THE THREE-DIMENSIONAL STRUCTURE OF AN ACTIVE REGION FILAMENT AS EXTRAPOLATED FROM PHOTOSPHERIC AND CHROMOSPHERIC OBSERVATIONS

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ABSTRACT

The three-dimensional structure of an active region filament is studied using nonlinear force-free field extrapolations based on simultaneous observations at a photospheric and a chromospheric height. To that end, we used the Si i 10827 Å line and the He i 10830 Å triplet obtained with the Tenerife Infrared Polarimeter at the Vacuum Tower Telescope (Tenerife). The two extrapolations have been carried out independently from each other and their respective spatial domains overlap in a considerable height range. This opens up new possibilities for diagnostics in addition to the usual ones obtained through a single extrapolation from, typically, a photospheric layer. Among those possibilities, this method allows the determination of an average formation height of the He i 10830 Å signal of ≃2 Mm above the surface of the Sun. It allows, as well, a cross-check of the obtained three-dimensional magnetic structures to verify a possible deviation from the force-free condition, especially at the photosphere. The extrapolations yield a filament formed by a twisted flux rope whose axis is located at about 1.4 Mm above the solar surface. The twisted field lines make slightly more than one turn along the filament within our field of view, which results in 0.055 turns Mm−1. The convex part of the field lines (as seen from the solar surface) constitutes dips where the plasma can naturally be supported. The obtained three-dimensional magnetic structure of the filament depends on the choice of the observed horizontal magnetic field as determined from the 180° solution of the azimuth. We derive a method to check for the correctness of the selected 180° ambiguity solution.

Key words: Sun: activity – Sun: filaments, prominences – Sun: magnetic topology

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1. INTRODUCTION

Active region (AR) filaments are observed above polarity inversion lines (PILs) where the vertical component of the magnetic field changes sign, separating the two opposite polarities (Babcock & Babcock 1955). They are called filaments when observed on the solar disk and prominences when observed above the solar limb, although the two terms refer to the same phenomenon (see Demoulin 1998; Mackay et al. 2010, for a review on filaments and prominences). Filaments/prominences are formed by plasma that has been lifted up above the solar surface and is cooler and denser than its surroundings. The necessary force to sustain this plasma is of magnetic origin. Here we shall focus on AR filaments, which are characterized by a strong horizontal component of the magnetic field along the filament axis reaching several hundred gauss (Kuckein et al. 2009, 2012; Guo et al. 2010; Canou & Amari 2010; Jing et al. 2010). These filaments typically lie low above the solar surface (Lites 2005) compared with quiescent filaments.

There are two classes of models that aim to describe the magnetic structure of filaments: the sheared magnetic arcade model and the twisted flux rope (TFR) model. The former involves photospheric motions of magnetic footpoints near the PIL produced by various mechanisms such as photospheric flows, vortical motions, or the emergence of the upper part of a flux rope (Antiochos et al. 1994; DeVore & Antiochos 2000; Aulanier et al. 2002; Welsch et al. 2005; DeVore et al. 2005). The flows force the magnetic field to get reconfigured creating a variety of field configurations, as dipped field lines (Mackay et al. 2010).

The TFR model assumes that the filament is formed by a dipped flux rope where the material can naturally be located and lifted up (van Ballegooijen & Martens 1989; Leka et al. 1996; Titov & Démoulin 1999; Amari et al. 1999; Lites 2005; Lites et al. 2010). Flux emergence of a TFR to the solar atmosphere has also been numerically modeled (Magara & Longcope 2003; Fan & Gibson 2004; Archontis et al. 2004; Amari et al. 2004, 2005; Galsgaard et al. 2005; Cheung et al. 2007; Martínez-Sykora et al. 2008; Tortosa-Andreu & Moreno-Insertis 2009; Fan 2009; MacTaggart & Hood 2010). From observations, Okamoto et al. (2008, 2009) have shown that the change in the horizontal field from normal to inverse configuration can be interpreted as the signature of an emerging flux rope. This has been shown as well in three-dimensional MHD simulations of an emerging flux rope, where the spectropolarimetric signal exhibits similar changes of the horizontal field from normal to inverse (Yelles Chaouche et al. 2009a) using the same pair of iron lines Fe i 6301 Å and Fe i 6302 Å as the ones of Hinode SP/SOT.

The numerical models aiming to simulate the properties of filaments assume a certain number of conditions, such as, e.g.: the mere pre-existence of a flux rope in the convection zone or in the atmosphere, the amount of twist necessary for a given flux rope to emerge into the atmosphere, its morphology and emergence velocity, etc. These assumptions and conditions can hardly be directly tested using observed magnetograms only, and it turns out to be very helpful to use extrapolations in order to get information on the observed three-dimensional magnetic field and its properties. This gives feedback to numerical models and allows them to be fine tuned.

