Chin. J. Astron. Astrophys. Vol. 5 (2005), No. 4, 426–432
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Magneto-induced Line Broadening of Magneto-sensitive Lines in Solar Magnetized Atmospheres *

Zhong-Quan Qu[1], Shuai Wang[1,2], Cheng-Lin Xu[1,2], Xiao-Yu Zhang[1],
Ming-Guo Sun[1,2] and Chun-Lan Jin[1,2]

[1] National Astronomical Observatories/Yunnan Astronomical Observatory, Chinese Academy of Sciences, Kunming 650011; *zqqu@vip.km169.net*
[2] Graduate School of the Chinese Academy of Sciences, Beijing 100039

Received 2005 January 19; accepted 2005 April 22

Abstract We analyze the spectral line broadening of those magneto-sensitive lines in solar magnetized atmospheres. The broadening at the line wings is due to the increase of the effective width of energy levels involved in Zeeman splitting, and the broadening at the line core also originated in Zeeman splitting under the condition that the Zeeman components are mixed. Therefore, the magneto-induced or Zeeman broadening take effects on the whole line. The observed Stokes parameter data in a sunspot and outside it acquired by Solar Stokes Spectrum Telescope (S^3T) are analyzed for the demonstration of this mechanism, and the Zeeman broadening rates are calculated for FeI 6302.5 under some assumptions. Our result shows that the broadening is increased as the magnetic field strength becomes stronger, but the rate of increase at the line core is decreased as the field strength increases, while the rate at the wing does not show such an obvious regularity. The broadening is more effective in the line core than in the wings.

Key words: sunspots – line: profiles-magnetic fields – radiative transfer-polarization

1 INTRODUCTION

Studies of magnetic fields via Stokes profile analysis in stellar (especially in solar) atmospheres generally focus on the magnetic field structure and its evolution, as well as on the line-of-sight velocities. For example, Westendorp Plaza et al. obtained three-dimensional magnetic structure of a round sunspot (2001a) and velocity stratification (2001b), Casini et al. (2003) gave magnetic field maps of solar prominence via full Stokes profile analysis. Earlier, the temperature and velocity of active regions were studied by del Toro Iniesta et al. (1994), and Lites et al. (1998) examined the vector magnetic fields of emerging solar flux, etc. Theoretically, Weiss et al. (2004) studied the downward pumping of magnetic flux in penumbrae of sunspots. However, magnetic

* Supported by the National Natural Science Foundation of China.

fields can alter the intrinsic properties of magneto-sensitive lines, including line broadening, absorption, and can cause departure from thermodynamical equilibrium. In this paper, we focus on the influence of magnetic field on the line broadening, which may be instructive when diagnosing the physical structure via Stokes spectral analysis of magneto-sensitive lines.

The magneto-sensitive lines forming in stellar atmospheres contain information on the physical conditions (such as magnetic field, plasma flow velocities, temperature, density, and pressure, etc.) and the abundances of chemical elements. Therefore one can obtain these quantities via diagnosing the magneto-sensitive lines. To carry out an analysis of the observed line profiles one needs to know how the distribution of opacity with frequency in the line - the *absorption profile*- depends on local values of the above listed quantities. Furthermore, the magnetic field, thermodynamical quantities as well as the line-of-sight velocities are strongly coupled in stellar atmospheres. The polarized or Stokes radiative transfer equation (cf., Lites et al. 1988) describes the coupling among the received full Stokes profiles. If we also wish to extract information on the magnetic field which is responsible for solar activities and atmospheric structure, its influence on the measured lines must be analyzed and polarization measurement must be used.

