The Astrophysical Journal, 619:L191–L194, 2005 February 1

THE HANLE AND ZEEMAN EFFECTS IN SOLAR SPICULES: A NOVEL DIAGNOSTIC WINDOW ON CHROMOSPHERIC MAGNETISM

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Received 2004 October 6; accepted 2004 December 16; published 2005 January 11

ABSTRACT

An attractive diagnostic tool for investigating the magnetism of the solar chromosphere is the observation and theoretical modeling of the Hanle and Zeeman effects in spicules, as shown in this Letter for the first time. Here we report on spectropolarimetric observations of solar chromospheric spicules in the He I λ10830 multiplet and on their theoretical modeling accounting for radiative transfer effects. We find that the magnetic field in the observed (quiet-Sun) spicular material at a height of about 2000 km above the visible solar surface has a strength of the order of 10 G and is inclined by approximately 35° with respect to the local vertical direction. Our empirical finding based on full Stokes vector spectropolarimetry should be taken into account in future magnetohydrodynamical simulations of spicules.

Subject headings: magnetic fields — polarization — radiative transfer — scattering — stars: magnetic fields — Sun: chromosphere

1. INTRODUCTION

Spicules were described in 1877 by Father Angelo Secchi as jetlike, elongated plasma structures in the solar atmosphere (Secchi 1877). These features are best seen when observing a few arcsec off the limb in various chromospheric emission lines, such as Hα or the lines of neutral helium at 5876 and 10830 Å. It is commonly believed that most of the chromospheric emission in these lines comes from spicules, and that at heights exceeding 1500 km above the photosphere the solar chromosphere is mainly composed of spicular material (Beckers 1972). These needle-shaped plasma structures show apparent upward velocities reaching 25 km s^{-1} lasting for some 5 minutes, and are frequently slanted with respect to the solar radius vector through the observed point (hereafter solar local vertical). After reaching a typical maximum height of 9000 km, the ejection stops and is followed by a fading of the spicule brightness or a return of the emitting material to the photosphere. Interestingly, in the upward-moving phase the spicule mass flux exceeds by 2 orders of magnitude the mass loss of the solar corona through the solar wind.

Practically, all theoretical models aimed at explaining the origin of spicules require the presence of magnetic fields (e.g., the review by Sterling 2000). For instance, in order to model dynamic jets in active region fibrils, De Pontieu et al. (2004) assume a rigid flux tube whose magnetic strength changes from 1600 G in the photosphere to 120 G in the low corona. What has been really lacking up until now are spectropolarimetric investigations to infer the strength and geometry of the magnetic field that is thought to channel the spicular motion. To fill this gap, a few years ago we started an investigation that combines spectropolarimetric observations and theoretical modeling based on the quantum theory of spectral line polarization (see Trujillo Bueno 2003b for a brief advance of the results of this investigation). In this Letter we report on a selection of the observed off-limb Stokes profiles in the He I λ10830 multiplet, which clearly show how the Hanle effect (Hanle 1924; Stenflo 1994; Trujillo Bueno 2001) rotates the direction of polarization of the scattered light.

2. SPECTROPOLARIMETRIC OBSERVATIONS

The observations reported here were carried out on 2001 May 10 with the Tenerife Infrared Polarimeter (see Martínez Pillet et al. 1999) mounted on the German Vacuum Tower Telescope at the Observatorio del Teide (Spain). The spectrograph slit was located at about 2″.5 off the east solar visible limb and parallel to it, thus crossing the spicular material that we could see clearly in the corresponding Hα slitjaw images. Note that this off-limb location corresponds approximately to an atmospheric height of 2000 km above the visible solar surface, because one has to take into account that the visible solar limb corresponds to a height of about 250 km (e.g., Asensio Ramos et al. 2003). It is important to point out that during our observation the visible east solar limb region was fairly quiet without any indication of active regions in the slitjaw images. For each fixed slit position we took various independent time series of 50 consecutive images, with each of the images resulting from the accumulation of five snapshots of 100 ms.