In recent years, extrapolations have played an important role in probing AR filament properties (Guo et al. 2010; Canou & Amari 2010; Jing et al. 2010). This is due to (a) the progress in mathematical and computing techniques of

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extrapolations (e.g., Amari et al. 1997; Wiegelmann 2004; Wiegelmann et al. 2006; Schrijver et al. 2006; Aly & Amari 2007; Metcalf et al. 2008) and (b) to the large improvement in spectropolarimetric facilities which allows the measurement of the full Stokes vector with ever higher sensitivity and resolution (e.g., SP/SOT on board Hinode, TIP at the VTT, THEMIS/MTR, etc.; see, e.g., López Ariste et al. 2006; Okamoto et al. 2008; Kuckein et al. 2009, 2010; and the review by Mackay et al. 2010 for further references.)

In the past, extrapolations of AR filaments have exclusively been computed using photospheric fields as boundary values. Knowing that the photospheric plasma is not completely force free, it is important to compare these extrapolations with ones of the same region but using chromospheric magnetic field as boundary values for the extrapolations. The plasma β in the chromosphere is usually much smaller than in the photosphere, so that the magnetic field in the former must be closer to force-free than in the latter. Simultaneous observations of the magnetic field vector at the photosphere and chromosphere (Kuckein et al. 2012; Sasso et al. 2011) offer the possibility of such a study. Based on the observations in Kuckein et al. (2012; see also Kuckein et al. 2009, 2010), we will perform extrapolations starting from the photosphere and, independently, from the chromosphere. This allows to cross check the extrapolation results and test whether the latter have been affected by, e.g., the finite plasma β and the preprocessing procedure.

We will focus here on two representative times (one for each day of observation). Then for each of them we have two snapshots: one at the photosphere using the Si i 10827 Å line and one at the chromosphere using the He i 10830 Å triplet. The time evolution of the filament over the entire observation period can be further retrieved from the paper by Kuckein et al. (2012).

2. OBSERVATIONS AND DATA ANALYSIS

In this paper, we study a filament located along the PIL of AR NOAA 10781, which was found to be in its slow decay phase when the observations were performed. The full Stokes spectropolarimetric data were acquired with the Tenerife Infrared Polarimeter (TIP-II; Collados et al. 2007) at the German Vacuum Tower Telescope (VTT, Tenerife, Spain) on 2005 July 3 and 5, at coordinates N16-E8 and N16W18, respectively. Several scans were taken with the slit (0.5′′ wide and 35′′) parallel to the filament obtaining maps with a field of view (FOV) of ∼26 × 25 Mm and ∼22 × 25 Mm, for July 3 and July 5, respectively. It is important to note that the FOV was not centered on the same location on both days. However, the upper half of the map from July 3 overlaps with the lower half of the map from July 5. The observed spectral range comprises the photospheric Si i 10827 Å line and the chromospheric He i 10830 Å triplet, which allows us to simultaneously study both heights and their magnetic coupling. The reader is referred to the papers of Kuckein et al. (2009, 2012) for an extensive description of the data and the magnetic evolution of this AR filament.

Figure 1 shows slit-reconstructed maps of the two selected data sets. From left to right different wavelengths are presented: continuum, Silicon line core intensity, helium red core intensity,
and Silicon Stokes-V magnetogram (at \(-150\) mA from line center). The upper map was taken on 2005 July 3, between 14:39 and 15:01 and clearly shows the filament in the He I absorption panel (third panel starting from top left). The filament extends along the vertical axis and lies on top of the PIL, as shown in the upper Stokes-V panel. The lower map was observed on 2005 July 5, between 8:42 and 9:01. The spine or filament axis is still seen in the lower half of the He I panel, but above, a more diffuse filament is located on top of the pores and orphan penumbral which have newly formed.

Two different inversion codes were used to fit the Stokes profiles. A binning in the spectral and spatial domain was applied to increase the signal-to-noise ratio. Hence, the final spectral sampling is \(33.1\) mA pixel\(^{-1}\) and the average pixel size is \(\sim 1''\). For the helium 10830 Å triplet we used a Milne-Eddington inversion code (MELANIE; Socas-Navarro 2001), which computes the Zeeman-induced stokes spectra in the incomplete Paschen–Back regime (Socas-Navarro et al. 2004). In the case of the Silicon 10827 Å line we used the SIR code (Stokes Inversion based on Response functions; Ruiz Cobo & del Toro Iniesta 1992). Kuckein et al. (2012) showed that the non-local thermodynamical equilibrium (NLTE) effects of the Si i 10827 Å line reported by Bard & Carlsson (2008) do not significantly affect the inferred vector magnetic field from the SIR inversion code and therefore were not taken into account. We transformed the vector magnetic field from the line of sight (LOS) into the local solar reference frame. The 180° ambiguity was solved using the AZAM code (Lites et al. 1995). Response functions to magnetic field perturbations for the inferred atmospheres were computed at different positions inside and around the filament. An average optical depth of \(\log \tau \sim -2\) for the formation height of Silicon has been obtained for both days.

