly needed to bring enough energy from deep below into the photosphere and heat the penumbra. On the one hand, the convective velocities are too strong to have remained unseen for so long. A possible explanation is that near $\tau_5 = 1$ the vertical velocities are smaller: ($\lesssim 1$ km·s^{-1}). On the other hand, the Evershed flow in these simulations is clearly a factor 2–3 weaker than observed. Indeed, it is commonly found that the Evershed flow carries supercritical velocities (at least 30 % of the penumbra[23]). If indeed the vertical (convective) velocities are much smaller than the radial velocities, then the energy input associated with the Evershed flow can have a non-negligible contribution to the heating of the penumbra.

Another important point of discrepancy is related to the inclination of the magnetic field inside the plumes. Figure 1 (top-right panel) shows that B_z inside the plume does not totally vanish (these simulations are representative of the inner penumbra, see footnote on page 1673). It is not clear what process will switch $B_z < 0$ inside the plumes to explain the large regions exhibiting flux return in the outer penumbra. Perhaps the solution to this riddle will be some sort of magnetic flux pumping occurring inside the plume at the outer penumbra due to the interaction with the surrounding granulation[60].

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