In order to improve the signal-to-noise ratio, we temporally averaged the 50 consecutive images of the time series selected, which implies a net integration time of 209 s. We find that while Stokes Q has a sizable signal that is always positive at all the spatial points along the spectrograph slit, the Stokes U parameter turns out to vary rather smoothly from zero at the extremes of the spatial domain defined by the length of the spectrograph's slit (~40″ long), to a negative value ($U/I_{\max} \approx -0.4\%$) at a spatial point corresponding approximately to the center of the slit. Our spectropolarimetric observations of spicules in the He I λ10830 multiplet are very encouraging, especially because of the detection of nonzero Stokes U profiles such as the illustrative example shown in Figure 1. According to the theory of the Hanle effect, a nonzero Stokes U profile is the observational signature of the presence of a magnetic field *inclined* with respect to the local vertical direction. Finally, note that the amplitudes of the Stokes V profiles of the spicules observed on 2001 May 10 were very weak, lying almost at the noise level.

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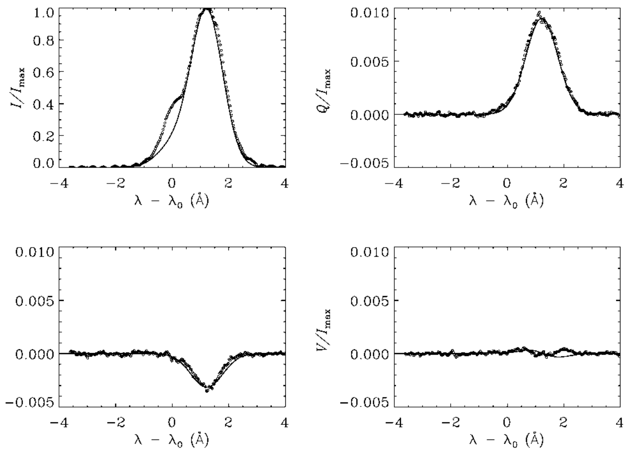

FIG. 1.—*Open circles*: Observed Stokes profiles at one of the spatial points that show nonzero Stokes *U* signals in the observed (quiet-Sun) chromospheric spicules. The reference direction for Stokes *Q* is the parallel to the solar limb. The origin of the wavelength scale corresponds to the blue component of the He I λ10830 multiplet. *Solid line*: Optically thin theoretical modeling for strength $B = 10$ G, inclination $\theta_B = 35°$, azimuth $\chi_B = 172°$, and a thermal velocity of 22 km s^{-1}. The alternative determination $B = 10$ G, $\theta'_B = 180° - \theta_B$, and $\chi'_B = -\chi_B$ gives the same theoretical Stokes profiles. See footnote 6 for the definition of the angles θ_B and χ_B.

3. THEORETICAL MODELING OF THE HANLE AND ZEEMAN EFFECTS IN SOLAR SPICULES

The determination of the magnetic field vector in solar spicules can be achieved via theoretical modeling of the Hanle and Zeeman effects in suitably chosen spectral lines, such as those of the He I λ10830 multiplet. To this end, we have applied the quantum theory of spectral line polarization, calculating the wavelength positions and strengths of the Zeeman components in the incomplete Paschen-Back effect regime, as explained in detail in Landi Degl'Innocenti & Landolfi (2004). We have assumed that a collection of helium atoms located at a given height above the visible solar "surface" is illuminated by the (limb-darkened) photospheric radiation field, whose center-to-limb variation has been tabulated by Pierce (2000). The anisotropic radiation pumping induces population imbalances and quantum coherences among the magnetic substates of energy levels (that is, atomic polarization), which gives rise to linearly polarized light. The atomic level polarization (and the ensuing emergent polarization) is efficiently modified in the presence of an inclined magnetic field of strength $B_{\rm H} \approx 1.137 \times 10^{-7}/(t_{\rm life} g_{\rm L})$, with $B_{\rm H}$ expressed in gauss and where $t_{\rm life}$ and $g_{\rm L}$ are the lifetime (expressed in seconds) and Landé factor of the atomic level under consideration, respectively (e.g., the review by Trujillo Bueno 2001 on the Hanle effect).