2 BRIEF THEORETICAL ANALYSIS

We concentrate on the 'pressure broadening' which can be classified further according to the physical causes into two subclasses. One is due to the interaction between the radiators and its surrounding particles, e.g., the resonance and van der Waals force, and in such cases the term 'pressure broadening' is used. The other is due to the physical fields, say, the electric field, and it is then termed "Stark broadening". However, it should be added, that what is termed Zeeman broadening due to the magnetic field produces an effect just like that due to the electric field in most aspects. Therefore, it is useful to give the term 'field broadening' to cover both the two mechanisms. Let us compare Stark broadening and Zeeman broadening. Stark broadening originates from the effect of electric field on the energy levels involved. When an electric field exists, the level will be split into $2n^2$ sub-levels from its degenerate state. This results in the line profile consisting of a number of Stark components and an observed broadened line profile. Very similarly, when a magnetic field exists, it can cause the level splitting (the Zeeman effect). The splitting pattern depends on the quantum properties of the energy levels involved (normal splitting or anomalous splitting).

Now, one can expect the Zeeman broadening to affect both the line wing and core. Because the magnetic field in solar atmosphere is not very strong (especially for the visible light band), the components are not separated completely and the observed line is just a combination of those components, and this effect causes the broadening of the line core. On the other hand, the Zeeman broadening at the line wing is ascribed to increase in the effective widths of the energy levels where there are more than one sub-levels. The difference between Stark and Zeeman broadenings lies in the aspect that, formally, the latter can be more easily dealt with in most cases.

3 EVIDENCE AND DEMONSTRATION FROM THE OBSERVATION OF S^3T

To demonstrate the above statements, we use the observed full Stokes spectra of a sunspot in the active region NOAA 9960 of 2002 May 22, UT1915, obtained by the Solar Stokes Spectrum Telescope (S^3T, Qu et al. 2001) mounted at the Yunnan Astronomical Observatory. The slit was set across the sunspot from north to south as shown in Fig. 1, where the darkest part in the panel of Stokes I/I_c spectrum covers the umbra and the grey, the penumbra. The full Stokes I, Q, U and V spectra of FeI 6301.5 Å and FeI 6302.5 Å lines are plotted in units of the local continuum. The *rms* of noise level of the Stokes polarization measurement is estimated to be

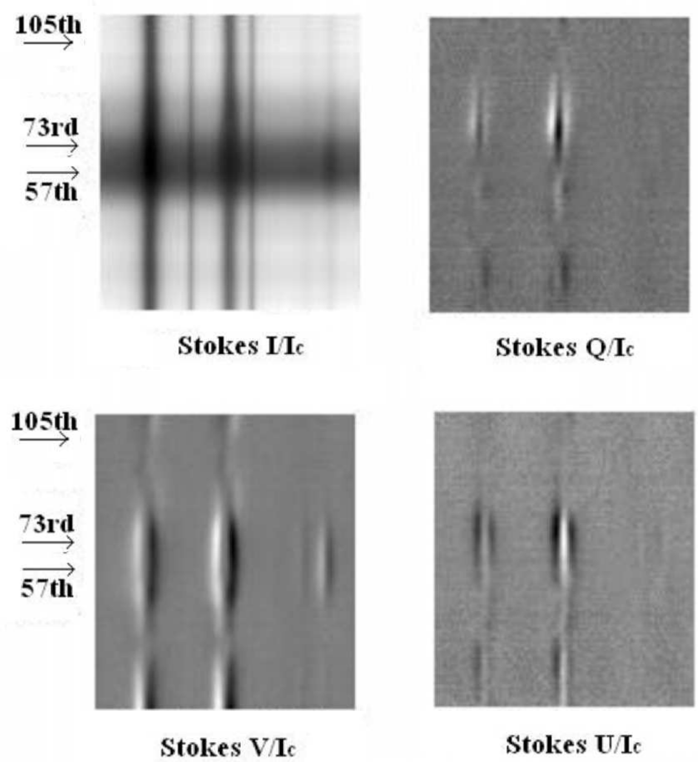

Fig. 1 Full Stokes I, Q, U and V spectra in units of local continuum of one slit across the sunspot of NOAA9960. One can easily see the broadening in the strong field parts, say, the umbra (the darkest stripe) in Stokes I/I_c. The arrows and figures indicate the locations of the Stokes profiles shown in Fig. 2.

2.1×10^{-3}. The spatial resolution was about $1.8''$, which is sufficient for our present study. The spectrum resolution is 30.4 mÅ.