3. FORCE-FREE FIELD EXTRAPOLATION

Using the photospheric or chromospheric magnetic field as boundary values, it is possible to calculate the three-dimensional magnetic field vector in the atmosphere using force-free field (FFF) extrapolations. The force-free (or zero-Lorentz force) assumption is equivalent to assuming that the electrical current and the magnetic field are parallel, or, using Ampère’s law and cgs units:

\[
\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{j} = \alpha \mathbf{B},
\]

where \(\alpha\) in Equation (1) is the so-called force-free parameter and measures the level of twist of the field lines. Given that \(\mathbf{B}\) is solenoidal, \(\alpha\) must be constant along each field line. We use here nonlinear force-free extrapolations, where \(\alpha\) is constant along each given field line but can change from one field line to another. The extrapolations are carried out using the optimization method (Wiegelmann 2004).

The observed magnetic field is not necessarily force free. This is especially the case in the photosphere where the plasma \(\beta\) is not small (with \(\beta\) the ratio of gas to magnetic pressures). For instance, \(\beta \approx 1\) in the lower part of the photosphere (Yelles Chaouche et al. 2009b, from calculations using three-dimensional MHD simulations).

Schrijver et al. (2006, 2008), Metcalf et al. (2008), and De Rosa et al. (2009) have implemented a variety of tests to compute the coronal magnetic field using several nonlinear force-free field (NLFFF) extrapolation codes. The different codes were tested using analytical, numerical, and observational models. Among other conclusions, these papers have addressed the issue that the NLFFF extrapolations are sensitive to the boundary conditions (usually, photospheric vector magnetograms). These might suffer from uncertainties due to low signal-to-noise conditions, inaccuracies in the resolution of the 180° ambiguity, or more importantly from non-force-free conditions of the photospheric plasma.

In order to make the observed magnetic field maps more consistent with the force-free assumption and greatly enhance the correctness of the force-free extrapolations, it is necessary to apply some preprocessing (Wiegelmann et al. 2006; Metcalf et al. 2008). This consists of minimizing the magnetic force and torque (Aly 1989), minimizing the difference between the observed magnetic field and the preprocessed one, and applying a smoothing operator to remove the small-scale variations of the magnetic field. The preprocessing routine used here is the one developed by Wiegelmann et al. (2006). It is useful to quantify the change produced on the magnetograms by the preprocessing procedure. For that we use the usual vector correlation (Schrijver et al. 2006) between the observed vector magnetic field and the preprocessed one. It is found that for the case of the Si i 10827 Å vector magnetogram, the correlation between the original and preprocessed field is approximately 0.84. In the case of the He i 10830 Å vector magnetogram, the correlation is about 0.90 between the observed and preprocessed magnetic field. This indicates that the observed He i 10830 Å magnetic field is closer to a force-free condition than the Si i 10827 Å case.

The observed vector magnetograms have a relatively small field of view and are not isolated from the rest of the AR. This might introduce some errors in the NLFFF extrapolated model. Some authors proceed in enlarging the field of view by embedding the observed vector magnetograms in MDI maps; nevertheless this might introduce inconsistencies because the MDI magnetograms contain only the LOS component of the magnetic field, and therefore would inconsistently connect magnetic field lines throughout the NLFFF model. It is therefore safer to just use the existing vector magnetograms (after preprocessing) as lower boundary for the NLFFF extrapolations. A further test of the effect of reduced field of view on the extrapolation results is carried out in Section 4.6.

The extrapolation starts with potential lateral and top boundaries, whereas the bottom one is the preprocessed observed vector magnetogram. A description of the code can be found in Wiegelmann (2004), Schrijver et al. (2006), and Metcalf et al. (2008). The NLFFF extrapolated model is expected to be more correct in the lower central part of the computational domain (Schrijver et al. 2006).

The extrapolations are computed in a box of \(33 \times 38 \times 38\) grid points in the \(x, y,\) and \(z\) directions, respectively. \(x\) and \(y\) being the horizontal directions perpendicular and parallel to the filament’s axis, respectively. This yields a distance of \(\sim 650\) km between grid points. The same distance between grid points is used in the vertical direction.