The atomic model that we have adopted includes the five lower terms of the triplet system of helium, namely, $2\,^3S$, $2\,^3P$, $3\,^3S$, $3\,^3P$, and $3\,^3D$. The 10830 Å multiplet results from transitions between the metastable term $2\,^3S$ (which has a single level with total angular momentum $J = 1$) and the term $2\,^3P$ (which has three levels with $J = 2, 1, 0$ in order of increasing energy). Therefore, it has three spectral lines: a "blue" line at 10829.09 Å (with $J_l = 1$ and $J_u = 0$) and two "red" lines at 10830.25 Å (with $J_u = 1$) and at 10830.34 Å (with $J_u = 2$) that appear blended at the plasma temperatures of solar spicules. The multiplet that results from transitions between the term $2\,^3P$ (the upper term of the He I λ10830 multiplet) and the term $3\,^3D$ produces the well-known He I D3 "line" at 5876 Å, which is also of diagnostic interest (see § 4).[4]

Our interpretation of the spectropolarimetric observations is based on the solution of the statistical equilibrium equations for the spherical tensor components $[\rho^K_Q(J, J')]$ of the atomic density matrix (see the equations of § 7.6.a in Landi Degl'Innocenti & Landolfi 2004). We have done this by assuming that the helium atoms (located at ∼2″ above the visible solar limb) are radiatively excited by the *given* continuum radiation coming from the underlying solar photosphere, which is virtually spectrally flat around the wavelengths of the line transitions that play a significant role on the $\rho^K_Q(J, J')$-values of the upper and lower terms of the 5876 and 10830 Å multiplets.[5] Such $\rho^K_Q(J, J')$ elements allow us to quantify the overall population of each level of total angular momentum *J*, as well as the population imbalances between the magnetic sublevels pertaining to each *J*-level and the quantum coherences between pairs of magnetic substates, even between substates pertaining to different *J*-levels of the same term. From the calculated density-matrix elements it is then possible to compute the emission coefficients in the four Stokes parameters, and the coefficients of the 4 × 4 propagation matrix of the Stokes vector transfer equation for each of the line transitions of the assumed multiterm model atom (see the equations of § 7.6.b in Landi Degl'Innocenti & Landolfi 2004).

3.1. *Optically Thin Modeling*

In a first modeling step we have neglected radiative transfer effects along the line of sight. This optically thin assumption is identical to that generally adopted for inferring the magnetic field vector from the Stokes profiles of emission lines observed in solar prominences (see, e.g., Bommier et al. 1994).

The result of our best fit to the observed Stokes profiles is shown by the solid lines of Figure 1. With the exception of Stokes *I*, there is a good fit to Stokes *Q*, *U*, and *V* for a magnetic field vector of strength $B = 10$ G, inclination $\theta_B = 35°$ with respect to the local vertical direction, and azimuth[6] $\chi_B = 172°$. The inferred magnetic field vector at those spatial points where the observed Stokes *U* was found to be negligible is also inclined by about 35°, while the azimuth turns out to be significantly different (e.g., $\chi_B = 186°$ for a slit point situated at a distance of 7″ from that of Fig. 1). The discrepancy found in Stokes *I* around the wavelength location of the blue component of the He I λ10830 multiplet (see Fig. 1) indicates that the optically thin assumption is not suitable for modeling the Stokes *I* profiles of solar chromospheric spicules.

3.2. *Optically Thick Modeling*

There are various levels of sophistication to account for radiative transfer effects in solar plasma structures such as prominences, coronal filaments, and chromospheric spicules. Here we consider a relatively simple model with the basic aim of

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[4] Spectropolarimetric observations of spicules in the D3 line have been presented by Sheeley & Keller (2003) and also by López Ariste & Casini (2005) in a recently submitted paper.

