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Spectro-Polarimetric Analysis of an Umbral Filament

S.L. Guglielmino^{1,*}, P. Romano², B. Ruiz Cobo^{3,4}, F. Zuccarello¹, and M. Murabito⁵

¹Dipartimento di Fisica e Astronomia “Ettore Majorana” – Sezione Astrofisica, Università degli Studi di Catania, Catania, I-95123, Italy

²INAF – Osservatorio Astrofisico di Catania, Catania, I-95123, Italy

³IAC – Instituto de Astrofísica de Canarias, La Laguna, Tenerife, E-38200, Spain

⁴Departamento de Astrofísica, Univ. de La Laguna, La Laguna, Tenerife, E-38205, Spain

⁵INAF – Osservatorio Astronomico di Roma, Monte Porzio Catone, I-00078, Italy

*Email: salvatore.guglielmino@inaf.it

Abstract. High-resolution observations of the solar photosphere have recently revealed the presence of elongated filamentary bright structures inside sunspot umbrae. These features, which have been called umbral filaments (UFs), differ in morphology, evolution, and magnetic configuration from light bridges that are usually observed to intrude in sunspots.

To study an UF observed in the leading sunspot of active region NOAA 12529, we have analyzed spectro-polarimetric observations taken in the photosphere with the spectropolarimeter (SP) aboard the *Hinode* satellite. High-resolution observations in the upper chromosphere and transition region taken with the *IRIS* telescope and observations acquired by *SDO/HMI* and *SDO/AIA* have been used to complement the spectro-polarimetric analysis.

The results obtained from the inversion of the *Hinode*/SP measurements allow us to discard the hypothesis that UFs are a kind of light bridge. In fact, we find no field-free or low-field strength region cospatial to the observed UF. In contrast, we detect in the structure Stokes profiles that indicate the presence of strong horizontal fields, larger than 2500 G. Furthermore, a significant portion of the UF has opposite polarity with respect to the hosting umbra. In the upper atmospheric layers, we observe filaments being cospatial to the UF in the photosphere. We interpret these findings as suggesting that the UF could be the photospheric manifestation of a flux rope hanging above the sunspot, which triggers the formation of penumbral-like filaments within the umbra via magneto-convection.

1 Introduction

Light bridges (LBs) are bright features that intrude sunspots from the leading edge of penumbra into the umbra, being usually observed during the decay phase of sunspot evolution (e.g., Falco et al. 2016). High-resolution observations allow investigating their internal structure, distinguishing between granular or filamentary LBs, and their magnetic configuration.

Recently, Kleint & Sainz Dalda (2013) have studied unusual curled intruding structures around the preceding sunspot of active region (AR) NOAA 11302, which have been called umbral filaments (UFs). Although at a first glance these features may resemble filamentary LBs, they appear to be different from the latter in morphology and in evolution.

To assess the properties of these newly discovered features, we have analyzed an UF located inside the umbra of the giant leading sunspot of AR NOAA 12529 (Guglielmino et al. 2017). Using photospheric data acquired by *SDO/HMI*, we have found that this intruding structure has a strong horizontal magnetic field (≈ 2000 G), with a portion of the UF characterized by opposite polarity than the hosting sunspot. Considering the cospatial structures seen at chromospheric and coronal heights with *SDO/AIA*, we have proposed that this UF is the counterpart of a flux rope embedded in the solar atmosphere above the umbra.

Here, we describe the analysis of high spectral and spatial spectro-polarimetric observations of the same UF performed by the *Hinode* spectropolarimeter (SP; Lites et al. 2013). The results reinforce the scenario suggested by the analysis of *SDO* data and completely rule out the idea that the UF is a low-field or field-free region, as usual LBs.

2 Observations and data analysis

The *Hinode*/SP instrument obtained a single raster scan along the Fe I line pair at 630.2 nm in Fast Mode (pixel size $0''.32$, step cadence of 3.8 s), covering a field of view (FoV) of about $300'' \times 162''$ that encompassed the whole AR. The scan lasted from 02:21 to 03:24 UT on April 14, 2016, at the time of the passage at the central meridian of the AR ($\mu = 0.96$).

For the analysis, we removed the stray light contamination using a regularization method, based on a principal component decomposition of the Stokes profiles (Ruiz Cobo & Asensio Ramos 2013), using 15 eigenvectors. This led to an enhancement of the continuum contrast in the quiet Sun from 6.9% in the original data to 12.1% in the deconvolved data.

We considered a sub-FoV of $130'' \times 130''$ centered on the preceding sunspot of the AR, as shown in Figure 1. We inverted the spectra dividing this sub-FoV into three regions, identified by different thresholds of the normalized continuum intensity I_c to account for the different physical conditions: quiet Sun ($I_c > 0.9$), penumbra ($0.5 < I_c < 0.9$), and umbra ($I_c < 0.5$). Accordingly, we used the SIR inversion code (Ruiz Cobo & del Toro Iniesta 1992) with different initial models for the temperature stratification, following Murabito et al. (2016). Except for the temperature, the physical quantities were assumed to be constant with height. For more details, we defer the reader to Guglielmino et al. (2019).

3 Results

Figure 1 displays the deconvolved maps derived from *Hinode*/SP measurements, as well as the maps of the physical parameters retrieved by the SIR inversion, detailed in the following.

