THE MAGNETIC SENSITIVITY OF THE Mg II k LINE TO THE JOINT ACTION OF HANLE, ZEEMAN, AND MAGNETO-OPTICAL EFFECTS

E. ALSINA BALLESTER\textsuperscript{1,2}, L. BELLUZZI\textsuperscript{3,4}, and J. TRUJILLO BUENO\textsuperscript{1,2,5}

\textsuperscript{1} Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain; ealsina@iac.es, jtb@iac.es
\textsuperscript{2} Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain
\textsuperscript{3} Istituto Ricerche Solari Locarno, CH-6605 Locarno Monti, Switzerland; belluzzi@irsol.ch
\textsuperscript{4} Kiepenheuer-Institut für Sonnenphysik, D-79104 Freiburg, Germany
\textsuperscript{5} Consejo Superior de Investigaciones Científicas, Spain

Received 2016 July 21; revised 2016 September 30; accepted 2016 October 2; published 2016 November 3

ABSTRACT

We highlight the main results of a radiative transfer investigation on the magnetic sensitivity of the solar Mg II k resonance line at 2795.5 Å, accounting for the joint action of the Hanle and Zeeman effects as well as partial frequency redistribution phenomena. We confirm that at the line center, the linear polarization signals produced by scattering processes are measurable, and that they are sensitive, via the Hanle effect, to magnetic fields with strengths between 5 and 50 G, approximately. We also show that the Zeeman effect produces conspicuous circular polarization signals, especially for longitudinal fields stronger than 50 G, which can be used to estimate the magnetization of the solar chromosphere via the familiar magnetograph formula. The most novel result is that magneto-optical effects produce, in the wings of the line, a decrease of the $Q/I$ scattering polarization pattern and the appearance of $U/I$ signals (i.e., a rotation of the plane of linear polarization). This sensitivity of the $Q/I$ and $U/I$ wing signals to both weak ($\sim$5 G) and stronger magnetic fields expands the scientific interest of the Mg II k line for probing the chromosphere in quiet and active regions of the Sun.

Key words: line; profiles – polarization – radiative transfer – scattering – stars: atmospheres – Sun: chromosphere

1. INTRODUCTION

The inference of the magnetic field in the upper chromosphere and transition region of the Sun is a very important challenge of modern astrophysics. In such external atmospheric layers, the temperature of the solar plasma ranges from $10^4$ to $10^6$ K, so that its primary emission lies at wavelengths shorter than 3000 Å. Since the magnetic field leaves its fingerprints on the spectral line polarization (e.g., Stenflo 1994; Landi Degl’Innocenti & Landolfi 2004), in order to probe the magnetic properties of the outer solar atmosphere, we need to measure and interpret the four Stokes profiles ($I, Q, U, V$) of strong ultraviolet (UV) spectral lines (e.g., the review by Trujillo Bueno 2014 and references therein).

Recent investigations pointed out that the hydrogen Ly$\alpha$ line of the solar disk radiation should be linearly polarized and that via the Hanle effect the line-center polarization is sensitive to the presence of magnetic fields, with strengths between 10 and 100 G, in the corrugated boundary that delineates the chromosphere–corona transition region (see Trujillo Bueno et al. 2011, 2012; Belluzzi et al. 2012; Stépán et al. 2012). Such theoretical advances motivated the development of the Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP), a suborbital rocket experiment that has provided the first successful measurement of the $Q/I$ and $U/I$ profiles of the Ly$\alpha$ line at 1216 Å in relatively quiet regions of the solar disk (Kano et al. 2016).

The success of CLASP and the results of a recent theoretical investigation (see Belluzzi & Trujillo Bueno 2012) have led the CLASP international team to propose a second flight aimed at observing the four Stokes profiles across the Mg II $h$ & $k$ lines around 2800 Å. In their theoretical work, Belluzzi & Trujillo Bueno (2012) investigated the linear polarization signals of these lines due to scattering processes and the circular polarization due to the Zeeman effect. In particular, they demonstrated that the joint action of partial frequency redistribution (PRD) and quantum interference between the upper $J$-levels of the $h$ & $k$ lines (hereafter $J$-state interference) produces a complex scattering polarization $Q/I$ pattern showing extended wings with sizable amplitudes and a positive peak at the center of the $k$ line surrounded by two negative peaks (see the solid curve of Figure 1). They also pointed out that the two-level atom approximation is suitable for modeling the center and near wings of the Mg II $k$ line, including the $Q/I$ negative peaks surrounding the positive line-center one (compare the solid and dashed curves of Figure 1).