[5] Under such circumstances, the atomic density matrix does not depend on the velocity of the helium atoms in the spicular gas and the complete redistribution theory described by Landi Degl'Innocenti & Landolfi (2004) can be safely applied.

[6] See Fig. 13.1 in Landi Degl'Innocenti & Landolfi (2004) for the definition of the angles θ_B and χ_B and note that a magnetic field vector lying in the scattering plane has $\chi_B = 0°$ or $\chi_B = \pm 180°$. We have taken $\delta = 0$ in that Fig. 13.1, which implies that the spicular material is supposed to lie in the plane of the sky.

demonstrating that radiative transfer effects are indeed at work in solar chromospheric spicules, but that such effects affect mainly the shape of the emergent Stokes I profiles. To this end, we assume a constant-property slab of optical thickness τ at the wavelength under consideration, which accounts for the collective effect of several individual spicules along the line of sight. The helium atoms of this slab are assumed to be polarized as in the previous optically thin case.

It is not difficult to show that for this optically thick case of a constant-property slab, the *emergent* Stokes I and Stokes X profiles (X being Q, U, or V) are given by

$$I(\tau) = I_0 e^{-\tau} + \frac{\epsilon_I}{\eta_I}(1 - e^{-\tau}), \tag{1}$$

$$X(\tau) = X_0 e^{-\tau} + \frac{\epsilon_X}{\eta_I}(1 - e^{-\tau}) - \frac{\epsilon_I \eta_X}{\eta_I^2}(1 - e^{-\tau}) + \frac{\eta_X}{\eta_I}\tau e^{-\tau}\left(\frac{\epsilon_I}{\eta_I} - I_0\right), \tag{2}$$

where I_0 and X_0 specify the boundary condition—that is, the Stokes parameters that illuminate the slab's boundary that is most distant from the observer. In these expressions (ϵ_I, ϵ_X) are the components of the emission vector, while (η_I, η_X) are the absorption and dichroism components of the (4 × 4) propagation matrix. The approximation that we have used to obtain this analytical solution to the radiative transfer problem in a constant-property slab is that the general Stokes vector transfer equation can be simplified as indicated by equations (55)–(58) of Trujillo Bueno (2003a), which is indeed justified in our case because in the spicular material the Zeeman splitting turns out to be a very small fraction of the spectral line width and also because at a few thousand kilometers above the solar visible "surface" the degree of anisotropy of the photospheric radiation field is weak (see also Sánchez Almeida & Trujillo Bueno 1999).

The boundary condition for modeling the emergent Stokes parameters from optically thick solar spicules observed off-the-limb is $I_0 = Q_0 = U_0 = V_0 = 0$. Therefore, in contrast with the previously discussed optically thin case, we now have that the slab's optical thickness at the line-core of the red line ($\tau_{\rm red}$) is the only *additional* free parameter whose value has to be chosen to fit the observed Stokes profiles. Figure 2 shows the result of our radiative transfer modeling of the observed Stokes profiles discussed previously in Figure 1. The solid and dotted lines correspond approximately to the same thermal velocity ($w_T \approx 14$ km s^{-1}), which is now significantly lower than that required to fit the observed spectral line widths via the optically thin modeling. The slab's optical thickness $\tau_{\rm red}$ is also similar in the two modeling cases corresponding to the solid and dotted lines. The same happens with the magnetic field vector, which in both cases turns out to be practically identical to that inferred via the optically thin approximation (that is, we now find $B \approx 10$ G and $\theta_B \approx 37°$).

The only relevant difference between the two modeling cases of Figure 2 is the following. The dotted lines result from calculations with a damping constant of the Voigt profile that has not been artificially enhanced—that is, with that resulting from the natural broadening and the assumed "thermal" velocity, as was the case in Figure 1. Interestingly, the corresponding theoretical Stokes Q profile shows a tiny negative signal around the wavelength position of the blue line of the He I λ10830 multiplet. This is nothing but the observational signature of a differential absorption of polarization components (dichroism) caused by the presence of a significant amount of atomic polarization in the ground level of the triplet system of helium. As seen in Figure 2, we obtain a fairly good fit to the observed Stokes profiles, except in the far wings. We point out that the fit of the far wings can be improved by artificially enhancing the damping parameter of the Voigt profile, as shown by the solid lines, which might be interpreted as an indication of nonthermal broadening mechanisms associated with non-Maxwellian velocity distribution functions.

