

ACTIVE REGION FILAMENTS MIGHT HARBOR WEAK MAGNETIC FIELDS

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Draft version March 18, 2016

ABSTRACT

Recent spectropolarimetric observations of active region filaments have revealed polarization profiles with signatures typical of the strong field Zeeman regime. The conspicuous absence in those observations of scattering polarization and Hanle effect signatures was then pointed out by some authors. This was interpreted either as a signature of mixed "turbulent" field components or as a result of optical thickness. In this article, we present a natural scenario to explain these Zeeman-only spectro-polarimetric observations of active region filaments. We propose a two-component model, one on top of the other. Both components have horizontal fields, the azimuth difference between them being close to 90 degrees. The component that lies lower in the atmosphere is permeated by a strong field of the order of 600 G, while the upper component has much weaker fields, of the order of 10 G. The ensuing scattering polarization signatures of the individual components have opposite signs, so that its combination along the line of sight reduces –and even can cancel out– the Hanle signatures, giving rise to an apparent only-Zeeman profile. This model is also applicable to other chromospheric structures seen in absorption above active regions.

Subject headings: Sun: chromosphere — Sun: filaments, prominences — Sun: magnetic topology — polarization — scattering — radiative transfer

1. INTRODUCTION

Solar filaments are dark thready structures seen on the disk as absorption in the core of some strong chromospheric lines (such as H α or Ca II lines), other weak chromospheric lines such as the He I multiplets at 10830 Å and 5876 Å (D₃), and in the extreme ultraviolet continua. They are called prominences when they are seen as diffuse bright clouds at the limb, as they scatter light from the underlying disk. Broadly speaking, they can be segregated in Active Region (AR) and Quiescent (QS) filaments. The former lie above polarity inversion lines (PILs; the observationally defined line that delineates opposite polarity magnetic fields) of active regions. The latter lie above PILs in quiet Sun regions. QS filaments are very long structures that often live for weeks or even months, and that are suspended at heights up to 100 Mm (Mackay et al. 2010, and references therein). AR filaments are formed in active regions, often in recurrent flaring areas, and are shorter in length and life time as compared to QS filaments. They are hardly seen as prominences at the limb because they probably lie lower in the atmosphere, at only a few Mm above the photosphere (Mackay et al. 2010, and references therein).

From a physical point of view, solar filaments and prominences are cool chromospheric plasma overdensities embedded in the extremely hot and less dense corona. Magnetic fields play a fundamental role in the formation, support, and eruption of these structures. It is commonly agreed that these dense structures are formed in local dips of the magnetic field (e.g. Kippenhahn & Schlüter 1957; Aulanier & Démoulin 2003; López Ariste et al. 2006). However, the magnetism of solar filaments and prominences is very difficult to constrain observationally since it requires high precision spectro-polarimetric measurements and the interpretation of signals coming from

the joint action of atomic polarization and the Hanle and Zeeman effects.

The He I 10830 Å and D₃ multiplets are very useful spectral lines to diagnose the dynamic and magnetic properties of plasma structures at chromospheric temperatures. One of the advantages is that the absorption of these lines is usually negligible in quiet regions, so that any absorption can be regarded as due to a levitating cloud at a certain height, which greatly simplifies the solution of the radiative transfer equation for polarized radiation (Leroy et al. 1977; Sahal-Brechot et al. 1977; Trujillo Bueno & Asensio Ramos 2007). In particular, these spectral lines have been widely used for the study of solar prominences and filaments (e.g. Bommier et al. 1981; Casini et al. 2003; Merenda et al. 2006; Orozco Suárez et al. 2014; Martínez González et al. 2015), the reconstruction of magnetic fields in flux emerging regions (Solanki et al. 2003; Xu et al. 2010) and in chromospheric spicules (e.g. López Ariste & Casini 2005; Centeno et al. 2009; Martínez González et al. 2012; Orozco Suárez et al. 2015).

