Proper Motions in Sunspot Penumbral: Signs of Convection

J. A. Bonet, I. Márquez, and J. Sánchez Almeida

Instituto de Astrofísica de Canarias, C/ Vía Láctea s/n, E-38200
La Laguna, Tenerife, Spain

Abstract. Proper motions in penumbra have been measured using local correlation tracking techniques in a high spatial resolution series of images (∼ 0′:12). Assuming these motions to trace true plasma motions, we have detected converging flows that arrange the plasma in long narrow filaments mostly placed along dark penumbral filaments. These converging flows suggest downflows in the filaments of ∼ 200 m s⁻¹. We interpret the association between downflows and dark features as a sign of convection that, once several observational biases are considered, could transport enough energy to balance the radiative losses of penumbra.

1. Introduction

Despite the long observational record of sunspot penumbral, a consistent physical scenario describing its structure, origin and nature is not known yet. The difficulties of understanding and modeling penumbral are probably a consequence of the small spatial scale at which the relevant physical processes take place. The advent of the Swedish Solar Telescope (SST; Scharmer et al. 2003a,b) has opened up new possibilities in high spatial resolution imaging. The purpose of this work is to describe our findings arising from SST observations of penumbral.

2. Observations and Data Reduction

This work is based on the data set of Scharmer et al. (2002) with spatial resolution ∼ 0′:12, kindly offered for public use by the authors. The observations were carried out on July 15, 2002, with the 1m SST equipped with AO (Scharmer et al. 2003a,b). The data set consists of a time sequence of G-band (λ4305 Å) images following the evolution of a portion of sunspot penumbra along 28 min with a cadence of 22 s. The penumbra belongs to the large sunspot of the active region NOAA 10030 at μ = 0.96 covering a field-of-view of 26″ × 40″, sampled with pixels of 0′:041. The images were restored with Joint Phase Diverse Speckle (see Löfdahl & Scharmer 2003).

Proper motions in the penumbra have been evaluated by local correlation tracking techniques (LCT; November & Simon 1988). The tracking window is a Gaussian of FWHM suitable for tracking structures of ∼ 0″4. The method provides a map of displacements or proper motions per time step that we average in time along the whole series (28 min). Using the mean velocity field, (∂x, ∂y), we construct a “cork movie” following the evolution of passively advected tracers (corks) spread out over the penumbra at time equals zero.
Figure 1. (a) Mean image of the penumbra sharpened by subtraction of the local mean. (b) Image with corks (in white) remaining in penumbra after 110 min. The large arrow points out the direction of the closest solar limb.

Figure 1b shows the corks remaining in the penumbra after 110 min. Some 30% of the original corks have moved from the penumbra to the umbra, the photosphere, or the penumbra outside the field-of-view. The rest are concentrated in long narrow filaments or chains (many corks end up in a single pixel).

To study the correspondence between position of cork filaments and brightness in the penumbra, low spatial frequencies in the intensity fluctuations are removed from the time average image by subtraction of the local mean. The analysis in the next sections refers to the penumbra enclosed in the white box of Fig. 1a, where the effects we discuss are more pronounced.

3. Proper Motions

A comparison of the histograms of the horizontal velocities, \( U_h = \sqrt{U_x^2 + U_y^2} \), in the whole penumbra and at the positions of corks after 110 min reveals that the corks drift toward regions with low horizontal velocity. Large proper motions expel the corks making it difficult to form chains. Furthermore, the histogram of the angle between the horizontal velocities and the horizontal gradients of intensity shows that the proper motions are predominantly radial, i.e., parallel to the bright and dark filaments traced by the intensity. We also observe that the radial motions tend to be inward in the inner penumbra and outward in the outer penumbra. However, on the top of this predominantly radial flow, there is a small transverse velocity responsible for the accumulation of corks in
Figure 2. Histograms of the distribution of intensity associated with the cork filaments. Solid line: original distribution corresponding to the corks uniformly spread out throughout the penumbra. Dotted line: final distribution at the cork filaments. A global shift of ~20% to dark structures can be appreciated.

filaments as shown in Fig. 1b. Assuming that the observed proper motions trace true mass motions, the horizontal velocities should be accompanied by vertical motions with velocity $U_z$. Following November (1989), we infer the direction and magnitude of $U_z$ as

$$U_z = h_z \left( \frac{\partial U_x}{\partial x} + \frac{\partial U_y}{\partial y} \right),$$

where $h_z$ is the mass flow scale height, mostly set by the drop of density with the height in the atmosphere.

4. Discussion and Conclusions

Previous studies with lower resolution find predominantly radial proper motions in penumbral filaments, a result that we confirm. On top of this trend, however, we find the convergence of the radial flows to align passive tracers (corks) in long chains or filaments (see Fig. 1b). Motions diverge away from bright penumbral filaments to converge toward dark filaments, as evidenced by the time evolution of the corks. After 110 min, the corks overlie features which are significantly fainter than the mean penumbra, as shown in Fig. 1b and the histograms in Fig. 2. Assuming that the proper motions reflect true stationary plasma motions, the need for mass conservation allows us to estimate the vertical velocities at the cork filaments, places where the plasma converges. These velocities tend to be directed downward with a mean of the order of 200 m s$^{-1}$ (see Fig. 3).

The physical scenario described above resembles the flows in the solar granulation, where the matter moves horizontally from the sources of uprising plasma.
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Figure 3. Histograms of $U_z$ computed from $(U_x, U_y)$ for $h_z = 100$ km. Upflows correspond to positive $U_z$. Solid line: distribution of $U_z$ in all pixels of the penumbra (no preferred upflows or downflows). Dotted line: distribution of $U_z$ in the pixels of the cork filaments: cork filaments prefer downflows with a mean value of $-0.2$ km s$^{-1}$.

...to the sinks in cold downflows (dark lanes). This similarity suggests that part of the penumbral phenomenon is of convective nature. The measured vertical velocities are insufficient to transport the energy lost by penumbral radiative flux, which would require values of $\sim 1$ km s$^{-1}$ (see, e.g., Spruit 1987). However, the finite resolution imposed by the LCT algorithm leads to underestimating the true velocities so that our measurements of 200 m s$^{-1}$ can be compatible with 1 km s$^{-1}$. We repeat the analysis in a non-magnetic region finding $\sim 150$ m s$^{-1}$, although the true vertical velocities in the quiet Sun are larger than 1 km s$^{-1}$.

A detailed account of this work is given by Márquez, Sánchez Almeida, & Bonet (2006).

References