Within the framework of a rigorous quantum theory of spectral line polarization (Bommier 1997), we have developed a PRD two-level atom radiative transfer (RT) code taking into account collisional and radiative transitions and the joint action of scattering processes and the Hanle and Zeeman effects produced by arbitrary magnetic fields (see Alsina Ballester et al. 2016). In the illustrative calculations presented in that paper, we pointed out that in strong resonance lines the magneto-optical terms $\rho_\nu U$ and $\rho_\nu Q$ of the transfer equations for Stokes $Q$ and $U$, respectively, can produce an interesting magnetic sensitivity in the wings of the $Q/I$ and $U/I$ profiles. The aim of the present Letter is to show and discuss the results we have obtained for the four Stokes parameters of the Mg II $k$ line, highlighting the interesting magnetic sensitivity that results from the joint action of Hanle, Zeeman, and magneto-optical effects.

Since we are using the two-level atom approximation, which by definition cannot account for the effects of $J$-state interference, our results apply mainly to the center and near wings of the Mg II $k$ line (i.e., to the spectral region between 2795 and 2796 Å), which encode information on the magnetism of the solar chromosphere. The next step of our work will be to consider the case of a two-term atom by...
Figure 1. Scattering polarization $Q/I$ pattern of the Mg II $h$ & $k$ lines calculated in the semi-empirical model C of Fontenla et al. (1993; hereafter FAL-C) assuming CRD (dotted curve) and taking into account PRD effects (solid curve), in both cases including the effects of J-state interference. The dashed curve indicates the two-level atom PRD solution for the Mg II $k$ line; note that it is a reasonable approximation for modeling the positive line-center peak and the two negative peaks located in the near wings of the $Q/I$ profile. The reference direction for positive Stokes $Q$ is the parallel to the nearest limb.

generalizing the PRD with J-state interference approach that Belluzzi & Trujillo Bueno (2014) developed for the unmagnetized reference case.

2. FORMULATION OF THE PROBLEM

The upper levels of the Mg II $h$ and $k$ lines have total angular momenta $J = 1/2$ and $J = 3/2$, respectively, while the lower level, which is common to the two spectral lines, has $J = 1/2$. Both resonance lines are sensitive to the Zeeman effect, but observing that atomic levels with $J = 1/2$ cannot carry atomic alignment, only the Mg II $k$ line is sensitive to the Hanle effect. The critical magnetic field for the onset of the Hanle effect in the Mg II $k$ line is $B_H = 22$ G, which means that in the presence of magnetic fields with strengths $B > 0.2B_H \approx 5$ G we can expect a significant modification of the line-center amplitudes of the $Q/I$ and $U/I$ profiles with respect to the zero-field reference case.

As mentioned in Section 1, the spectral region of the Mg II $k$ line between 2795 and 2796 Å is of great scientific interest. In this region, the scattering polarization $Q/I$ pattern shows a positive line-center peak surrounded by two negative peaks (see Figure 1). The line-center peak is sensitive to the presence of magnetic fields via the Hanle effect, but what about the two negative peaks? In order to investigate this issue, we relax the commonly used weak-field approximation (i.e., the assumption that outside active regions the linear polarization is fully dominated by scattering processes, and the Zeeman splitting can be neglected in the absorption and emission profiles), and we therefore consider the joint action of the Hanle and Zeeman effects. It can be easily shown that if the lower level is unpolarized (as it is assumed in this work), and the Zeeman splittings are neglected, the absorption coefficient for the intensity, $\eta_I$, is the only non-zero element of the propagation matrix (see Landi Degl’Innocenti & Landolfi 2004), and the RT equations for the Stokes $Q$ and $U$ parameters read:

$$\frac{dQ}{ds} = \epsilon_Q - \eta_I Q,$$

$$\frac{dU}{ds} = \epsilon_U - \eta_I U,$$

with $s$ the geometrical distance along the ray and $\epsilon_X$ the emissivity for the Stokes parameter $X$ (with $X = Q, U$). However, if the Zeeman splitting of the line’s atomic levels is taken into account, then the absorption coefficients $\eta_Q$, $\eta_U$, and $\eta_V$, as well as the magneto-optical terms $\rho_Q$, $\rho_U$, and $\rho_V$, are in general non-zero, and the transfer equations for the Stokes $Q$ and $U$ parameters are

$$\frac{dQ}{ds} = \epsilon_Q - \eta_Q I - \rho_U V - \eta_U Q + \eta_I Q,$$

$$\frac{dU}{ds} = \epsilon_U - \eta_U I + \rho_Q Q - \eta_Q V - \eta_U U + \eta_I U.$$