4. RESULTS

4.1. Extrapolations Starting from the Photosphere

The vertical component of the magnetic field \((B_{\text{Si,O}}^{\text{Si}})\) inverted from the photospheric Si i 10827 Å data is plotted in Figure 2 using a color scale. The lower case “z” in \(B_{\text{Si,O}}^{\text{Si}}\) refers to the vertical component of the magnetic field, while the upper case “O” and “Si” refer to the field obtained from Observations.
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Figure 2. Background: vertical component of the magnetic field on July 5 at the photosphere ($B_{Si}$). The arrows represent the horizontal component of the magnetic field. The field strength is proportional to the length of the arrows.

(A color version of this figure is available in the online journal.)

The arrows in Figure 2 indicate the direction of the horizontal magnetic field. The length of the arrows is proportional to the horizontal field strength. In the vicinity of the PIL, some arrows point from the negative polarity to the positive one, which is called inverse configuration. A normal configuration is obtained when the field arrows point from the positive to the negative polarity. The inverse configuration in the PIL region suggests that the filament above is formed by a TFR.

The extrapolated magnetic field is plotted in the top panel of Figure 3 using UCAR’s Vapor three-dimensional visualization package (www.vapor.ucar.edu). This three-dimensional view shows a sample of magnetic field lines in the filament region in order to outline its structure. The background map represents the vertical component of the magnetic field ($B_{Si,E}$) at the bottom of the extrapolated cube. The upper case “E” and “Si” refer to the field obtained by extrapolations using the Si i 10827 Å line vector magnetograms as lower boundary condition. In the background map of the top panel of Figure 3, purple and blue colors correspond to $B_{Si,E} > 0$; green and red are reserved for $B_{Si,E} < 0$. The magnetic field forming the filament is distributed as a flux rope with dips in the lower half of the figure (i.e., with field line stretches which are convex as seen from the solar surface). This goes in the same direction as the findings of Guo et al. (2010), Canou & Amari (2010), and Jing et al. (2010).

Figure 3. Top: three-dimensional view of the magnetic field of the filament on July 5. The extrapolation results are computed using the observed photospheric magnetic field as lower boundary condition. Top background image: vertical component of the magnetic field at the bottom of the extrapolation cube. Purple and blue: $B_{Si,E} > 0$; green and red: $B_{Si,E} < 0$ Bottom: Extrapolation results using the chromospheric magnetic field on July 5 as lower boundary condition. Bottom background image: the vertical component of the magnetic field at the bottom of the extrapolation cube $B_{He,E}$ (same color scale as the top panel). The field lines are plotted in the filament region. The field lines that cross the lateral sides of the box are cut 2 pixels away from the boundaries to avoid plotting the part that might be affected by the lateral boundaries.

(A color version of this figure is available in the online journal.)
Bard & Carlsson (2008) have studied the properties of the Si\textsc{i} 10827 Å line in NLTE conditions. They have determined using empirical models that the average formation height of Si\textsc{i} 10827 Å is about 320 km for a sunspot umbra and about 541 km in the quiet sun. In the case of the observed filament, we expect the average height of formation to be between these two boundary values.

At this height of formation the photospheric plasma does not have small values of the plasma $\beta$. Nevertheless, there are theoretical and observational indications (Wiegelmann et al.
\textit{2010}; Martínez González et al. 2010) that force-free extrapolations lead to a good retrieval of the actual magnetic field at higher atmospheric layers.

### 4.2. Extrapolations Starting from the Chromosphere

We have seen in the previous section that the extrapolation studies have been conducted exclusively using photospheric spectral lines. Here we would like to present an extrapolation using the helium triplet He\textsc{i} 10830 Å as lower boundary for the extrapolations. Chromospheric lines as H\textalpha and He\textsc{i} 10830 Å have been used to identify filaments but never as boundary condition for extrapolations.

The bottom panel of Figure 3 shows a three-dimensional display of a sample of field lines at the filament region. In this case the field lines harbor some shear in the lower half of the image but with no twist. Field lines have a normal configuration (from positive to negative), except at the very central part of the filament (shown by the yellow field line) where the field lines are almost parallel to the filament axis. The bottom panel of Figure 3 suggests that the magnetic flux rope forming the filament (lower panel of Figure 3) is located below the height of formation of the He\textsc{i} 10830 Å triplet. We will come back to this point in detail in the next sections.