Spectro-polarimetric observations of QS filaments and prominences revealed magnetic fields that have strengths of the order of a few tens of G (Trujillo Bueno et al. 2002; Casini et al. 2003; Merenda et al. 2006), where the linear polarization of the He I 10830 Å is dominated by the atomic level polarization due to the anisotropic radiation field. Yet, stronger fields are found for the same structures in active regions, in the range of 200-600 G (Wiehr & Stellmacher 1991; Sasso et al. 2011). Even larger field strengths (up to 800 G) were obtained when large, Zeeman-like linear polarization signatures were detected in AR filaments (Kuckein et al. 2009, 2012; Xu et al. 2012). The work of Kuckein et al. (2009) was the first to show such linear polarization profiles of the He I 10830 Å multiplet with the surprising typical symmetric

shape with three lobes of the transverse Zeeman effect.

Trujillo Bueno & Asensio Ramos (2007) and Casini et al. (2009) soon noted that, even for such strong fields, AR filaments spectropolarimetric observations should show signatures of scattering polarization and the Hanle effect. The obvious solution of having a magnetic field inclined by the Van Vleck angle (the angle that fulfills $\cos\theta_{VV} = 1/\sqrt{3}$ and for which the contribution of scattering polarization vanishes, Landi Degl’Innocenti & Landolfi 2004) in the whole filament looked clearly improbable (Kuckein et al. 2009). Trujillo Bueno & Asensio Ramos (2007) pointed out that when the optical thickness of the filament becomes larger than unity, radiative transfer effects start to play a role. In this case, the radiation field inside the filament becomes more horizontal (parallel to the solar surface) and it can compensate to some extent the predominantly vertical (along the radial direction) radiation field that is pumping the He I levels. Therefore, radiative transfer inside the filament produces a reduction of the radiation field anisotropy, that leads to a strong reduction of the scattering polarization and Hanle effect signals. Casini et al. (2009) invoked the presence of a quasi-random magnetic field co-existing with the organized magnetic field of a filament. The isotropic component of the magnetic field strongly reduces the Hanle signal produced by the deterministic field.

In this article, we propose a scenario based on a two-component model that naturally explains the predominantly Zeeman profiles observed in AR filaments. As a consequence of the model, we infer the presence of weak magnetic fields in AR filaments. The proposed scenario is extensive to other structures seen in absorption towards the solar disk in lines such as the He I multiplets (e.g., filaments, fibrils in emerging flux regions, ...).

2. A MODEL FOR ABSORPTION STRUCTURES IN THE HE I MULTIPLETS

To our knowledge, all inversions of spectropolarimetric observations of absorption features in the He I multiplets have been carried out using a single atmospheric component, as if the observed signal was generated only in the cool plasma overdensities. Even so, these structures (QS and AR filaments, fibrils in emerging flux regions, ...) usually have optical depths below or of the order of unity¹ (Kuckein et al. 2009, 2012; Sasso et al. 2011; Xu et al. 2012). Consequently, it is reasonable to think that the emergent polarization signal can have some contribution from underlying layers. This poses no problem in quiet regions because the He I multiplets yield almost no absorption. However, this turns out to be problematic in active regions because, for instance, their chromospheres produce a significant absorption in these multiplets.

We then propose a two-component approach to model the observed Stokes profiles of absorption features above active regions in the He I multiplets. This simplified model is made of two slabs with constant physical properties, one (slab 2) on top of the other (slab 1). Interestingly, this model allows us to naturally reproduce the Zeeman-only Stokes parameters observed by Kuck-

ein et al. (2009) in AR filaments without any additional mechanism to reduce the radiation field anisotropy. In such scenario, the emergent Stokes parameters $\mathbf{I} = (I, Q, U, V)^\dagger$ (with the \dagger symbol denoting transpose) can be written as (Trujillo Bueno 2003):

