

MOLECULAR LINE POLARIZATION IN THE SOLAR ATMOSPHERE: MgH LINES

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ABSTRACT

The polarimetric observations of the quiet Sun show linear polarization in molecular lines of C_2 , MgH, etc. The molecular lines are very faint in the intensity spectrum. We propose that the polarization is caused by coherent scattering processes in the solar atmosphere as in the case of atomic lines. The intensity and polarization profiles of MgH lines are calculated using the quiet-Sun model by Vernazza, Avrett, & Loeser. This procedure allows us to estimate the oscillator strengths (f), the inelastic collisional rates (Γ_i), and the depolarizing elastic collision rates ($D^{(2)}$) for the molecular line transitions in the solar atmosphere. It is found that for the line $\lambda 5165.933$, $f = 0.04$, $\Gamma_i = 1.85 \times 10^7 \text{ s}^{-1}$, and $D^{(2)} = 9.52 \times 10^6 \text{ s}^{-1}$. The line $\lambda 5168.147$ fits the observations for $f = 0.05$, $\Gamma_i = 2.91 \times 10^7 \text{ s}^{-1}$, and $D^{(2)} = 3.69 \times 10^7 \text{ s}^{-1}$.

Subject headings: molecular processes — polarization — radiative transfer — scattering — Sun: photosphere

1. INTRODUCTION

Stenflo, Twerenbold, & Harvey (1983a) and Stenflo et al. (1983b) performed spectropolarimetric observations at $10''$ inside the solar limb and found that a large number of lines show significant linear polarization, e.g., the resonance lines Ca I $\lambda 4227$, Ca II H and K, and Na I $\lambda 5890$. Later, using a much more sensitive polarimetric system (with a precision of 10^{-5} in the degree of polarization) called ZIMPOL (Zurich IMaging POLarimeter), Stenflo & Keller (1997) obtained a linearly polarized spectrum that contained a wealth of unexpected spectral features exhibiting the signatures of different physical processes like quantum interference, hyperfine structure, and isotope effects. One of the most interesting features of the spectrum is the linear polarization of molecular lines of C_2 and MgH.

1.1. Atomic Line Polarization

In the absence of magnetic fields, the origin of the atomic line polarization is due to the coherent scattering of the anisotropic photospheric radiation by the atoms. The absorption of anisotropic radiation field gives rise to a nonuniform population of the Zeeman sublevels of the excited state and the phase relations between these sublevels. If the atom does not suffer collision before its radiative decay, the coherences between the sublevels are preserved, and the reemitted radiation is linearly polarized. This is called resonance polarization (Mitchell & Zemansky 1934; Hamilton 1947; Stenflo 1976). A weak magnetic field modifies these coherences because of the relative Zeeman shifts of the magnetic sublevels. The reemitted radiation is linearly polarized, but the polarization plane is rotated, and the polarization rate is changed. This is called the Hanle effect and can be used as a diagnostic tool for the weak solar magnetic fields.

1.2. Theoretical Work on Atomic Resonance Line Polarization

Theoretical studies aimed at the interpretation of the linear polarization in resonance lines were made by several workers in this field (Dumont, Omont, & Pecker 1973; Auer, Rees, & Stenflo 1980). Rees & Saliba (1982) show that the wing maximum in polarization that was observed in certain solar lines was caused by a partial frequency redistribution mechanism. Faurobert-Scholl (1992) included the Hanle effect in the study

of the solar line Ca I $\lambda 4227$ and found that the observed polarization rates are consistent with the presence of a magnetic canopy in the lower solar chromosphere. Mohan Rao & Rangarajan (1993, hereafter Paper I) employed a parametric radiative transfer model to study the effect of depolarizing collisions on resonance line polarization. It was found that the percentage of polarization at the line center was a monotonic function of the coherence parameter γ .

In contrast to studies on atomic line polarization, molecular line polarization has not received much attention. One of the reasons is perhaps that the observations are quite recent. In this Letter, we choose the lines of MgH for our study since they show significant linear polarization. In the next section, we give a brief account of the work done on MgH lines in the solar spectrum.