Figure 2 shows the wavelength variation of $\eta_X/\eta_I$ and of $\rho_X/\eta_I$ (with $X$ equal to $Q$, $U$, or $V$) at a given chromospheric height in the FAL-C atmospheric model, where we have imposed a constant horizontal magnetic field with azimuth $\chi_B = 45^\circ$ (measured counterclockwise from the plane defined by the vertical and the line of sight, LOS). All the above-mentioned ratios are very small (or zero) at the line center, while they show either symmetric or antisymmetric peaks just outside the line-core region. As expected, all such ratios increase with the magnetic strength. For magnetic fields weaker than about 100 G, the amplitude of the peaks is, however, very small, with the clear exception of $\eta_U/\eta_I$ and $\rho_U/\eta_I$. Interestingly, all such ratios rapidly tend to zero toward the blue and red wings of the Mg II $k$ line, with the notable exception of $\rho_Q/\eta_I$. The reason why in the line wings $\rho_Q$, which couples Stokes $Q$ and $U$ (see Equations (3) and (4)), is large compared to the absorption coefficient $\eta_I$ is because of the broad wings of the Faraday–Voigt profiles that appear in its expression (see Landi Degl’Innocenti & Landolfi 2004). Note that the wing (e.g., $\lambda < 2795$ Å and $\lambda > 2796$ Å) and near wing (e.g., $\lambda = 2795$ Å and $\lambda = 2796$ Å) values of $\rho_Q/\eta_I$ are significant already for magnetic fields as weak as 10 G (i.e., of the order of the Hanle critical field for the Mg II $k$ line). For sufficiently weak magnetic fields (e.g., of the order of 100 G), the dominant terms of the RT equations for $Q$ and $U$ are therefore as indicated by the approximate equalities in Equations (3) and (4).

Although $\rho_U/\eta_I$ is negligible in the line-core region (see Figure 2), in the wings, the terms $\rho_U U$ and $\rho_V Q$ must, in general, be considered. Such terms can only be neglected if at the wing and near-wing wavelengths Stokes $Q$ and $U$ are negligible, as it happens when the complete frequency redistribution (CRD) approximation is used (see the dotted curve of Figure 1). However, in strong resonance lines, like the Mg II $h$ & $k$ lines, the effects of PRD and J-state interference produce complex scattering polarization profiles with extended wings (see the solid curve of Figure 1). As soon as there is a magnetic field, even as weak as 5 G, the $\rho_V$ coefficient, which...
couples Stokes $Q$ and $U$, becomes significant and it is responsible for the appearance of $U/I$ wing signals and a magnetic sensitivity of the wing and near-wing values of the $Q/I$ and $U/I$ profiles.

3. RESULTS

For the scientific purpose of this Letter, it suffices to discuss the results of our RT calculations in the FAL-C atmospheric model in the presence of magnetic fields of different intensity...
and orientation. We show examples of emergent Stokes profiles of the Mg II k line radiation, calculated for two different LOSs. Indicating with \( \mu \) the cosine of the heliocentric angle, we consider the LOS corresponding to \( \mu = 0.1 \) (close to the limb geometry) and \( \mu = 1 \) (disk center geometry).

### 3.1. Close to the Limb Geometry (LOS with \( \mu = 0.1 \))

Figure 3 shows the emergent Stokes profiles in the absence and in the presence of a vertical magnetic field of increasing strength, from \( B = 0 \) G to \( B = 200 \) G. The black curves show the zero-field reference case, with a \( Q/I \) pattern characterized by a central positive peak surrounded by two negative peaks, and \( U/I = V/I = 0 \). As expected, in the presence of a vertical magnetic field there is no modification of the \( Q/I \) and \( U/I \) line-center values because the applied vertical field cannot produce any Hanle effect (we recall that the Hanle effect only operates in the center of the spectral lines). Since for an LOS with \( \mu = 0.1 \) the applied vertical field has a longitudinal component, there is a non-zero circular polarization \( V/I \) pattern with positive and negative lobes, whose amplitudes increase with the magnetic strength. The most interesting feature is the very significant magnetic sensitivity seen in the wings of the \( Q/I \) and \( U/I \) profiles, which occurs already for magnetic fields as weak as 10 G. For the vertical field case, the wings of \( Q/I \) are increasingly depolarized as the magnetic strength increases, while between zero and 100 G the wing values of \( U/I \) increase.