$$\begin{aligned} \mathbf{I}_1 &= e^{-\mathbf{K}_1^* \tau_1} \mathbf{I}_{\text{sun}} + (\mathbf{K}_1^*)^{-1} \left(\mathbf{1} - e^{-\mathbf{K}_1^* \tau_1} \right) \mathbf{S}_1, \\ \mathbf{I} &= e^{-\mathbf{K}_2^* \tau_2} \mathbf{I}_1 + (\mathbf{K}_2^*)^{-1} \left(\mathbf{1} - e^{-\mathbf{K}_2^* \tau_2} \right) \mathbf{S}_2, \end{aligned} \quad (1)$$

where \mathbf{I}_{sun} is the Stokes vector that illuminates the lower boundary of the slab (essentially the photospheric continuum), $\mathbf{K}^* = \mathbf{K}/\eta_I$ is the propagation matrix normalized to the absorption coefficient for Stokes I , $\mathbf{S} = \boldsymbol{\epsilon}/\eta_I$ is the source function vector, with $\boldsymbol{\epsilon} = (\epsilon_I, \epsilon_Q, \epsilon_U, \epsilon_V)^\dagger$ the emissivity vector (see Landi Degl’Innocenti & Landolfi 2004; Asensio Ramos et al. 2008, for more details) and $\mathbf{1}$ the identity matrix. The previous expression considers two slabs with different optical depths (τ_1 and τ_2) and different magnetic fields.

In some sense, our approach galvanizes from an idea proposed by Judge (2009). This work suggested that the polarization signals observed in the 10830 Å multiplet in filamentary structures in emerging flux regions might not mainly come from the highest part, but from the low-lying chromosphere of the active region. Judge (2009) argues that it is difficult to distinguish the two possibilities because the Stokes profiles would look very similar. Previous observations reinforce this idea because the photospheric and chromospheric magnetic field maps obtained using inversion techniques look astonishingly similar. The chromospheric maps look slightly more fuzzy because of the reduction in the gas pressure with height and the ensuing expansion, but no hint on any filamentary structure is detected (Solanki et al. 2003; Xu et al. 2010; Asensio Ramos & Trujillo Bueno 2010). We go one step forward and stand on the idea suggested by Asensio Ramos & Trujillo Bueno (2010) to propose that what we see is in fact a combination of the two atmospheres. We do not need to distinguish the two options anymore because they are simultaneously present in the Stokes profiles.

All calculations are done with HAZEL² (HANle and ZEeman Light, Asensio Ramos et al. 2008), which is able to synthesize the He I 10830 Å multiplet taking into account the presence of atomic level polarization and the combined influence of the Zeeman and Hanle effects. The radiative transfer is carried out using a very simple slab model at a fixed height that assumes that all physical properties are constant within the slab. We use in this work the option of the code of two different slabs, so that the emergent Stokes parameters are computed using Eqs. 1. Each slab is permeated with a different magnetic field vector but the pumping radiation in the two slabs is the same. This simplification is probably not very realistic but this model suffices to make our point (see Appendix for more details).

To prove our idea, we synthesize the Stokes profiles using the parameters of one of the pixels along the filament displayed in Fig. 2 of Kuckein et al. (2010). The selected magnetic field has a strength of $B = 550$ G, an inclination

¹ We measure the optical depth in the red component of the He I 10830 Å multiplet.

² The latest version is hosted at <https://github.com/aasensio/hazel>.