4.3. Height of Coincidence Between the Photospheric and Chromospheric Magnetic Fields

A natural question to ask when analyzing the extrapolations starting from the photosphere and the chromosphere is: do the magnetic fields from the two extrapolations agree with each other? In order to answer this question, we first plot the field lines that result from the two three-dimensional extrapolation boxes (Figure 4). The field lines start inside a 2 Mm deep box that extends along most of the filament. The field lines can develop outside of the box but will be cut if they go below it. This configuration allows selecting field lines above a suitable height in order to make it possible to compare field lines starting from the photosphere with those starting from the chromosphere.

Therefore, the field lines in the left panel of Figure 4 are all above an imaginary boundary situated at $\approx$1.6 Mm above the bottom of the extrapolation cube. We have tried various heights and found that $\approx$1.6 Mm gives a good agreement between the field lines from the photospheric extrapolations (left panel) and the ones from the chromospheric extrapolations (right panel of Figure 4), which are drawn directly from the lower chromospheric boundary. A visual inspection of both panels suggests a good agreement between the morphology of the magnetic field obtained from photospheric and chromospheric extrapolations.

To provide a quantitative comparison between the two sets of extrapolations, we compute the magnetic field strength in the photospheric extrapolation cube and look for the height where this field strength matches the observed chromospheric one. This operation is repeated along each column of the photospheric extrapolation cube. At the height (H) where the two field strengths coincide, the magnetic field components $B_{\text{Si,C}}$, $B_{\text{Si,C}}$, and $B_{\text{Si,C}}$ are stored as two-dimensional arrays (the uppercase “C” stands for Coincide). For instance, the
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Figure 5. Red arrows: flow representation of the horizontal magnetic field from the photospheric extrapolations at the height where the extrapolated photospheric field strength matches the observed field strength in the helium vector magnetogram. Black arrows: flow representation of the observed horizontal magnetic field in the He I λ10830 Å vector magnetogram. Top panel: solution obtained with the correct 180° ambiguity solution computed with the AZAM utility (Lites2005, and references therein). Note that the solutions are obtained for both photospheric and chromospheric fields. Bottom panel: similar to the top panel but using the other solution of the 180° ambiguity. All data sets were taken on July 5.

(A color version of this figure is available in the online journal.)

extrapolations. The average height where $B_{\text{Si, E}}$ matches $B_{\text{He, O}}$ is 1.57 Mm in the filament region, with a standard deviation of 0.66 Mm. Therefore, it is possible to determine an average formation height of the He I λ10830 Å triplet. This would be 1.57 Mm + the formation height of the Si I λ10827 Å which leads to approximatively 2 Mm above the solar surface ($\tau = 1$).

4.4. A Complementary Method for Solving the 180° Ambiguity

The top panel of Figure 5 indicates that the magnetic field extrapolated from the photosphere matches well the one observed at the chromosphere. It is nevertheless interesting to redo the calculations but for the case where the observed horizontal magnetic field is taken from the solution with 180° shift of the azimuth in the LOS frame. This is done to test the coherence of the results with the other magnetic field configuration.

From the lower panel of Figure 5 it is found that, in this case, the magnetic field extrapolated from the photosphere and the one observed at the chromosphere have a quite different orientation in the horizontal plane although they have similar field strengths at the height of coincidence. This clearly discards the solution with 180° shift and provides a complementary method to test the validity of the chosen horizontal field as a result of the various routines used to solve the 180° ambiguity of the horizontal magnetic field.

4.5. Location of the Dips Along the Filament Field Lines

The material carried by a filament must be sustained against gravity by the magnetic curvature force associated with the dips in the field lines. Using the extrapolated magnetic field from the Si vector magnetogram, we compute all the field lines that have a dip of at least 650 km depth (equivalent to the size of one grid cell). Figure 6 indicates that such field lines with dips exhibit a twisted structure, revealing the topology of the filament’s magnetic field. This X–Z view shows that the whole structure is lying relatively low. The axis of the filament is located some 1 Mm above the formation height of the Silicon line. This indicates that the axis of the TFR forming the filament is located below the formation height of the helium triplet. The lower part of the field lines in Figure 6 exhibits an inverse configuration (from negative to positive) whereas the upper part has a normal configuration. Recall that the average formation
height of the helium triplet (Section 4.3) in the filament region is 1.57 Mm above the formation height of the Silicon line. At that height the field lines have a normal configuration. This helps in understanding the lower panel of Figure 3, where the helium extrapolations exhibit no twist, which also fits with the presence of a normal configuration magnetic field at the lower boundary of the extrapolation box. It can be seen from Figure 6 that the field lines make slightly more than one turn. These field lines extend over a horizontal distance of \( \approx 18 \) Mm. This leads to \( \approx 0.055 \) turns Mm\(^{-1}\).