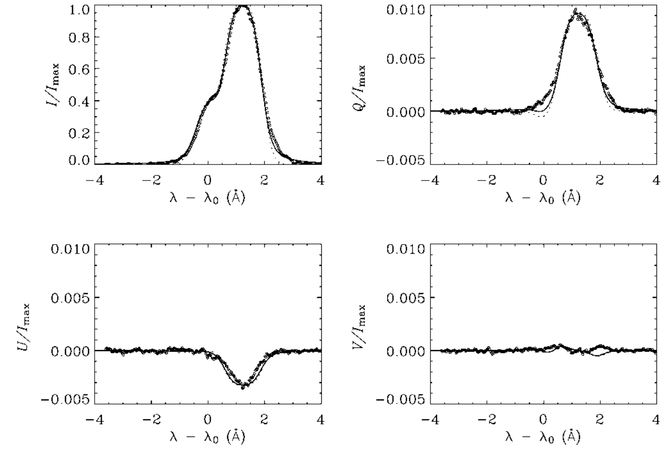

FIG. 2.—*Open circles*: Observed Stokes profiles at the same spatial point of Fig. 1. The reference direction for Stokes Q is the parallel to the solar limb. The origin of the wavelength scale corresponds to the blue component of the He I λ10830 multiplet. *Dotted line*: Optically thick theoretical modeling ($\tau_{\rm red} = 3.7$) for a magnetic field strength $B = 10$ G, inclination $\theta_B = 37°$, azimuth $\chi_B = 173°$, and a thermal velocity of 15 km s^{-1}. *Solid line*: Optically thick theoretical modeling ($\tau_{\rm red} = 3$) with enhanced damping parameter, for a magnetic field strength $B = 10$ G, inclination $\theta_B = 37°$, azimuth $\chi_B = 173°$, and a thermal velocity of 13.5 km s^{-1}. In both modeling cases, the alternative determination $B = 10$ G, $\theta'_B = 180° - \theta_B$, and $\chi'_B = -\chi_B$ gives the same theoretical Stokes profiles.

Obviously, the presence of nonthermal broadening mechanisms makes it difficult to detect the above-mentioned observational signature of dichroism (selective absorption of polarization components), which results from the presence of lower-level polarization.[7] In fact, that negative Stokes Q signal at the wavelength location of the blue line of the He I λ10830 multiplet turns out to be a very tiny observational signature for free-standing slabs with $\tau_{\rm red} < 6$. As shown by Trujillo Bueno et al. (2002), the situation is, however, much more favorable for solar prominences seen against the bright background of the solar disk—that is, for the solar filament case where the boundary condition $I_0 \neq 0$ and one measures the polarization of the *transmitted* beam after having been selectively absorbed.

It is important to point out that for magnetic strengths sensibly larger than 10 G, the He I λ10830 multiplet enters into the saturation regime of the upper-level Hanle effect where the Stokes Q and U parameters are only sensitive to the orientation of the magnetic field vector. For this reason, it is crucial to measure also Stokes V, as we have done in this investigation, since the observed amplitude allows us to estimate in a rather

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[7] It is also of interest to mention that when the calculations are carried out assuming a completely unpolarized ground level, then the inferred magnetic strength is still $B \approx 10$ G, while the inclination of the magnetic field vector is sligtly smaller (i.e., $\theta_B \approx 32°$).