Four locations, two within the umbra, one within the penumbra (the 81st point, not labelled in Fig. 1) and one outside the sunspot, are selected from Fig. 1 for our purpose. The Stokes profiles of the two umbral points and the one outside are drawn in Fig. 2. It should be mentioned that the sample like this is very commonly used in such studies. Similar plots can also be found with other authors, e.g., in fig. 1 of Lites et al. (1988), and in part of fig. 2 of Tritschler et al. (2004). The reason for selecting the four points on this slit is that they form a sequence of decreasing field from which we can observe the influence of the magnetic field strength on the broadenings.

Almost at first glance, one finds clues in Fig. 2. First, by comparing the line wings of Stokes I/I_c of the three plotted points, the wing of the Stokes I/I_c profile of the umbral point (the 57th point) with the strongest magnetic field of 1421 Gauss (see Table 1) is obviously more widely open and depressed than those of the other points. This clearly exhibits that the broadening at the line wings is enhanced as the magnetic field strength increases. Secondly, the line cores of the profiles of the umbral points are markedly wider than that of the point outside the sunspot. All of these demonstrate intuitively the statements in Section 2.

Now, we analyze the data quantitatively. We invert the profiles of the four points by the method proposed by Lites et al. (1988) with the code MELANIE version 2.0 downloaded from the website *www.hao.ucar.edu/public/research/cic/index.html*. This method presumes that the atmosphere can be described by the Eddington-Milne model, and that only the source functions vary with depth. Therefore, all the parameters except the source functions are averages over the whole atmosphere along the line-of-sight. Figure 3 shows the profiles of the 73rd point as labelled in Fig. 1. One can see that at this point the fitting profiles simulate the observed very well except the asymmetry in the Stokes Q and U. The inversion results of these four points are summarized in Table 1, where $\Delta\lambda_{\rm wing}$ denotes the line wing broadening in units of line core broadening $\Delta\lambda_{\rm core}$ in mÅ; η_0 represents the line strength and S and S_G, the source function and its gradient in units of intensity. The strength (H), inclination (γ) and azimuth (χ) of the vector magnetic field are in units of Gauss and degrees, respectively, while the velocities $v_{\rm los}$ and $v_{\rm mac}$ are in units of km s^{-1}. Finally, the figures listed in the 2nd row represent typical errors from the inversion. It can be easily found that the errors in $\Delta\lambda_{\rm wing}$ and $\Delta\lambda_{\rm core}$ are very small, as well as the errors in magnetic field strength and line-of-sight velocity compared with the recovered values. This gives confidence that the following analysis on line broadening is reliable.