Following each field line in Figure 6, it is possible to calculate the location of the lowest part of the dips. These places are likely to be the preferred location where the plasma inside the filament would be gathered. Guo et al. (2010) and Canou & Amari (2010) have found a correspondence between the location of dips and the filament as observed in H\(_\alpha\). It is reasonable to argue that in order to build up opacity (e.g., in the H\(_\alpha\) spectral region), filaments are filled with material that will be preferentially located in dips.

Figure 7 shows the locations of dips on top of the Si\(_i\) 10827 Å line core intensity image (left panel) and the intensity image of the red core of the He\(_i\) 10830 Å triplet (right panel). There is an agreement between the location of the filament and the dips, which are located in the lower half of the image where the filament has a flux rope structure. There are no dips in the upper part of the panel since the magnetic field in this region has a normal configuration with no flux rope. An even clearer case is seen in Figure 8 where we repeated the same calculations as for Figure 7 but for a snapshot taken on July 3. Note the correspondence with both line cores. This analysis also provides a further indication on the location of the filament (as the H\(_\alpha\) spectral signature of a filament) and also allows the corroboration...
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Figure 9. Location of dips calculated from the photospheric extrapolations. Top row: locations of dips on top of Si\textsc{i} 10827 Å line core intensity on July 5. Lower row: locations of dips on top of Si\textsc{i} 10827 Å line core intensity on July 3. Left column: the extrapolation of the whole field of view of Si\textsc{i} 10827 Å vector magnetogram is used, but the field line calculation to find the locations of dips starts from the lower dashed line until the upper dashed line. This covers a portion similar to the reduced field-of-view test. Right column: the extrapolations of the reduced field-of-view of Si\textsc{i} 10827 Å vector magnetogram are used (same size as displayed in the background Silicon line core image). Dips are calculated in this reduced field of view.

(A color version of this figure is available in the online journal.)

of the extrapolation results since the spectral signature of the line cores of Si\textsc{i} 10827 Å and He\textsc{i} 10830 Å is independent of the extrapolation analysis, which involves the magnetic field and the force-free condition.

4.6. Testing the Effect of the Reduced Field of View on the Extrapolations

The observations made with TIP-II have a somewhat reduced field of view. Ideally the field of view should include the whole filament or even the whole AR (in general, a flux balanced region). The fact that we use part of the filament might influence the large scale magnetic connectivity through the filament. It is very useful to make quantitative tests to clarify the effects of reduced field of view (G. Aulanier 2011, private communication). We present here a test in which we cut part of the observed filament and analyze how that affects the extrapolations. The chosen reduced field-of-view region is the one delimited by the two dashed lines in Figure 2. The resulting region is the one shown in the top-right panel of Figure 9 corresponding to July 5. Similarly, the reduced field-of-view portion for July 3 is shown in the lower-right panel of Figure 9. On these two panels we have drawn the location of dips using yellow “U” shapes. For the left column of panels in Figure 9, we used the extrapolation of the whole field of view of Si\textsc{i} 10827 Å vector magnetogram, but the field line calculation to find the locations of dips starts from the lower dashed line until the upper dashed line. This covers a region similar to the reduced field-of-view cases on both July 3 (bottom left) and July 5 (upper left). Figure 9 exhibits less locations of dips than the cases of Figures 7 and 8. This is primarily due to the fact that the field lines in the reduced field-of-view portion are shorter than the ones in the original full field-of-view case, and therefore there are less field lines that fulfill the criteria of having dips of 650 km depth. A comparison between the left and right panels in Figure 9 shows that they have some similarities indicating that decreasing the field of view only slightly alters the structure of the obtained filament and, more precisely, the location of dips. Figure 10 provides a closer look to the field lines forming the dips plotted in the upper panels of Figure 9. The field lines in the upper/lower panels of Figure 10 correspond to the upper left/right panels of Figure 9, respectively. The two sets of field lines are very similar indicating that the fact of reducing the field of view does not severely affect the magnetic structure.
Figure 10. Lower panel: field lines with dips calculated in the extrapolation with reduced field of view corresponding to the region indicated in the upper-right panel of Figure 9. Upper panel: field lines forming dips computed from the extrapolation with the whole field of view, but calculated inside the region included between the two dashed lines in the upper-left panel of Figure 9. (A color version of this figure is available in the online journal.)

of the extrapolated filament. Nevertheless, a more complete test of the effect of field of view on the results of extrapolation of AR filament would be useful and interesting. That would include the observation of a whole filament (ideally in an isolated and flux balanced region) and repeated extrapolations while reducing gradually the field of view. In the present work we were limited with the original field of view, therefore we could not run such a test. We intend to include a test of that sort as part of a future investigation. This test is complementary to the more complete series of tests presented in, e.g., Schrijver et al. (2006, 2008), Metcalf et al. (2008), and De Rosa et al. (2009).