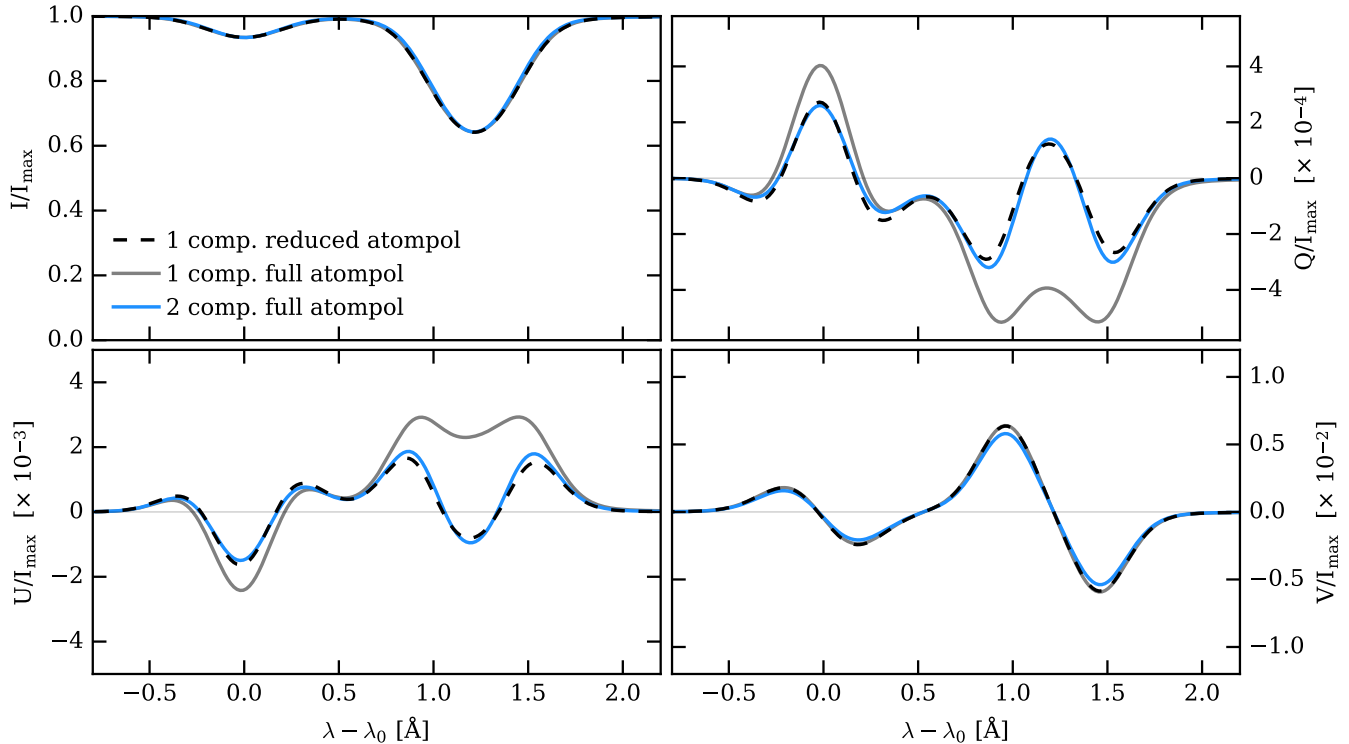


Figure 1. Synthetic Stokes profiles with one component allowing atomic polarization but reducing the anisotropy by a factor of 0.2 (dashed black curve) that reproduces one of the profiles inverted by Kuckein et al. (2010). The same profile but taking the full atomic polarization into account (grey curve). The blue curve is the fit with two components. The reference wavelength $\lambda_0 = 10829.0991$ Å is the central wavelength of the blue component of the He I 10830 Å multiplet. A color version of this figure is available online.

of $\theta_B = 95^\circ$, and an azimuth of $\phi_B = 49^\circ$, both angles defined in the local reference system (the quantization axis being the local vertical). Since the geometry of the field was provided in the observer’s reference frame, we have transformed them to the local reference system taking into account that the heliocentric angle of their observations was $\theta = 23^\circ$ ($\mu = \cos \theta = 0.92$). Following Kuckein et al. (2009), our synthetic profile is obtained by artificially reducing the anisotropy of the radiation field by a factor 0.2. We apply this correction to the radiation field anisotropy computed in HAZEL, which is obtained from the solar center-to-limb variation of the continuum at nearby wavelengths and correcting from the geometrical factor due to the height of the filament. The synthesized Stokes profiles are displayed in Fig. 1 with dashed black lines and are very similar to those published by Kuckein et al. (2009). We note that these profiles are almost indistinguishable from a scenario in which the presence of atomic level polarization is neglected. The grey lines show how the profile would look like using the very same physical properties but fully taking into account atomic level polarization (i.e., using the radiation field anisotropy computed by HAZEL). As already pointed out by Trujillo Bueno & Asensio Ramos (2007), clear signatures of atomic level polarization are seen even at fields above 1 kG, especially in the red component of the multiplet.