2. LINES OF MgH IN THE SOLAR SPECTRUM

The identification of MgH spectral lines in the solar spectrum that are due to the (0, 0) vibration band of the electronic transition $A^2\Pi-X^2\Sigma^+$ is well established. Schadee (1964) studied in detail the formation and intensities of these lines. Lambert, Mallia, & Petford (1971) derived an estimate for the band oscillator strength $f_{0,0} = 0.055$ by analyzing the equivalent width. Isotopic abundance ratios (i.e., $^{25}\text{Mg}/^{24}\text{Mg}$ and $^{26}\text{Mg}/^{24}\text{Mg}$) were estimated from the photospheric and penumbral MgH lines and from strong Mg I lines with measurable isotopic wavelength shifts. Kulaczewski, Degenhardt, & Kneer (1990) calculated the behavior of a MgH spectral line at 5175 \AA as a function of temperature and pressure fluctuations using a linear perturbation method. They found that spectral lines of MgH are only moderate indicators of temperature and pressure fluctuations in the solar photosphere.

3. THE PRESENT STUDY

In this Letter, we consider the linear polarization in MgH lines ($\lambda = 5165.933$ and $\lambda = 5168.147$) obtained by Stenflo & Keller (1997) in the solar spectrum. These lines are very faint in the intensity spectrum but show a linear polarization on the order of 0.1% at the line center. The electronic states $A^2\Pi$ and $X^2\Sigma^+$ of MgH belong to Hund's case *b*. The lines belong to a Q -branch with rotational levels $J = 14.5$ and 12.5 , respectively. We use the quiet-Sun model "C" of Vernazza, Avrett,

& Loeser (1981). The abundance of Mg is chosen to be 3.0×10^{-5} . The dissociation energy D_0 of MgH is chosen to be 1.27 eV from Kirby, Saxon, & Liu (1979). If we assume chemical equilibrium between the different atomic and molecular species, the number density of MgH can be calculated from Grevesse & Sauval (1994) as follows:

$$n_{\text{MgH}}(z) = n_{\text{Mg}}(z)n_{\text{H}}(z) \left(\frac{h^2}{2\pi m} \right)^{3/2} [kT(z)]^{-3/2} \times \frac{Q_{\text{MgH}}(z)}{Q_{\text{Mg}}(z)Q_{\text{H}}(z)} 10^{D_0\Theta(z)}, \quad (1)$$

where the Q 's are the partition functions for the atoms and molecules, and z is the spatial variable in the atmosphere. The Q 's are evaluated using polynomial expressions given by Sauval & Tatum (1984); m is the reduced mass and $\Theta(z) = 5040/T(z)$.

For the purpose of calculating the number densities of the molecules in various energy levels, we assume that the lower solar atmosphere is in local thermodynamic equilibrium (LTE). Then the number of particles, n_j , in a specified rotation level is related to the total number of particles in all levels, n_{MgH} , according to the following relation (Larson 1994):

$$\frac{n_j(z)}{n_{\text{MgH}}(z)} = \frac{(2J+1)e^{-E_j/kT(z)}}{Q_{\text{MgH}}(z)}, \quad (2)$$

where $(2J+1)$ is the degeneracy factor and $e^{-E_j/kT}$ is the Boltzmann factor. In the next section, we describe the polarized transfer equation that was employed in this study to obtain the linear polarization and the intensities of the lines.

4. POLARIZED LINE TRANSFER EQUATION

We assume that the molecular line polarization in the solar atmosphere is caused by the scattering of anisotropic radiation, as in the case of atomic resonance line polarization. The vector transfer equation for polarized radiation, using a two-level model, is

$$\pm \mu \frac{\partial \mathbf{I}(\nu, \pm \mu, z)}{\partial z} = -\chi(\nu, z)[\mathbf{I}(\nu, \pm \mu, z) - \mathbf{S}(\nu, \pm \mu, z)], \quad (3)$$

where $\mathbf{I} = (I_j, I_r)^T$ and μ is the cosine of the angle made by the ray to the normal. At the limb, the Stokes parameters I_j and I_r denote the components perpendicular and parallel to the surface of the atmosphere. The total intensity is defined as $I = I_j + I_r$, and the Stokes Q -parameter is defined as $Q = I_r - I_j$. The total absorption coefficient is given by