As advanced in Section 2, the reported magnetic sensitivity of the \( Q/I \) and \( U/I \) wing signals is due to the \( \rho_v^U \) and \( \rho_v^Q \) terms of Equations (3) and (4), respectively. Such magneto-optical terms have an important impact on the wings of the \( Q/I \) and \( U/I \) profiles of strong resonance lines like Mg II k because outside the line center \( \rho_v^U / \eta_q \) is very significant already for weak magnetic fields (see Figure 2), and because in strong resonance lines PRD effects produce broad scattering polarization profiles with sizable wing amplitudes (Belluzzi & Trujillo Bueno 2012). As a matter of fact, if the same RT calculations are performed neglecting the \( \rho_v^U \) terms, \( Q/I \) shows no magnetic sensitivity, and no \( U/I \) signal is obtained.

We consider now the case of a magnetic field inclined with respect to the local vertical direction, so as to see the Hanle effect in action. Figure 4 shows the emergent Stokes profiles of the Mg II k line calculated in the absence (black curves) and in the presence of a horizontal magnetic field with azimuth \( \chi_B = 0^\circ \). As expected, the polarization amplitudes at the center of the \( Q/I \) and \( U/I \) profiles are now modified by the Hanle effect. As the intensity of the magnetic field increases, the \( Q/I \) line-center amplitude decreases, while the \( U/I \) line-center signal (which is zero in the absence of the magnetic field) first increases until a maximum \( \sim 1\% \) for \( B \approx 10 \) G, and then decreases until reaching 0.1% for \( B = 200 \) G. Figure 4 shows the above-mentioned very interesting magnetic sensitivity of the \( Q/I \) and \( U/I \) profiles in the line wings, due to the \( \rho_v^Q \) magneto-optical terms. Note that the wings of the \( Q/I \) profile are also increasingly depolarized as the intensity of the magnetic field increases, while the \( U/I \) wing signals first increase and then decrease. Also in this case, when the same calculations are carried out neglecting the \( \rho_v^Q \) terms, only the
line-center signals are modified with respect to the zero-field case.

In terms of linear polarization degree, \( p_L = \frac{\sqrt{Q^2 + U^2}}{I} \), and linear polarization angle, the considered vertical and horizontal field cases of increasing intensity produce in the near wings (where \( Q/I \) reaches its largest negative signal) a monotonic decrease of \( p_L \) and a monotonic rotation of the plane of linear polarization.

3.2. Disk Center Geometry (LOS with \( \mu = 1 \))

For the case of a vertical magnetic field we only have \( V/I \) in the disk center geometry considered in this section. The left panel of Figure 5 shows the \( V/I \) profiles of the emergent Mg II \( k \) line radiation, for a vertical field with \( B = 50 \) G. The red solid curve shows the full solution, while the dashed curve has been obtained assuming that the only non-zero component of the radiation field tensor is \( J_0^0 \) (i.e., the familiar mean intensity). Interestingly, the main \( V/I \) peaks close to the line center basically coincide in the two cases, while the secondary lobes in the near wings of the line are significantly weaker when the symmetry properties of the incident radiation field (quantified by the \( J_0^0 \) and \( J^0_0 \) components) are not taken into account. This demonstrates that the wing lobes of the \( V/I \) profiles are partly influenced by the symmetry properties of the radiation field. In spite of this fact, we point out that a good estimate of the longitudinal component of the magnetic field can still be obtained using the familiar weak-field magnetograph formula for Stokes \( V \).

The right panel of Figure 5 shows the \( Q/I \) profiles produced by horizontal fields of increasing strength. Obviously, in the zero-field case \( Q/I = 0 \). The axial symmetry around the local vertical direction is broken in the presence of a horizontal magnetic field. As a result, the Hanle effect creates linear polarization at the very line center, with a \( Q/I \) amplitude that increases with the magnetic strength until the Hanle saturation regime is reached. All this is well known. What is new and interesting are the \( Q/I \) wing signals. They are still due to magneto-optical effects produced by \( \rho_V \), though in an indirect way. Indeed, \( \rho_V \) is zero for the radiation propagating in the \( \mu = 1 \) direction (i.e., perpendicularly to the magnetic field). However, the emissivities \( \epsilon_Q \) and \( \epsilon_U \) appearing in Equations (3) and (4) depend (through the redistribution matrix) on the pumping radiation coming from all directions, whose wings are sensitive to magneto-optical effects. Due to the coherency of scattering, such sensitivity is transferred to the radiation scattered at \( \mu = 1 \).