We carry out an inversion with HAZEL of the dashed black profiles shown in Fig. 1 with a two-component model. The resulting Stokes parameters are displayed as solid blue lines in Fig. 1. The inferred values for the low-lying component are $B_1 = 650$ G, $\theta_1 = 92^\circ$,

$\phi_1 = 48^\circ$, and $\tau_1 = 0.6$. The upper component has $B_2 = 10$ G, $\theta_2 = 85^\circ$, $\phi_2 = 140^\circ$, and $\tau_2 = 0.3$. The fit is almost indistinguishable from the profile with reduced anisotropy. Our inversion indicates that the magnetic field of the low-lying component increases with respect to the single-component inversion but its geometry is not modified much because the Stokes Q , U and V signals are very strong. The magnetic field in the upper slab turns out to be almost horizontal, with an azimuth that is roughly perpendicular to that of the lower component and to the axis of the filament. We have carried out extensive tests that indicate that the presence of a weak field in the filament is a robust result. We stress the fact that the low-lying component has to have a stronger magnetic field. Otherwise, the profiles cannot be fitted. The magnetic configuration as well as the remaining slab properties were retrieved without imposing such a configuration as starting point of the inversion.

The profiles of the two-component model can be understood by noting that the scattering polarization signatures generated in each individual component have opposite signs because the azimuths of the fields differ by $\sim 90^\circ$. The solution of the radiative transfer equation combines them reducing the Hanle contribution, with the possibility of even fully cancelling it out. We point out that the Hanle contribution to the line profile of both components is similar even though the fields differ by more than an order of magnitude because the He I 10830 Å is already in the Hanle saturation regime for fields above $\sim 10 - 50$ G. In this regime, the Hanle signals are insensitive to the magnetic field strength, so B_2 can be in this range.

3. STABILITY OF THE SOLUTION

It is obvious that the proposed model presents a handicap because a two-component model has a larger number of parameters and the inversion becomes highly degenerate. For instance, HAZEL has some problems converging to the same model when starting from different initial positions in the parameter space. One of the most obvious degeneracies takes place on the optical depth of each slab. We can only safely obtain the total optical depth $\tau = \tau_1 + \tau_2$ and the optical depth of each slab remains undetermined provided their sum equals τ . This affects the inference of the magnetic field because it is sensitive to the specific value of the optical depth. The only sensible way that we can think of to overcome this degenerate problem is to use context information and take advantage of the whole observed map to introduce constraints (e.g., use extrapolations from the photosphere to the chromosphere).

In spite of the increase in the complexity of the model, we honestly think that the model proposed in this paper is more physically realistic than any other single-component model used in the past. Considering the increased degeneracy, it is very important to verify the consistency of the model and check that the space of parameters that is compatible with the observations is not exponentially small. This would give us the idea that our fit is just a coincidence. To this end, we slightly perturb the original profile and inspect whether the inferred parameters do not vary much. The perturbed Stokes profiles are obtained by changing the magnetic field vector but keeping fixed the thermodynamic and dynamic properties of the single slab. We consider relative changes of 2, 5 and 10% for the three spherical components of the magnetic field vector. After that, we carry out an inversion with HAZEL and calculate the relative change in the 2-component model parameters with respect to the initial configuration. The results are shown in Table 1. The table indicates the relative change in the magnetic fields of the upper and lower components when the magnetic field vector in the single-component is modified with a certain relative change. All horizontal lines refer to changes below 0.5%, that is compatible with no change at all. We note that all changes are roughly of the same order than the modification in the original profile. Obviously, larger modifications of the profile lead to larger modifications of the 2-component model parameters. The important point of this table is that our proposed model is very robust to changes in the profile. Of special relevance is the fact that the azimuth difference between the two components is always $\sim 90^\circ$ for each perturbation. Converging to the solution with a two-component model is tougher and slower. For that reason, some values of the Table 1 are obtained by setting the initial values to the original ones.