$$\chi(\nu, z) = \chi_l(z)\phi(\nu, z) + \chi_c(\nu, z), \quad (4)$$

where $\phi(\nu, z)$ is the profile function and χ_c is the continuous absorption coefficient. The integrated line absorption coefficient can be determined from the relation

$$\chi_l(z) = \frac{\pi e^2}{m_e c} f n_j(z), \quad (5)$$

where f is the oscillator strength of the transition. Since the line is very weak in intensity, we choose the profile function

as

$$\phi(\nu, z) = \frac{1}{\sqrt{\pi}\Delta\nu_D(z)} e^{-[(\nu-\nu_0)/\Delta\nu_D(z)]^2}, \quad (6)$$

where $\Delta\nu_D$ is the thermal Doppler width. We neglect the microturbulent broadening. The continuous absorption coefficient is obtained from a code developed by Carlsson (1986). The continuum polarization ($\approx 0.06\%$) caused by the Thomson scattering by the electrons and the Rayleigh scattering by neutral hydrogen is not considered here. To compensate for this, we measure the line polarization from the polarized continuum level. The source function is given by

$$\mathbf{S}(\nu, \pm \mu, z) = \frac{\phi(\nu, z)\mathbf{S}_L(\nu, \pm \mu, z) + \beta(z)\mathbf{S}_C(z)}{\phi(\nu, z) + \beta(z)}, \quad (7)$$

where $\beta(z) = \chi_c(z)/\chi_l(z)$ and the continuum source function \mathbf{S}_C is defined as

$$\mathbf{S}_C(z) = \frac{1}{2} B(\nu, z) \mathbf{1}; \quad \mathbf{1} = [1 \ 1]^T, \quad (8)$$

where $B(\nu, z)$ is the Planck function. To include the role of elastic collisions in the polarized line transfer equation, we follow the phenomenological treatment of quantum theory by Stenflo (1994). If we assume complete redistribution, the line source function can be written as

$$\begin{aligned} \mathbf{S}_L(\nu, \pm \mu, z) = & \frac{(1-\epsilon)}{2} \int_0^\infty \phi(\nu', z) d\nu' \int_{-1}^1 [(\gamma+b)\mathbf{P}(\mu, \pm \mu')] \\ & + c\mathbf{P}_{is}] \mathbf{I}(\nu', \mu', z) d\mu' + \frac{\epsilon}{2} B(\nu, z) \mathbf{1}. \end{aligned} \quad (9)$$

Here the collisional de-excitation parameter ϵ is defined as $\epsilon = \Gamma_l/(\Gamma_l + \Gamma_R)$, where Γ_R is the spontaneous emission rate. The branching ratios are

$$\begin{aligned} \gamma = & \frac{\Gamma_l + \Gamma_R}{\Gamma_R + \Gamma_l + \Gamma_C}, \quad b = \gamma \frac{\Gamma_C - D^{(2)}}{\Gamma_R + \Gamma_l + D^{(2)}}, \\ d = & \gamma + b = \frac{\Gamma_R + \Gamma_l}{\Gamma_R + \Gamma_l + D^{(2)}}, \quad c = 1 - d. \end{aligned} \quad (10)$$

In these expressions, $D^{(2)}$ is the rate of the elastic collisions that destroy alignment; γ is the probability that a de-excitation occurs before any elastic collisions, and b is the probability that an elastic collision that does not destroy alignment occurs, followed by a de-excitation of the atom. Therefore, c gives the probability that the elastic collision that destroys alignment occurs, followed by a de-excitation of the atom.

For resonance *atomic line scattering*, the phase matrix \mathbf{P} is given in Chandrasekhar (1950). It can be written in the following form:

$$\mathbf{P} = E_1 \mathbf{P}_R + E_2 \mathbf{P}_{is}, \quad (11)$$

where E_1 and E_2 are certain constants, depending on the total angular momentum quantum numbers of the levels involved,

