A Look into the Guts of Sunspots

L.R. Bellot Rubio
Instituto de Astrofísica de Andalucía (CSIC), Apdo. 3004, 18080 Granada, Spain
lbellot@iaa.es

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Advances in instrumentation have made it possible to study sunspots with unprecedented detail. New capabilities include imaging observations at a resolution of 0′′ 1 (70 km on the sun), spectroscopy at ∼ 0′′ 2, and simultaneous spectropolarimetry in visible and infrared lines at resolutions well below 1″. In spite of these advances, we still have not identified the building blocks of the penumbra and the mechanism responsible for the Evershed flow. Three different models have been proposed to explain the corpus of observations gathered over the years. The strengths and limitations of these models are reviewed in this contribution.

1 Introduction

Sunspots were the first celestial objects known to harbor magnetic fields, a discovery made by Hale in 1908 [15]. One year later, Evershed described a nearly horizontal plasma outflow in sunspot penumbrae [14]. This flow produces the so-called Evershed effect: redshifted spectral lines in the limb-side penumbra and blueshifts in the center-side penumbra (Fig. 1). As seen in continuum images, the penumbra is formed by bright and dark filaments oriented radially. Observations have revealed a close relationship between the filamentary structure of the penumbra, its magnetic field, and the Evershed flow.

The penumbra exhibits a complex magnetic topology, with fields of different strengths and inclinations interlaced both vertically and horizontally (see [37] and [5] for reviews). The more inclined fields channel the Evershed flow, while the more vertical fields are not associated with significant mass motions. In the inner penumbra, the magnetic field and the flow are directed upward [26, 34, 3, 7, 27], but in the outer penumbra one observes downward flows [26, 34, 32] along magnetic field lines returning back to the solar surface [14, 21, 3, 9, 17, 28]. The vertical interlacing of different magnetic field components with different velocities is responsible for the non-zero net circular polarization (NCP) of spectral lines emerging from the penumbra.
These ingredients led to the concept of uncombed penumbra (39) (see also 43 and 19). Basically, an uncombed penumbra consists of nearly horizontal magnetic flux tubes embedded in a stronger and more vertical ambient field. The tubes carry the Evershed flow, with the ambient field being essentially at rest. The uncombed penumbral model is supported by numerical simulations of interchange convection (31 and references therein), but the detection of individual flux tubes in spectropolarimetric observations has proven elusive due to their small sizes (100–200 km in diameter).

Recently, high-resolution (0.1–0.2) images taken with the Swedish 1-m Solar Telescope and the Dutch Open Telescope on La Palma have demonstrated that many penumbral filaments possess internal structure in the form of a dark core (29, 42). The dark core is surrounded by two narrow lateral brightenings (Fig. 2, left), both of which are observed to move with the same speed and direction as a single entity. The fact that the various parts of dark-cored filaments show a coherent behavior have raised strong expectations that they could be the fundamental constituents of the penumbra, i.e., the flux tubes postulated by the uncombed model. Spectroscopy at 0.2 resolution suggests that the Evershed flow is stronger in the dark cores (Fig. 2, right) and that dark-cored filaments possess weaker fields than their surroundings close to the umbra (6). Other than that, the magnetic and kinematic properties of dark-cored penumbral filaments remain unknown, so for the moment it is not possible to confirm or reject the idea that they represent individual tubes.
Fig. 2. Multi-line spectroscopy of dark-cored penumbral filaments at 0".2 resolution. The data were taken at the SST on April 29, 2005, and correspond to the center-side penumbra of AR 10756. Left: Slit-jaw image. The slit crosses four dark-cored filaments. Right: Intensity profiles of Fe\textsc{i} 557.6, Fe\textsc{ii} 614.9, and Fe\textsc{i} 709.0 nm along the slit. The dark cores ("DC") are marked with small horizontal lines. Their large blueshifts are produced by Evershed flows directed upward. See [6] for details.

In the meantime, alternative models of the penumbra have emerged: scenarios based on Micro-Structured Magnetic Atmospheres (MISMAs; [23, 24]) and field-free gaps (the gappy penumbral model; [41]). These models try to explain the morphological and spectropolarimetric properties of the penumbra. They also claim to solve important problems of the uncombed model. In the following, the strengths and limitations of the different models are examined.