4.7. Magnetic Field Increasing From the Photosphere Upward

Due to magnetohydrostatic equilibrium, the field of concentrated vertical magnetic structures usually decreases with height above the photosphere. This is a typical case in a stratified atmosphere. Nevertheless, vertical gradients of the field strength, indicating stronger fields in the upper layers, have been observed (e.g., in polar crown prominences as shown by Leroy et al. 1983) and modeled in the past (Aulanier & Démoulin 2003) and have been ascribed to the presence of dips (Anzer 1969; Demoulin & Priest 1989). Here, we would like to analyze the possibility of an upward increase of the magnetic field strength in the filament region. The upper panel of Figure 11 shows the difference between the observed field strengths of $|B|^{\text{Si},0}$ and $|B|^{\text{He},0}$. For the sake of clarity, the figure only shows negative values of those quantities. A proxy of the location of the neutral line is indicated by the contour plots of $B_{\text{He},0}$ (i.e., small values of $B_{\text{He},0}$ coincide with the neutral line location). In the central part of the figure, the values of $|B|^{\text{He},0}$ are larger than $|B|^{\text{Si},0}$, indicating that the magnetic field in the chromosphere is larger than the photospheric one, suggesting that the magnetic field has increased upward. In order to understand this phenomenon we look for the height where the extrapolated magnetic field from the photosphere reaches its maximum along each column. This height is plotted in the lower panel of Figure 11. It can be seen in the central region of the figure that the magnetic field reaches a maximum well above the photosphere, at an average height of about 1 Mm above the formation height of the Si i 10827 Å line.

Figure 12 schematically explains the situation observed in those pixels where the magnetic field increases upward. First the magnetic field increases up to a maximum reached at the height $H_0$ (plotted, in fact, in the lower panel of Figure 11), then the magnetic field decreases gradually until reaching the height of formation of the helium signal ($H_1$) where the magnetic field is still larger than the one at the photosphere. It is also seen that there are two solutions for the height of formation of the helium signal ($H_1$ and $H_2$). The solution $H_2$ is ruled out because it leads to abnormally low formation height. The $H_1$ solution is kept and is consistent with the average height of formation of the helium signal (see Section 4.3).

The reason why the magnetic field increases lies in the fact that the corresponding part of the filament resembles the structure of a force-free flux rope. In an ideal force-free flux rope, the azimuthal component of the field yields an inward-pointing magnetic tension force, which is balanced by an increase of the magnetic pressure toward the rope axis. This leads to an increase of the magnetic field strength in the central regions of the rope.
4.8. Complementary Comments on the Filament Observed on July 3

Along the previous sections, we have used observations taken on July 3 and 5, but with some focus on the filament as observed on July 5. This has been done in order to convey a clear message and not overwhelm the reader with information about the time evolution of the filament (this time evolution will be discussed in Kuckein et al. 2012). Additionally, the filament on July 5 is very low lying (the filament’s axis is located below the formation height of He i 10830 Å). This represents a peculiar and interesting case that we have chosen to address. In order to complete the picture of the actually observed filament, we will briefly describe some further features of the filament as observed on July 3.

It can be seen in Figure 8 that the line core of the Si i 10827 Å and the red core of the He i 10830 Å show a spectral signature reminiscent of the axis of the filament on July 3. The locations of dips along the filament coincide well with the line core signature (Figure 8). The filament in this case is located higher in the atmosphere and therefore imprints a clear spectral signature on both photospheric and chromospheric lines. The observed magnetic field from photospheric vector magnetograms exhibits an inverse configuration (field lines going from negative to positive polarities) in the filament region. The observed chromospheric vector magnetograms indicate that the magnetic field in the filament region has a slightly inverse configuration, with most of the field being parallel to the filament’s axis. From extrapolations (Figure 13), it can be seen that the filament is formed by a TFR. This is revealed from both photospheric and chromospheric extrapolations.
5. DISCUSSION AND SUMMARY