4. CONCLUDING COMMENTS

We have investigated the magnetic sensitivity of the Mg II \( k \) line at 2795.5 Å due to the joint action of Hanle, Zeeman, and magneto-optical effects. To this end, we applied a new RT code for a two-level atom (see Alsina Ballester et al. 2016). This atomic model is suitable for investigating the polarization of the Mg II \( k \) line between the \( k_V \) and \( k_R \) intensity peaks (see Figures 3 or 4), where the effects of J-state interference are not very significant. This is arguably the most interesting spectral region of the Mg II \( h \) & \( k \) line system because in this wavelength interval the line opacity is relatively large so that it encodes information on the physical properties of the solar chromosphere (see Figure 1 in Belluzzi & Trujillo Bueno 2012). Moreover, only the Mg II \( k \) line is sensitive to the Hanle effect, and in the considered spectral region the sensitivity of the line scattering polarization to the thermal structure of the solar atmosphere is not as important as in the far wings of the Mg II \( h \) & \( k \) lines, which can be useful for facilitating the inference of the magnetic field.

Via the Hanle effect the line-center amplitudes of the \( Q/I \) and \( U/I \) profiles of the Mg II \( k \) line are sensitive to magnetic fields with strengths between 5 and 50 G, approximately. Moreover, the Zeeman effect produces conspicuous circular polarization signals, with two main lobes just around the line center surrounded by two wing lobes whose weaker amplitudes are sensitive to the symmetry properties of the pumping radiation field. Nevertheless, the familiar magnetograph formula can be used to estimate the longitudinal field component.

The most novel result is that the magneto-optical \( \epsilon_Q \) terms of the Stokes \( Q \) and \( U \) transfer equations tend to depolarize the wings of the \( Q/I \) scattering polarization pattern and create...
signals in the wings of $U/I$. The sensitivity of these $Q/I$ and $U/I$ wing signals to both weak ($\sim 5 \text{ G}$) and stronger magnetic fields expands the scientific interest of the MgII $k$ line for probing the solar chromosphere in quiet and active regions of the Sun.

Since our two-level atom approach cannot account for the effects of $J$-state interference, we cannot provide quantitative information outside the spectral region between the $k_{1V}$ and $k_{1R}$ peaks, but it is clear that the same magneto-optical effects are expected to also affect the spectral region between the $h$ and $k$ lines, as well as their far wings. A correct modeling of such spectral regions requires the application of a two-term or multi-term atom approach in order to take into account the impact of $J$-state interference.

The authors are grateful to T. del Pino Alemán, R. Casini (both HAO), and R. Manso Sainz (MPS), who have been working on a similar problem applying a multi-term PRD formalism, for stimulating scientific conversations. Financial support by the Spanish Ministry of Economy and Competitiveness through projects AYA2014-60476-P and AYA2014-55078-P is gratefully acknowledged. E.A.B. wishes to acknowledge Fundación La Caixa for financing his Ph.D. grant. L.B. gratefully acknowledges financial support from SERI, Canton Ticino, the city of Locarno, local municipalities, Daccò foundation, and the Swiss SNF through grant 200021-163405.

REFERENCES

Alsina Ballester, E., Belluzzi, L., & Trujillo Bueno, J. 2016, ApJ, in press
Belluzzi, L., & Trujillo Bueno, J. 2012, ApJL, 750, L11
Belluzzi, L., & Trujillo Bueno, J. 2014, A&A, 564, A16
Belluzzi, L., Trujillo Bueno, J., & Štěpán, J. 2012, ApJL, 755, L2
Bommier, V. 1997, A&A, 328, 726
Fontenla, J. M., Avrett, E. H., & Loeser, R. 1993, ApJ, 406, 319
Kano, R., Trujillo Bueno, J., Winebarger, A., et al. 2016, in ASP Conf. Ser., Solar Polarization 8, ed. L. Belluzzi et al. (San Francisco, CA: ASP), in press
Landi Degl’Innocenti, E., & Landolfi, M. 2004, Polarization in Spectral Lines (Dordrecht: Kluwer)
Stenflo, J. 1994, Solar Magnetic Fields: Polarized Radiation Diagnostics (Dordrecht: Kluwer)
Trujillo Bueno, J. 2014, in ASP Conf. Ser. 489, Solar Polarization 7, ed. K. N. Nagendra et al. (San Francisco, CA: ASP), 137
Trujillo Bueno, J., Štěpán, J., & Belluzzi, L. 2012, ApJL, 746, L9
Trujillo Bueno, J., Štěpán, J., & Casini, R. 2011, ApJL, 738, L11
Štěpán, J., Trujillo Bueno, J., Carlsson, M., & Leenaarts, J. 2012, ApJL, 758, L43