4. DISCUSSION AND CONCLUSIONS

We have presented a natural way to explain the absence of atomic level polarization signatures in some observed AR filaments. This absence was interpreted in the past as an indication that the magnetic field in AR filaments was very large, well above 500 G. Additionally, an extra mechanism had to be invoked to destroy the, otherwise present for these fields, signatures of atomic

Table 1

Relative change in the model parameters of the 2-component model when the magnetic field vector of the single-component model is modified. The horizontal lines indicate relative changes below 0.5%, compatible with no change at all.

Δ [%]	2%			5%			10%		
	B	θ	ϕ	B	θ	ϕ	B	θ	ϕ
B_1	1	-	-	4	-	-	10	-	-
θ_1	-	2	-	-	6	-	-	12	1
ϕ_1	-	-	1	-	-	4	-	-	8
B_2	2	-	-	5	-	-	12	-	-
θ_2	-	2	-	-	4	5	-	14	7
ϕ_2	-	-	1	-	-	3	-	2	6

polarization and the Hanle effect.

We propose a two-component model, one on top of the other³. At certain configuration of the magnetic field in the two components, the scattering polarization and the Hanle effect signals can cancel out. Therefore, we do not need any additional mechanism to reduce the anisotropy. To show this idea, we inverted a synthetic profile computed from the results of Kuckein et al. (2010). We infer a weak magnetic field (around tens of G) in the top component, and a strong hG field in the bottom one. Both are horizontal but have an azimuth difference of around 90° . A filament harboring weak fields suspended above an active chromosphere is then a plausible scenario. Other compatible scenario is associating the lower part to the filament over the PIL, under overarching loops (upper component more tenuous) with perpendicular fields to the first one. However, the magnetic skeleton of the flux rope-like filament observed by Kuckein et al. (2009) can also reach low chromospheric layers (Yelles Chaouche et al. 2012). In this case, our model would suggest that the filament has strong fields in its lower layers and weak fields in the upper ones. In this case, using the magnetic topology inferred by Yelles Chaouche et al. (2012), the ensuing vertical magnetic field strength gradient would be larger than 500 G/Mm.

The key aspect of the solution found is the 90° difference in azimuth between the top and bottom slabs. This extreme misalignment between the azimuths of both components is freely retrieved from the inversion since the profiles show no evidence of atomic polarization.

After an exhaustive search, we were unable to find a solution where the two components have similar magnetic field inclinations but a difference in azimuth significantly smaller than 90° . We note that forcing more similar azimuths in the two components ($\sim 30^\circ$) unavoidably leads to putting the magnetic field of the upper component roughly vertical ($\sim 150^\circ$), which is not favored by theoretical models. However, the quality of the fit in this case is much worse, only compatible with the observations at the level of 10^{-3} .

In our opinion, two factors can contribute to the explanation of why sometimes Hanle-dominated signals are found while Zeeman-dominated profiles are found in other cases. First, the filament in Kuckein et al. (2009) goes above penumbral regions of the active region, so that the field in the lower chromosphere turns out to be

³ Two atmospheres combined with a filling factor could also be an option but this physical configuration still has to be justified, like other potential scenarios as the one presented by Trujillo Bueno (2010).

much higher. On the contrary, in our observations, the filament is above the granulation, so that the field and the absorption in the chromosphere are smaller. Second, there is a dependence of the emergent profiles on the optical depth of the filament.

Finally, we note that inferring the magnetic field properties of filaments under this model will be more complicated because of the potential ambiguities. More work needs to be done in order to improve the inversions, possibly using the full field-of-view to constrain the model parameters. However, we can safely say that a single-component inversion correctly retrieves: the total optical depth of the plasma in the filament (the difficult part is to separate it into two contributions) and the magnetic field of the dominant component (in our case, the lower component).