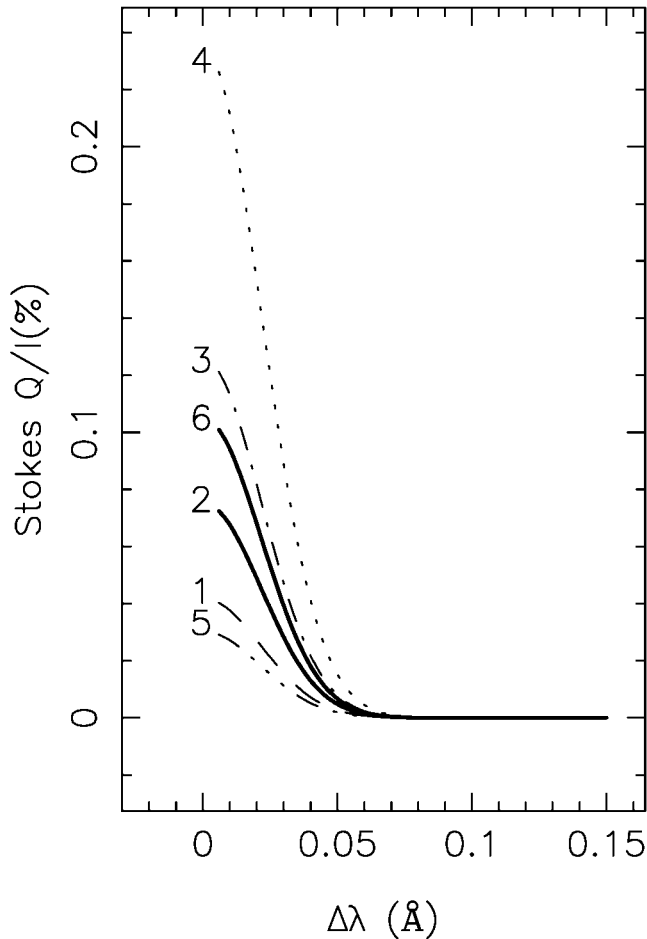


FIG. 1.—Percentage of linear polarization plotted against wavelength from the line center. The dashed curve 1 is for $\epsilon = 0.65$ and $d = 0.3$. The solid curve 2 is for $\epsilon = 0.70$ and $d = 0.53$, which fits closely with observations of $\lambda 5168.14$. The dot-dashed curve 3 is for $\epsilon = 0.65$ and $d = 0.9$. The dotted curve 4 is for $\epsilon = 0.2$ and $d = 0.75$. The dash-triple-dotted curve 5 is for $\epsilon = 0.9$ and $d = 0.75$. The solid curve 6 is for $\epsilon = 0.65$ and $d = 0.75$, which fits closely with the observation of $\lambda 5165.933$. Curve 2 has $f \approx 0.05$, but the remaining curves have $f \approx 0.04$.

and $E_1 + E_2 = 1$. \mathbf{P}_R is the Rayleigh scattering phase matrix, and \mathbf{P}_{is} is the isotropic matrix. We use the same matrix for *molecular resonance line scattering* but use the rotational quantum number in the expressions of E_1 and E_2 . This can be explained as follows: in the atoms, the incident anisotropic radiation on them gives rise to a nonuniform population of the Zeeman sublevels of the excited state, and this leads to a scattered radiation that is linearly polarized. Analogously, in the molecules, the nonuniform population of the Zeeman sublevels of the rotation state leads to a linearly polarized radiation when anisotropic radiation is incident on them (Herzberg 1950). We solve the transfer equation (3) using the method given in Paper I.

5. RESULTS AND DISCUSSION

The linear polarization ($Q/I\%$) and the intensity (I/I_c , where I_c is the continuum) profiles at the limb ($\mu = 0.11$) for the lines $\lambda 5165.93$ and $\lambda 5168.14$ are plotted in Figures 1 and 2. Since the intensities of the lines are affected by the dispersion wings of the strong atomic line Mg I $\lambda 5167$, the observed molecular line depths are measured by the “quasi-continuum” of the de-