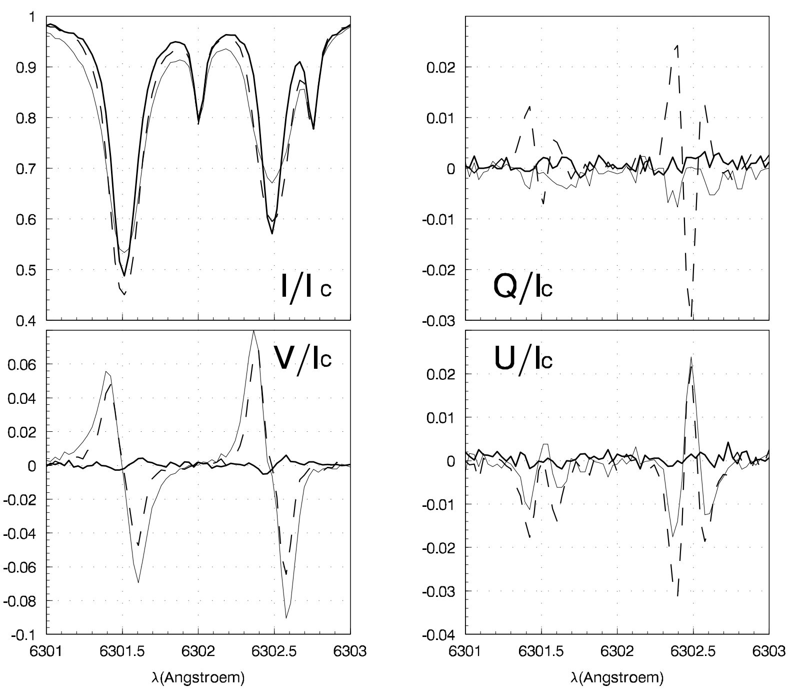

Fig. 2 Full Stokes I, Q, U and V profiles in units of local continuum taken from Fig. 1 at the 57th (thin solid curves), 73rd (dashed) and 105th (thick solid curves) points, counting from the south (lower)to north (upper) of the slit. The whole slit length covers about 1 arcminute on the solar disk. One can easily find the Zeeman line broadenings at both the line core and wings by comparison.

Table 1 Inversion Result of the Profiles by the Code MELANIE V2.0

Spatial Points	$\Delta\lambda_{\rm wing}$	$\Delta\lambda_{\rm core}$ (mÅ)	η_0	S	S_G	H (Gauss)	γ (°)	χ (°)	v_{los} (km s^{-1})	$v_{\rm mac}$ (km s^{-1})
Error	0.005	0.14	0.14	3.7E-4	4.2E-4	28	1.6	5.7	0.016	0.010
57th	0.68	51	11	0.46	0.49	1421	50	127	0.31	0.40
73rd	0.45	50	12	0.39	0.56	1121	65	151	0.35	0.41
81st	0.41	46	18	0.43	0.53	765	82	168	0.4	0.42
105th	0.37	26	40	0.44	0.53	220	97	8	0.74	2.4

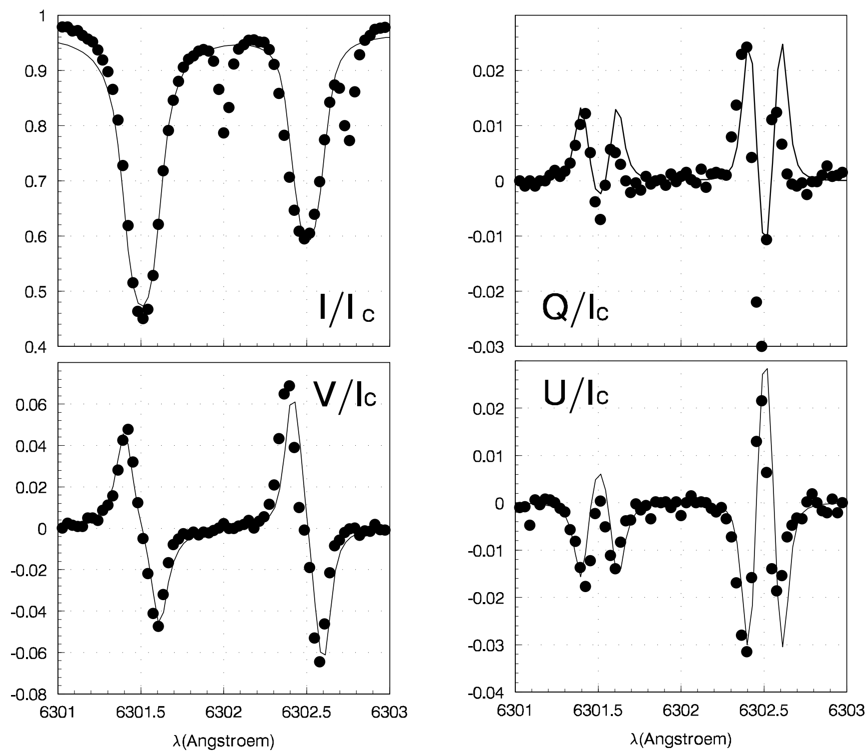

Fig. 3 ME fittings of Stokes I, Q, U and V. The observed profiles shown in Fig. 2 at the 73rd point are plotted as dotted lines and the fitting profiles as solid lines.

It can also be found from the table that, as the magnetic field strength increases, both $\Delta\lambda_{\rm wing}$ and $\Delta\lambda_{\rm core}$ are enhanced.