The authors are very grateful to Drs. C. Kuckein and R. Manso Sainz for very helpful discussions that improved the work and strengthened our conclusions. Financial support by the Spanish Ministry of Economy and Competitiveness through projects AYA2014-60476-P, AYA2014-60833-P and Consolider-Ingenio 2010 CSD2009-00038 are gratefully acknowledged. C. J. Díaz Baso acknowledges Fundación La Caixa for the financial support received in the form of a PhD contract. AAR also acknowledges financial support through the Ramón y Cajal fellowships. This research has made use of NASA's Astrophysics Data System Bibliographic Services.

APPENDIX

APROXIMATIONS IN THE RADIATIVE TRANSFER PROBLEM

In order to solve the radiative transfer problem we are assuming that the tensor components of the radiation field J_0^0 (mean intensity) and J_0^2 (radiation anisotropy) that illuminate the top component are the same as those illuminating the lower component. This is a necessary simplification in HAZEL to solve a linear problem in the statistical equilibrium equations. Otherwise, the full non-LTE problem of the second kind has to be solved, something that is well beyond our aims. However, in the following, we estimate the possible impact of the presence of the lower component on the illumination of the top component.

Concerning the radiation anisotropy of the upper component, $[J_0^2]_2$, the expression of this tensor component for the top slab in the plane-parallel case is given by:

$$[J_0^2]_2 = \frac{1}{2\sqrt{2}} \int_{-1}^1 d\mu \int_0^\infty d\nu (3\mu^2 - 1) [\phi_\nu]_2 [I_\nu(\mu)]_1, \quad (\text{A1})$$

where $[\phi_\nu]_2$ is the line absorption profile in the upper component and $[I_\nu(\mu)]_1$ is the specific intensity at frequency ν and heliocentric angle μ that emerges from the lower component. Let us assume a Gaussian line absorption profile with line width $\Delta\nu$ centered at frequency ν_0 . For simplicity, we assume that the emergent intensity is an absorption Gaussian line with depression d and that there is no differential Doppler shift between the two slabs (this case would generate atomic orientation). Also for simplicity, we assume that only the continuum has center-to-limb variation (d does not depend on μ). Then, the ratio r between the anisotropy of the upper slab illuminated with and without a spectral line is given by:

$$r = 1 - \frac{d}{\sqrt{2}}. \quad (\text{A2})$$

Assuming values of $d \sim 0.25 - 0.4$ (this value is difficult to estimate because we only observe the total absorption of the two components), the ratio yields values $r \sim 0.71 - 0.82$. Therefore, the influence of the presence of an absorption spectral line on the lower component seems to be negligible, specially given the difficulty in solving the full problem.

The second simplification in HAZEL is that the atomic orientation of the upper slab is zero. However, when the second layer is illuminated by circularly polarized light there is a non-zero orientation of the radiation field $[J_1^0]_2$ which, in turn, produces atomic orientation in the top slab.

In order to quantify $[J_0^1]_2$, Martínez González et al. (2012) showed that it is possible to generate atomic orientation, if there is a relative motion between the lower and upper component. The general expression for the orientation of the radiation field is given by:

$$[J_0^1]_2 = \sqrt{\frac{3}{2}} \int_{-1}^1 d\mu \int_0^\infty d\nu \mu [\phi_\nu]_2 [V_\nu(\mu)]_1, \quad (\text{A3})$$

where $V_\nu(\mu)$ is the emergent Stokes V from the lower component. According to Martínez González et al. (2012), if the relative velocity between the two components is of the order of 10-12 km s⁻¹, some atomic orientation can be generated in the upper component. However, this would produce a visible symmetric Stokes V profile, something that we do not observe.