2 Competing penumbral models

2.1 Uncombed model

As mentioned before, the uncombed model envisages the penumbra as a collection of small magnetic flux tubes embedded in an ambient field. The thermal, magnetic, and kinematic properties of the flux tubes and the ambient field (Fig. 3) have been determined from Stokes inversions that use two different magnetic atmospheres. These inversions [2, 5, 11, 9, 1, 10] have demonstrated that the uncombed model is able to explain the shapes of the polarization profiles of visible and infrared lines emerging from the penumbra at resolutions of \( \sim 1'' \) (see Fig. 4 for examples). Perhaps the most important achievement of the model, however, is that it quantitatively reproduces the NCP of visible [19, 10] and infrared [9, 22] lines, which are due to strong gradients or discontinuities of the atmospheric parameters (including velocities) along the line of sight. This success is not trivial, since the spatial distribution of the NCP is determined primarily by discontinuities of field inclination in the case of visible lines and discontinuities of field azimuth in the case of infrared lines [16, 33].
As can be seen in Fig. 3, the tubes are inclined upward in the inner penumbra and downward in the mid and outer penumbra. The flow along the tubes is parallel to the magnetic field at all radial distances. The agreement is remarkable, but it hides a serious difficulty: a single flux tube cannot extend across the penumbra with the inclinations of Fig. 3 because it would quickly leave the line forming region (even if the Wilson depression is taken into account). A possible way out of this problem is that the values shown in Fig. 3 do not represent individual tubes, but rather azimuthal averages over short flux tubes whose number density is constant with radial distance (cf. [36]).

The flux-tube properties and their radial variation, as derived from Stokes inversions, agree well with those resulting from simulations of moving tubes in the thin tube approximation [31]. The simulations provide a natural explanation for the Evershed flow in terms of a pressure gradient that builds up along the tube as it rises buoyantly from the magnetopause and cools off by radiative losses near the solar surface. The moving tube model explains the motion of bright penumbral grains toward the umbra and the overall morphology of penumbral filaments in continuum images. It also gives convincing arguments why the flux tubes possess more horizontal and weaker fields than the ambient atmosphere, and why the flux tubes return to the solar surface in the mid and outer penumbra (i.e., why their field inclinations are larger than 90°, cf. Fig. 3). The apparent inability of moving tubes to explain the surplus brightness of the penumbra [35] has been used by [41] as an argument to propose the gappy penumbral model. However, the remark made in [35] that dissipation of the kinetic energy of the Evershed flow could account for the penumbral brightness has been overlooked by [41]. Rejecting the idea of hot Evershed flows as the origin of the penumbral brightness cannot be done without 2D or 3D simulations of the evolution of flux tubes including a realistic energy equation and stratified atmospheres.

The very existence of flux tubes embedded in a more vertical field has been put into question alleging that such a configuration is not force-free [41]. The imbalance of forces at the top and bottom of the tubes would cause a verti-
Fig. 4. Simultaneous spectropolarimetry of AR 10425 with TIP and POLIS at the German VTT of Observatorio del Teide on August 9, 2003. Left: Stokes V profiles of Fe i 630.15 and 630.25 nm. Right: Stokes V profiles of Fe i 1564.8 and 1565.2 nm. The three rows correspond to three different pixels in the limb-side penumbra ($\theta = 27^\circ$). Filled circles are the observations. Solid lines give the best-fit profiles resulting from an uncombed inversion of the data using the code described in [2]. Adapted from [1].

cal stretching that would eventually destroy the tubes. However, it has been demonstrated [12] that the vertical stretching is limited by buoyancy in convectively stable (subadiabatic) layers. Also, it has been shown that penumbral tubes can be brought into exact force balance if the field within the tube has a small transversal component [8]. Interestingly, the temperature distributions derived from the condition of magnetohydrostatic equilibrium of penumbral tubes produce dark-cored filaments whose properties are very similar to the observed ones [8]. The ability of the uncombed model to explain the existence of dark-cored penumbral filaments has also been demonstrated by means of 2D heat transfer simulations of flux tubes carrying a hot Evershed flow [28].

From a modeling point of view, even the most complex Stokes inversions of penumbral spectra use only two rays to describe the flux tube and the ambient field, which is a very simplistic approximation (see [4] for details). Actually, the two rays represent homogeneous tubes with square cross sections and ambient field lines that do not wrap around the tubes. More sophisticated treatments of the uncombed penumbra are thus desirable for a better interpretation of the observations. Such treatments could remove the small differences between observed and best-fit profiles (Fig. 4). However, one should not expect qualitatively different results, since the uncombed models implemented in current
inversion codes already capture the essential physics needed to explain the shapes of visible and infrared lines.

### 2.2 MISMA penumbral model

The MISMA model assumes that the penumbra is formed by optically thin magnetic fibrils a few km in diameter \[23, 24\]. Each resolution element contains a messy bunch of field lines with random strengths and inclinations that, for an unknown reason, are more or less parallel to the radial direction. The model, implemented in practice as a simple two-component atmosphere, successfully reproduces the asymmetries and NCPs of the Fe\textsubscript{I} 630.15 and 630.25 nm lines observed in sunspots at a resolution of \(\sim 1''\) [24].