Now we analyze in some detail the influence of magnetic field, temperature as well as macro-turbulence on the line broadening. The following equation shows the correlation of the Doppler width $\Delta\lambda_D$ and the temperature and macro-turbulence velocity $v_{\rm mac}$ (cf., Mihalas 1978; Wang & Qu 1993),

$$\begin{aligned}\Delta\lambda_D &= \lambda_0/c\sqrt{2kT/m+v_{\rm mac}^2}\\ &= \lambda_0/c\sqrt{16.6(T/10^4A)+v_{\rm mac}^2}\quad ,\end{aligned}\tag{1}$$

where A is the atomic weight, c the light speed and $v_{\rm mac}$ the macro-turbulence velocity in units of km s^{-1}, while λ_0 refers to the wavelength of the unshifted line center, T the temperature in Kelvin.

Evidently, the lower the temperature is, the smaller the Doppler width of a given line. Furthermore, it is easily found in Table 1 that in the umbra, the macro-turbulence velocity $v_{\rm mac}$ is also smaller than that outside the sunspot, most probably because of the frozen-in effect (cf. Priest 1984). It is well known that the temperature is lower inside sunspots than outside (also evident from the white-light image). From the above equation one may conclude that if we only considered the factors of temperature and macro-turbulence in the umbra, then the width of the line core would be smaller in the umbra than outside of the sunspot. However, the inversions illustrated in the table show us an opposite effect. Therefore, the line core width enhancement is most probably due to the magnetic field, which is also the unique source that causes the temperature to be lower than the surroundings by pressure balance (cf., Priest 1984).

In order to estimate the increase of the line core broadening, we select the 105th point as the reference point because its physical condition is very close to that of the quiet sun. We then find that $\Delta\lambda_{\rm core}$ increases by 25 mÅ, 24 mÅ and 20 mÅ at the 57th, 73rd and 81st points, respectively, with respect to the 105th point.

Now, let us denote the line core broadening as

$$\Delta\lambda_{\rm core} = \Delta\lambda_{\rm core}(T, v_{\rm mac}, H). \tag{2}$$

Then we have

$$\begin{aligned} d\Delta\lambda_{\rm core} = &\ (\partial\Delta\lambda_{\rm core}(T, v_{\rm mac}, H)/\partial T)dT \\ &+\ (\partial\Delta\lambda_{\rm core}(T, v_{\rm mac}, H)/\partial v_{\rm mac})dv_{\rm mac} \\ &+\ (\partial\Delta\lambda_{\rm core}(T, v_{\rm mac}, H)/\partial H)dH. \end{aligned} \tag{3}$$

To evaluate the broadening rate, we shall assume for simplicity that the terms $\partial\Delta\lambda_{\rm core}/\partial T$ and $\partial\Delta\lambda_{\rm core}/\partial v_{\rm mac}$ can be calculated from Eq. (1), and the average temperatures in the umbra, the penumbra and the 105th point outside the sunspot are 4000 K, 4250 K and 4500 K, respectively. These figures are somewhat arbitrary, but even if the temperatures are changed to 3000 K, 4000 K and 5000 K, the resulting line width variation will not be greatly changed. With these assumptions, the results for the cases listed in the table are, respectively, 2.52×10^{-2} mÅ G^{-1}, 3.24×10^{-2}mÅ G^{-1} and 4.61×10^{-2} mÅ G^{-1} for the 57th, 73rd and 81st points. Thus the rate of increase of the line core with magnetic field strength decreases as the magnetic field increases. This indicates that saturation may take place when the field strength reaches a certain value. Meanwhile, the rates due to the temperature and macro-turbulence are 5.0×10^{-4} mÅ K^{-1} and 1.67×10^{-2} mÅ m^{-1} s^{-1} for the data shown in Table 1. At this point, one can see that the broadening rate due to magnetic field is very high. For example, a difference of 1000 G between the umbra and the outside of the sunspot increases the line core width by about 30 mÅ, while a temperature difference of 500 K will decrease it by less than 1 mÅ. This is the reason why though in sunspot the temperature is lower than that outside the sunspot, the line is much broader within the sunspot, as observed.