The continuum intensity map (Figure 1a) reveals that the leading edge of the UF corresponds with a penumbral gap, while the trailing edge ends sharply inside the umbra. According to the *Hinode*/SP spatial resolution ($\approx 0''.3$ at 630 nm) dataset, there is no granular pattern in the UF.

The map of integrated circular polarization (Figure 1b) indicates that the signal in a large part of the UF has opposite sign than that of the hosting umbra. Moreover, the integrated linear polarization map (Figure 1c) shows enhanced signal in the UF.

In Figure 1d (Doppler velocity map), we see that the flow pattern along the UF exhibits a redshift along the part of the structure inside the umbra (normal Evershed flow). Abruptly, a blueshift is observed at the edge of the penumbra, in correspondence of the penumbral gap.

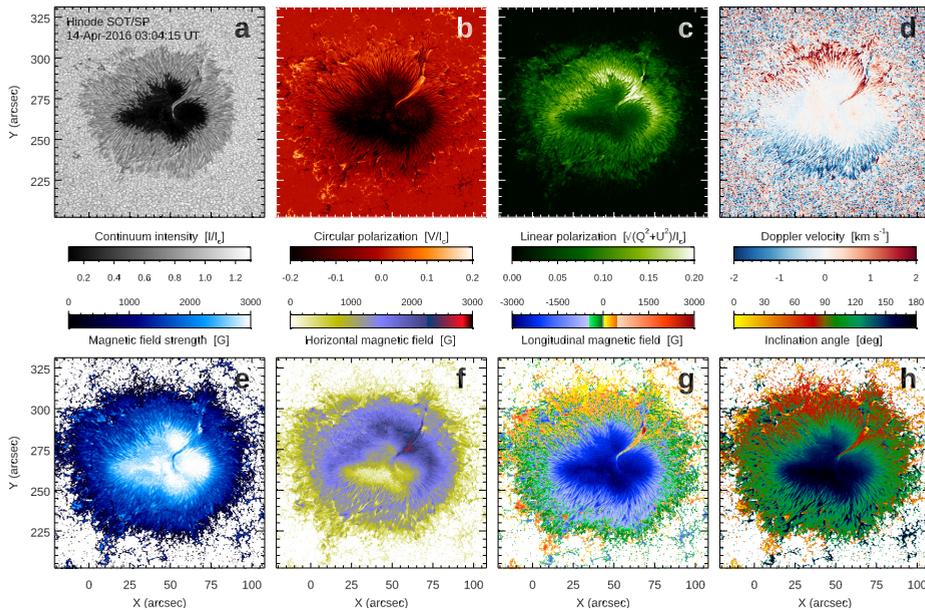


Figure 1. *Top panels:* Maps of the continuum intensity (a), integrated circular polarization (b) and linear polarization (c), and Doppler velocity (d) of the preceding sunspot of AR NOAA 12529. *Bottom panels:* Maps of the physical quantities retrieved by the SIR inversion: field strength (e), horizontal (f) and longitudinal (g) component of the vector magnetic field, and inclination angle (h).

The maps relevant to the vector magnetic field show that the UF has a magnetic field strength generally larger than 2000 G (Figure 1e), harboring strong horizontal fields. In fact, some patches have horizontal field values larger than 2500 G, stronger than in the surrounding penumbra (Figure 1f). In addition, both the longitudinal field map (Figure 1g) and the inclination angle map (Figure 1h) confirm the presence of the opposite magnetic polarity, with respect to the sunspot, along the interior of the UF.

It is worth noting that some pixels in the periphery of the UF need a two-component inversion to fit properly the emerging Stokes profiles. In these points, the ‘umbral’ component is weaker than the opposite-polarity ‘penumbral’ component.

4 Discussion and conclusions

Hinode/SP observations of the UF in AR NOAA 12529 indicate the presence of strong horizontal fields larger than 2500 G, with a significant portion of the UF having opposite polarity than the surroundings. Thus, we can safely confirm that the UF cannot be a kind of granular LB, usually corresponding to field-free or low-field strength regions, or a filamentary LB, usually with a magnetic field of about 1500 G of the same polarity of the hosting sunspot. Rather, our findings hint that the UF is a topologically separated structure.

The characteristics of the UF and its magnetic configuration suggest that it is a penumbral-like feature inside the sunspot umbra. This penumbral-like nature of UFs might be explained

taking into account the presence of a strong enough external horizontal field that is able to activate the penumbral magneto-convective mode (Jurčák et al. 2014, 2017). In fact, the onset of this physical mechanism has been related with the observations of horizontally inclined magnetic fields in different environments during penumbra formation. This occurs in regular penumbrae (Shimizu et al. 2012; Romano et al. 2013, 2014), also when they form in regions of ongoing flux emergence (Murabito et al. 2017, 2018), as well as in penumbral-like structures, such as orphan penumbrae, when the emerging flux is trapped by an overlying canopy (Lim et al. 2013; Guglielmino et al. 2014; Zuccarello et al. 2014).

This interpretation is further supported by simultaneous images acquired by the *IRIS* satellite that show filaments in the upper atmosphere, highly reminiscent of a flux rope, being cospatial to the UF in the photosphere (Guglielmino et al. 2019). Such a scenario, where the UF is the photospheric counterpart of an overlying flux rope touching the umbra and triggering magneto-convection, bears some resemblance to the *flux sheet* model proposed by Kleint & Sainz Dalda (2013). New observations from the photosphere to the corona, as well as numerical simulations are required to shed light on the nature of these structures.

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