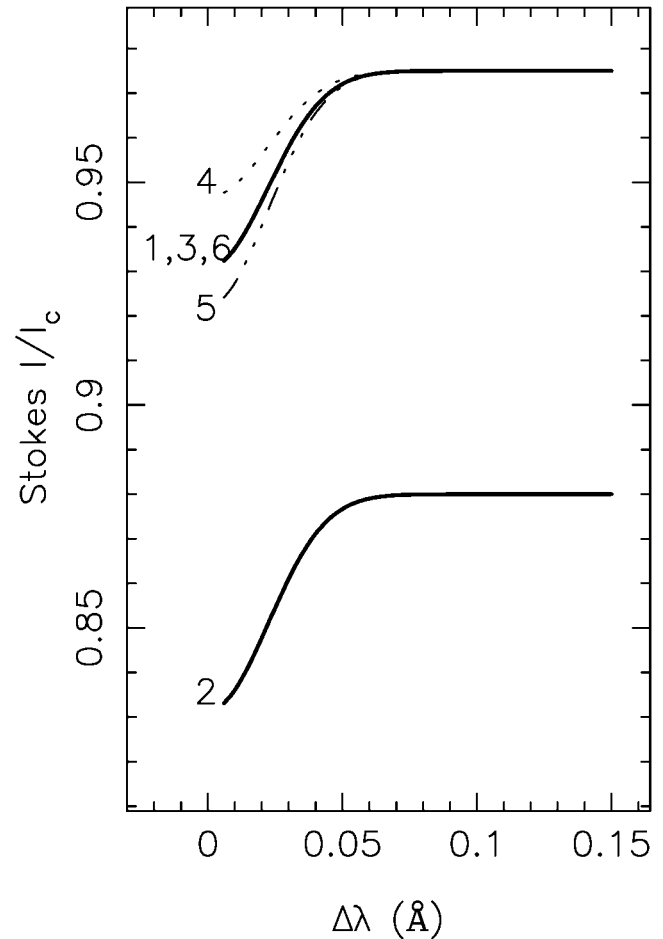


FIG. 2.—Same as in Fig. 1, but in this figure the specific intensity is plotted

pressed Mg I line wings. We fixed the quasi-continuum for the line $\lambda 5165.933$ at 0.975 and for the line $\lambda 5168.14$ at 0.88. The observed polarization at the continuum is on the order of 0.06% at the limb. Hence, we measure the polarization of the MgH lines from the polarized continuum level. The depolarization constant E_2 in equation (11) is 0.6 for both the line transitions, with $J = 14.5$ and $J = 12.5$ (with $\Delta J = 0$).

We assume that ϵ and d are independent of depth since the MgH line formation is confined to a narrow region in the photosphere. We found the linear polarization (Fig. 1) to be sensitive to the values of ϵ and d . The observed solar polarization measurements are consistent with $\epsilon = 0.65$ and $d = 0.75$ for $\lambda 5165.933$ and $\epsilon = 0.70$ and $d = 0.53$ for $\lambda 5168.147$. This can be seen in curves 6 and 2 in Figure 1. The other curves in the figure show the dependence of polarization for some typical values of ϵ and d .

The intensity is sensitive to the value of oscillator strength. We tried various combinations of f , d , and ϵ values. We found that the calculations with $f \approx 0.04$ and $\epsilon \approx 0.65$ fitted closely the observed intensity values for $\lambda 5165.933$ (see curve 6). The line $\lambda 5168.14$ has the parameters $f \approx 0.05$ and $\epsilon \approx 0.7$ (see curve 2). The intensity does not vary with d for a given ϵ , and we see this in curves 1, 3, and 6. The high values of ϵ are consistent with the fact that the lines are formed in the lower solar atmosphere where near-LTE conditions prevail.

From equation (10), we find that for $\lambda 5165.933$, $\Gamma_R = 9.9 \times 10^6 \text{ s}^{-1}$, $\Gamma_I = 1.85 \times 10^7 \text{ s}^{-1}$, and $D^{(2)} = 9.52 \times 10^6$

s^{-1} . For $\lambda 5168.147$, $\Gamma_R = 1.24 \times 10^7 s^{-1}$, $\Gamma_I = 2.91 \times 10^7 s^{-1}$, and $D^{(2)} = 3.69 \times 10^7 s^{-1}$. Elastic collisional rates Γ_C can be estimated if we know the ratio $D^{(2)}/\Gamma_C$. A simple classical estimate gives a ratio of ≈ 0.5 (Stenflo 1994).

So, in summary, we see that the molecular line polarization can be used as an additional diagnostic tool for inferring the physical parameters of the atmosphere. It gives us an estimate of the collisional rates for the transitions. More accurate calculations, which take into account the line wings of the strong

Mg I line and the polarization effects of continuous scattering, are desirable. A self-consistent quantum mechanical formulation for molecular line polarization, including collisions, is needed.

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