According to MISMA inversions, downward flows with velocities that often exceed 20 km s\(^{-1}\) exist everywhere in the penumbra [24]. This result is at odds with observations: 0'.2 resolution Dopplergrams show no evidence for downflows in the inner and mid penumbra [17]. In addition, the mechanism whereby the small-scale fibrils get organized to produce the large-scale (filamentary) structure of the penumbra remains unknown. This is indeed a serious problem, because negligible azimuthal fluctuations of magnetic field and velocity should be observed when both the number of fibrils per resolution element is large and the fibrils follow the same (random) distribution in different pixels.

As a proof of physical consistency, the MISMA deduced from the inversion was shown to satisfy the \(\nabla \cdot \mathbf{B} = 0\) condition, unlike simpler one-component models. However, azimuthally averaged atmospheric parameters were used rather than individual values. Since \(\nabla \cdot \mathbf{B} = 0\) must be verified locally pixel by pixel, this test does not really demonstrate the validity of the model.

It remains to be seen whether MISMAs are able to explain the shapes and NCPs of infrared lines, as well as the existence of dark-cored penumbral filaments. It is also necessary to find reasons why the magnetic fibrils that form the lateral brightenings of dark-cored filaments know of each other so well as to make them move coherently. If MISMAs are the building blocks of the penumbra, regions with zero NCPs will not be detected even at high spatial resolution, because there will always be fibrils interlaced along the LOS. This is perhaps the most important prediction of the MISMA model.

### 2.3 Gappy penumbral model

The gappy model represents a theoretical attempt to explain the existence of dark-cored penumbral filaments and the brightness of the penumbra \[41, 30\]. It postulates that dark-cored filaments are the signatures of radially oriented, field-free gaps located just below the visible surface of the penumbra. Such gaps would sustain normal convection, thereby providing energy to heat the penumbra. This raises a serious problem, because the existence of vigorous field-free convection plumes reaching the solar surface contradicts the accepted view \[40\] that the penumbra is deep (as opposed to shallow).
Another problem is that it is not clear how the model can generate magnetic fields pointing downward in the outer penumbra: the maximum field inclination in a gappy penumbra is 90°, representing horizontal fields. Last, but not least, the model does not offer any explanation for the Evershed flow. It does not even have a suitable place to accommodate horizontal flows, because they must reside where the field is nearly horizontal. Since this happens only in very small volumes just above the gaps, a large fraction of the line forming region would be devoid of flows.

The gappy model may be regarded as a limiting case of the uncombed model with zero field strengths in the flux-tube component. The essential difference is that a strong Evershed flow moves along the tube in the uncombed model, whereas in a gappy penumbra not even the field-free regions harbor radial outflows. Thus, an important ingredient for spectral line formation is missing in the model: the discontinuous velocity stratifications produced by confined Evershed motions several \( \text{km s}^{-1} \) in magnitude. Gappy models with potential fields do exhibit gradients of field strength, inclination, and azimuth with height [30], but it is unlikely that such gradients can reproduce the multi-lobed Stokes \( V \) profiles and the NCPs of spectral lines without including strong Doppler shifts in an ad hoc manner. Convection in the field-free gaps alone will not produce large NCPs or multi-lobed profiles because (a) it occurs near \( \tau = 1 \), i.e., far from the line forming region, and (b) the associated velocities will certainly be smaller than 5-6 \( \text{km s}^{-1} \).

In summary, although the idea may be appealing, radiative transfer calculations must be performed to demonstrate that the gappy model is able to reproduce the spectropolarimetric properties of the penumbra. Also, heat transfer simulations are required to prove that the field-free gaps would indeed be observed as dark-cored filaments, and that the gaps can heat the penumbra to the required degree. Without these calculations, it seems premature to accept the gappy model as a good representation of sunspot penumbrae.

3 Outlook

Currently available models of the penumbra have both strengths and limitations. The difference is that the uncombed model has been extensively confronted with observations, while the MISMA and gappy models still need to pass stringent observational tests to demonstrate their plausibility. Some of the basic claims made by the later models have not yet been confirmed by radiative and/or heat transfer calculations, and hence remain speculative.

Further advances in our understanding of the penumbra will come from spectropolarimetric observations at 0′′2–0′′3. This is the minimum resolution needed to identify the dark cores of penumbral filaments. We would like to measure the vector magnetic fields and velocities of dark-cored filaments not only to distinguish between competing models (which imply different convection modes in the presence of inclined fields), but also to drive holistic MHD
simulations of the penumbra. The required observations will be obtained with
instruments like the Spectro-Polarimeter \textsuperscript{18} aboard HINODE, TIP \textsuperscript{13} at
GREGOR, IMaX \textsuperscript{20} onboard SUNRISE, and VIM \textsuperscript{38} aboard Solar Orbiter.

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