straightforward way how large the magnetic strength can be. Indeed, for magnetic strengths weaker than the crossing field of the *J*-levels of the upper term (∼400 G), the circular polarization of the He I λ10830 multiplet is dominated by the Zeeman splitting, instead of by the alignment-to-orientation mechanism discussed by Landi Degl'Innocenti & Landolfi (2004). We have carried out several model calculations of the emergent spectral line polarization for increasing values of the magnetic field strength, paying particular attention to compare the calculated and observed circular polarization amplitudes. As a result, we have found that the best fit to the observed (temporally averaged) Stokes profiles is obtained for $B = 10$ G, and that magnetic strengths sensibly larger than 15 G would be incompatible with the (quiet-Sun) chromospheric spicules that we observed on 2001 May 10. It is, however, important to note that the observed Stokes profiles also include the unavoidable averaging along the line of sight. Obviously, we cannot exclude the possibility of stronger fields occupying only a small fraction of the integration volume along the line of sight.

Finally, it is of interest to mention that the measured circular polarization was also very weak for the off-limb spicules that we observed during 2003 September. However, some of the chromospheric spicules that we observed during 2004 September showed sizable Stokes *V* signals that seem to be compatible with an inclined magnetic field of strength $B \approx 38$ G. This suggests that the magnetic field strength of solar spicules can also be significantly larger than 10 G (see also López Ariste & Casini 2005).

4. CONCLUSIONS

The reported spectropolarimetric observations of solar chromospheric spicules in the He I λ10830 multiplet show clearly the observational signature of the Hanle effect (see the nonzero Stokes *U* profile of Fig. 1), which provides the first *direct* empirical demonstration that the spicular material is significantly magnetized.

In order to obtain information on the strength and geometry of the magnetic field vector, we have applied the quantum theory of spectral line polarization at two levels of sophistication: optically thin and optically thick modeling. This has allowed us to demonstrate that radiative transfer effects have to be taken into account for a correct modeling of the observed Stokes *I* profiles, and that such transfer effects reduce the value of the thermal velocity needed to fit the spectral line widths. Our spectropolarimetric observations of (quiet-Sun) chromospheric spicules indicate the presence of significantly inclined magnetic fields, with inclination angles similar to those of the observed spikelike features themselves (i.e., $\theta_B \approx 35°$). The magnetic field strength of the (quiet-Sun) spicular material that we observed on 2001 May 10 is about 10 G. We think that 10 G is the typical value for the magnetic strength of the (quiet-Sun) spicular material at an atmospheric height of 2000 km, but significantly stronger fields may also be present.

An interesting investigation for the near future concerns the height variation of the magnetic field that channels the spicular motions, with particular interest in determining whether or not it is twisted around the axis of the spicules. To this end, cospatial and simultaneous spectropolarimetry in the 10830 Å and D3 multiplets of neutral helium would be the most suitable ground-based diagnostic window. On the one hand, while the linear polarization of the 10830 Å multiplet is sensitive (via the upper-level Hanle effect) to magnetic strengths between 0.1 and 10 G, approximately, the sensitivity range for the D3 line lies between 0.7 and 70 G. On the other hand, such simultaneous observations would allow us to avoid a subtle ambiguity, which is different from the well-known 180° ambiguity mentioned in the figure legends. In reality, for magnetic field inclinations θ_B such that $\theta_1 < \theta_B < \theta_2$ (with $\theta_1 \approx 30°$ and $\theta_2 \approx 150°$ when we are in the Hanle effect saturation regime), the magnetic field vector inferred from the observed polarization in the He I λ10830 multiplet has an additional ambiguity for some values of the magnetic field azimuth (see Merenda et al. 2005). This 90° ambiguity in the plane of the sky, also referred to as the Van Vleck ambiguity, was pointed out by House (1977) and Casini & Judge (1999) concerning the scattering polarization in forbidden coronal lines. We should mention that from the two possible magnetic field orientations that produce similar Stokes profiles, in this Letter we have always chosen that which lies closest to the observed inclinations of spicules, because of the argument that the observed spicular motions are likely channeled by the magnetic field vector.

We thank Roberto Casini (HAO) and Arturo López Ariste (THÉMIS) for scientific discussions. This research has been funded by the Spanish Ministerio de Educación y Ciencia through project AYA2004-05792 and by the European Solar Magnetism Network.

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