REFERENCES

- Asensio Ramos, A., & Trujillo Bueno, J. 2010, *Mem. Soc. Astron. Italiana*, 81, 625
- Asensio Ramos, A., Trujillo Bueno, J., & Landi Degl'Innocenti, E. 2008, *ApJ*, 683, 542
- Aulanier, G., & Démoulin, P. 2003, *A&A*, 402, 769
- Bommier, V., Sahal-Brechot, S., & Leroy, J. L. 1981, *A&A*, 100, 231
- Casini, R., López Ariste, A., Tomczyk, S., & Lites, B. W. 2003, *ApJ*, 598, L67
- Casini, R., Manso Sainz, R., & Low, B. C. 2009, *ApJ*, 701, L43
- Centeno, R., Trujillo Bueno, J., & Asensio Ramos, A. 2009, *ApJ*, in press
- Judge, P. G. 2009, *A&A*, 493, 1121
- Kippenhahn, R., & Schlüter, A. 1957, *ZAp*, 43, 36
- Kuckein, C., Centeno, R., & Martínez Pillet, V. 2010, *Mem. Soc. Astron. Italiana*, 81, 668
- Kuckein, C., Centeno, R., Martínez Pillet, V., Casini, R., Manso Sainz, R., & Shimizu, T. 2009, *A&A*, 501, 1113
- Kuckein, C., Martínez Pillet, V., & Centeno, R. 2012, *A&A*, 539, A131
- Landi Degl'Innocenti, E., & Landolfi, M. 2004, *Polarization in Spectral Lines* (Kluwer Academic Publishers)
- Leroy, J. L., Ratier, G., & Bommier, V. 1977, *A&A*, 54, 811
- López Ariste, A., Aulanier, G., Schmieder, B., & Sainz Dalda, A. 2006, *A&A*, 456, 725
- López Ariste, A., & Casini, R. 2005, *A&A*, 436, 325
- Mackay, D. H., Karpen, J. T., Ballester, J. L., Schmieder, B., & Aulanier, G. 2010, *Space Sci. Rev.*, 151, 333
- Martínez González, M. J., Asensio Ramos, A., Manso Sainz, R., Beck, C., & Belluzzi, L. 2012, *ApJ*, 759, 16
- Martínez González, M. J., Manso Sainz, R., Asensio Ramos, A., Beck, C., de la Cruz Rodríguez, J., & Díaz, A. J. 2015, *ApJ*, 802, 3
- Merenda, L., Trujillo Bueno, J., Landi Degl'Innocenti, E., & Collados, M. 2006, *ApJ*, 642, 554
- Orozco Suárez, D., Asensio Ramos, A., & Trujillo Bueno, J. 2014, *A&A*, 566, A46
- . 2015, *ApJ*, 803, L18
- Sahal-Brechot, S., Bommier, V., & Leroy, J. L. 1977, *A&A*, 59, 223
- Sasso, C., Lagg, A., & Solanki, S. K. 2011, *A&A*, 526, A42
- Solanki, S. K., Lagg, A., Woch, J., Krupp, N., & Collados, M. 2003, *Nature*, 425, 692
- Trujillo Bueno, J. 2003, in *Stellar Atmosphere Modeling*, ed. I. Hubeny, D. Mihalas, & K. Werner, ASP Conf. Ser. 288 (San Francisco: ASP), 551
- Trujillo Bueno, J. 2010, *Astrophysics and Space Science Proceedings*, 19, 118
- Trujillo Bueno, J., & Asensio Ramos, A. 2007, *ApJ*, 655, 642
- Trujillo Bueno, J., Landi Degl'Innocenti, E., Collados, M., Merenda, L., & Manso Sainz, R. 2002, *Nature*, 415, 403
- Wiehr, E., & Stellmacher, G. 1991, *A&A*, 247, 379
- Xu, Z., Lagg, A., Solanki, S., & Liu, Y. 2012, *ApJ*, 749, 138
- Xu, Z., Lagg, A., & Solanki, S. K. 2010, *A&A*, 520, A77
- Yelles Chaouche, L., Kuckein, C., Martínez Pillet, V., & Moreno-Insertis, F. 2012, *ApJ*, 748, 23