This paper is dedicated to building diagnostics about an AR filament using nonlinear force-free extrapolations starting from the photosphere and the chromosphere. Extrapolations of AR filaments are usually done using the photospheric magnetic field as a lower boundary condition. This is generally convenient because the photospheric magnetic field is more accessible to observational techniques for various reasons, e.g., (1) it has a large magnetic field implying a large Zeeman splitting, (2) the photon flux coming from the photosphere is large producing a high signal-to-noise ratio, which makes it easily detectable, (3) there are many available instruments measuring photospheric field, etc. It is nevertheless interesting to probe the properties of filaments from two layers (or multi-layer if possible) since this approach provides several advantages like testing the validity of the extrapolation solutions. It also allows testing of the consistency between the extrapolations starting from the photosphere and the chromosphere. We just began to see the potential of multi-layer extrapolations, e.g., the determination of the matching height between the extrapolated photospheric field and the observed chromospheric one. This can be used as a method to determine the relative height of formation of higher-lying lines/multiplets compared to lower-lying ones. We find that the average formation height of the $\text{He I} \, \lambda 10830 \, \AA$ triplet is about $2 \, \text{Mm}$ above the surface of the Sun. Multi-layer extrapolations also provide a complementary method for testing the $180^\circ$ ambiguity solutions.

The AR filament studied here harbors a TFR structure with a rather low-lying axis on July 5, where the axis is located at about $1.4 \, \text{Mm}$ above the solar surface. This height is below the formation height of the helium signal. This result is consistent with the fact that the magnetic field as observed in helium magnetograms harbors a normal configuration.

In the present study, we have essentially focused on a snapshot taken on July 5 (see Figures 1 and 2). We have also briefly discussed a snapshot observed on July 3 (Figures 1 and 12). Recall that on July 3, the filament’s axis was higher located and clearly seen in the spectral signature of Si I $\lambda 10827 \, \AA$ and He I $\lambda 10830 \, \AA$ line cores. Actually, as discussed in Section 2 (observations and data analysis), the observations used here belong to a time series of snapshots covering 2005 July 3 and 5. In order to build a clear and detailed diagnostic we have essentially focused on studying one case (July 5). A more detailed analysis about the temporal evolution of the filament will be addressed at a later stage (see also Kuckein et al. 2012). Nevertheless, it is worth commenting on the other snapshots. An essential thing to mention is that snapshots observed on the same day exhibit similar properties (height of location of the filament axis, magnetic field strength, etc.). This means that the rest of the snapshots observed on July 5 have quite similar properties to the one described here, and similarly for the snapshots taken on July 3.

For the filament on July 5, we have seen that, if taken separately, the photospheric and chromospheric extrapolations would lead one to conclude that on the one hand the filament is formed by a TFR (from photospheric extrapolations), whereas on the other hand there is no TFR (from the chromospheric extrapolations). The multi-layer extrapolations helped solve this apparent discrepancy by showing that, depending on the location of the TFR, it might be seen at one layer or the other while the two extrapolations remain coherent with each other. Let us assume hypothetically that an AR filament is such that the lower part of the TFR is located at the upper chromosphere and does not extend to the photosphere. In this case, it would be seen in the chromospheric extrapolations, but the photospheric ones would not necessarily reveal it, especially since the photosphere is a relatively high plasma-$\beta$ medium and therefore the surrounding magnetic field in the AR might considerably alter the magnetic field near the PIL making the horizontal component of the magnetic field harbor a normal configuration. If we would only observe the photospheric field, this would lead to finding no TFR in the filament region, whereas in fact the filament’s structure is a TFR. In fact, this is true only if the electric currents present in the region are not remnant of a TFR, since it has been shown by Valori et al. (2010) that NLFFF extrapolations have the potential to find a TFR even if its dips are not present at the magnetogram level. Nevertheless, this hypothetical scenario highlights the usefulness of multi-layer extrapolations in helping to probe the properties of filament and extract further information about the observed magnetic structure.

In the case studied here, the material in the dense part of the filament, along its axis, is confined inside a flux rope where the field lines are bent producing an excess of magnetic tension toward the center of the TFR. This tension is compensated by the outward oriented magnetic pressure, producing an enhancement of the magnetic field inside the TFR. This is reflected by a vertical positive gradient of the magnetic field from the photosphere up to about $1 \, \text{Mm}$ above the formation height of the Si I $\lambda 10827 \, \AA$ signal. In brief, the field increases from the photosphere upward in the flux rope region.

There are only few studies dealing with extrapolations of AR filaments, the most recent being from Guo et al. (2010), Canou & Amari (2010), and Jing et al. (2010). These studies picture AR filaments as TFR with the exception of Guo et al. (2010), who have shown that TFR and dipped sheared arcades can coexist in the same filament. We also find a flux rope from photospheric extrapolations, but have seen that the chromospheric extrapolations might show different pictures if the observed spectral line/multiplet is formed above the filament’s axis. There is a clear necessity of further observational campaigns with the appropriate extrapolations to further clarify the properties of AR filaments and their temporal evolution. Multi-layer extrapolations would be helpful to compare the resulting three-dimensional structure of filaments with the variety of theoretical models existing in the literature (Mackay et al. 2010).

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