As for the broadening in the wings, it is related to the intrinsic property of the radiators, as stated above. As the magnetic field strength increases, the effective widths of the involved energy levels are increased. For the figures listed in the table, the increases in the absolute line wing broadening ($\Delta\lambda_{\rm wing} \times \Delta\lambda_{\rm core}/4\pi$) are 1.99 mÅ, 1.02 mÅ and 7.35×10^{-1} mÅ, respectively, for the 57th, 73rd and 81st points with respect to the 105th point. If, for simplicity, we ascribes the increase to only the field we shall have the relative values, 1.657×10^{-3} mÅ G^{-1}, 1.13×10^{-3} mÅ G^{-1} and 1.34×10^{-3} mÅ G^{-1}. Therefore, the rate does not change greatly as the magnetic field strength increases. And the wing width is not so sensitive to magnetic field as the core width.

4 DISCUSSION AND CONCLUSIONS

We investigated the influence of the magnetic field on the line broadening. It is shown that the Zeeman broadening affects both the line core and the line wings, i.e., on the whole line. As the magnetic field strength increases, the broadening rate at the line core decreases while the rate in the wings does not change so regularly. And the broadening is more effective in the core than in the wings. The Zeeman broadening is so effective that even in the sunspot where the temperature is lower, there is evident broadening in the observed line profile.

However, it is worth noting that not all the increase of line broadening can be ascribed to the magnetic field. This is because the three-dimensional structure of the vector magnetic field or that of the line-of-sight velocity have not been included in the above considerations. Thus we did not obtain any information on the induced electric fields that could lead to line broadening by the Stark effect, nor on the gradient of the line-of-sight velocity that could result in line core broadening. Furthermore, density variation due to the presence of magnetic field has not been checked, therefore, pressure broadening by the van der Waals force was not taken into account. Finally, the existence of molecular lines may be suspected of causing the line broadening. However, such lines are present only in the umbra and therefore they cannot influence the calculation in the penumbra case. Their influence in the umbra case will be investigated in the future.

It should also be noted that the parameters $\partial\Delta\lambda_{\rm core}$ $(T, v_{\rm mac}, H)/\partial H$ and $\partial\Delta\lambda_{\rm wing}$ $(T, v_{\rm mac}, H)/\partial H$ are estimated from the sample of the FeI line and the presumption that the relation of the line core broadening to the temperature and macro-turbulence velocity is the same as that of Doppler width. Thus the results presented in this paper are only estimates. They depend on the line accepted (the wavelength as well as the Landë factor), the Zeeman splitting pattern with different number of Zeeman components, as well as other factors. Therefore, a further study should be done in order to obtain more accurate results.

Acknowledgements This work is sponsored by the National Natural Science Foundation of China (Grant No. 19773016) and the Grand Basic Development and Study Foundation of China (Grant No. G2000078401).

References

Casini R., Lopez Ariste A., Tomczyk S. et al., 2003, ApJ, 598, L67
Lites B. W., Skumanich A., Rees D. E. et al., 1988, ApJ, 330, 493
Lites B. W., Skumanich A., Martinez Pillet V., 1998, A&A, 333, 1053
Mihalas D., 1978, Stellar Atmospheres, W. H. Freeman and Company
Priest E. R., 1984, Solar Magnetohydrodynamics, D. Reidel Publishing Company
Qu Z. Q., Zhang X. Y., Chen X. K. et al., 2001, Solar Phys., 201, 241
del Toro Iniesta J. C., Tarbell T. D., Ruiz Cobo B., 1994, ApJ, 436, 400
Tritschler A., Schlichenmai R., Bellot Rubio L. R. et al., 2004, A&A, 415, 717
Weiss N. O., Thomas J. H., Brummell N. H. et al., 2004, ApJ, 600, 1073
Wang Z. R., Qu Q. Y., Physics of Stellar Atmospheres, the Advanced Education Press, in Chinese
Westendorp Plaza C. et al., 2001a, ApJ, 547, 1130
Westendorp Plaza C. et al., 2001b, ApJ, 547, 1148