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LETTER

Letter to the Editor

The effects of opacity in the transition region of YZ CMi*

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Abstract. It has generally been assumed that the emission from the upper atmosphere of late-type stars is optically thin. In the present paper we use the Si IV and C IV resonance lines to investigate this assumption for the active dMe star YZ CMi. The significant deviations of the line ratios from their optically thin values, demonstrate that opacity can be quite important particularly in the case of stellar flares. These deviations are combined with a method of escape probabilities to derive optical depths of approximately unity for the lines under consideration. We demonstrate that, if the electron density in the atmosphere is known, opacity can provide important information on the linear dimensions of the scattering layer. Using this technique, we have estimated path lengths of a few kilometers for one of the flares under consideration.

Key words: atomic data – stars: activity – stars: atmospheres – stars: individual: YZ CMi – stars: late-type – ultraviolet: stars

1. Introduction

Solar and stellar atmospheres reveal a range of phenomena and processes which are usually attributed to the magnetic field. There are many branches of solar research that have been extended to cool stars. Despite the similarities found between the two fields, the extent to which the full range of stellar phenomena occur on the Sun, and vice versa, remains to be fully explored. Estimates of physical parameters for stellar transition regions and coronae often rely on diagnostics techniques that are based on emission line ratios. However, one of the basic assumption in this analysis is that the emission is optically thin, and that all the photons created for a certain line will escape from the atmosphere. Although this may be a good approximation for the vast majority of UV, EUV and X-ray lines, a number of transitions exist which may have significant optical depths.

In the solar case, line ratio anomalies have often been explained in terms of opacity. For example, Doyle & McWhirter (1980) and Keenan & Kingston (1986) have shown that the C III (1176 Å) and Si III (1206 Å) multiplets have measurable optical thickness near the solar limb. The method used was first proposed by Jordan (1967), and is based on the intensity ratio of lines arising from a common upper level. In optically thin conditions, the intensity ratio should be simply the ratio of the spontaneous decay rates, with any deviations being attributed to opacity.

In the stellar case, the low line to continuum ratio observed in the Extreme Ultraviolet spectra of some late-type stars led Schrijver et al. (1994) to suggest that opacity may be detectable in stellar coronae. This suggestion has been rather controversial as the same observational effect could be produced by a range of other processes, including abundance anomalies in the upper atmosphere of cool stars (see Mathioudakis 1999, Schmitt et al. 1996). In the case of thermal broadening, the optical depth at line center is given by (see Jordan 1977):

$$\tau_0 \;=\; 1.2\times10^{-14}\lambda f\sqrt{\frac{M}{T}}\frac{n_{\rm ion}}{n_{\rm el}}\frac{n_{\rm el}}{n_{\rm H}}\frac{n_{\rm H}}{n_{\rm e}}n_{\rm e}l \qquad (1)$$

where λ is the wavelength in Å, f the oscillator strength of the transition, M the mass of the absorbing atom, T the temperature in K, l the path length in cm and $n_{\rm ion}$, $n_{\rm el}$, $n_{\rm H}$, $n_{\rm e}$ the number densities in $\rm cm^{-3}$ of the ion, element, hydrogen and free electrons, respectively. It is assumed that the vast majority of ions are in the ground state. Hence, in conditions where the electron density is sufficiently high and/or the path lengths long, strong resonance lines with high oscillator strengths can have significant optical depths. Opacity can affect both the intensities and line widths of such lines. In the chromosphere, where the optical depths are large, the problem is treated by detailed radiative transfer calculations. In the transition region and corona, where the optical depths are considerably lower, the photons of strong resonance lines will not be trapped. However, depending on the geometry and density of the atmosphere overlaying the emitting region, these photons could be scattered out of the line of sight and therefore not be detected.

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* Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.

Table 1. The line transitions used in the present study.

Ion (Å)	Transition	Oscillator Strength
Si IV (1393.76)	3s $^2S_{1/2}$ – 3p $^2P_{3/2}$	0.52 [1]
Si IV (1402.77)	3s $^2S_{1/2}$ – 3p $^2P_{1/2}$	0.26 [1]
C IV (1548.20)	2s $^2S_{1/2}$ – 2p $^2P_{3/2}$	0.20 [2]
C IV (1550.77)	2s $^2S_{1/2}$ – 2p $^2P_{1/2}$	0.10 [2]

[1] Oscillator strengths from Maniak et al. (1993)
[2] Oscillator strengths from Wiese et al. (1966)

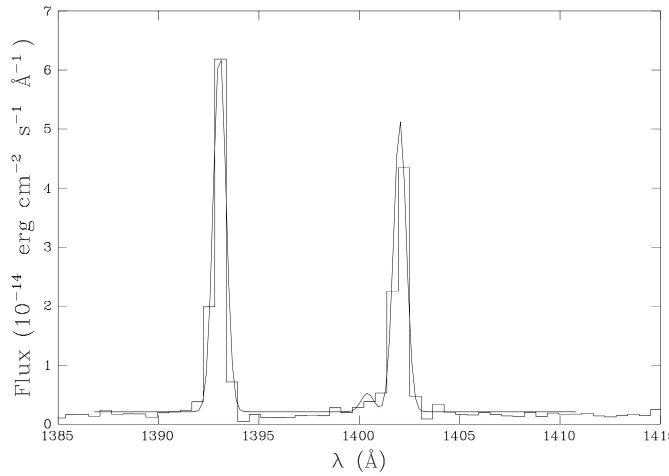

Fig. 1. The December 1994 flare spectrum of YZ CMi in the wavelength region of the Si IV lines. A gaussian fit is superimposed to the observed spectrum. The quiescent spectrum has been subtracted from the flare. The deviation of the line ratio from the 2:1 optically thin approximation, is evident.

In the present paper, we use HST/GHRS observations to investigate the effects of resonant scattering in the transition region of the active M-type dwarf YZ CMi. We use a method of escape probabilities to derive optical depths, and show that these can provide important information on the scattering layer of the atmosphere.

2. The method

The method that we will use is based on the relative intensities of two resonance lines of the same ion with different oscillator strengths. For the purpose of this work, the line with the lower oscillator strength will be termed *reference* line. We assume that opacity will only change the direction of line photons and scatter them out of the line of sight, a good approximation for small optical depths. The resonance lines that we will use are: Si IV (1393.76 Å) and C IV (1548.20 Å) which have high oscillator strengths and are therefore highly susceptible to opacity. Details of the transitions used are given in Table 1. In order to avoid any abundance or ionization equilibrium uncertainties, the reference lines were taken from the same element and ionization stage but with lower oscillator strengths (Si IV 1402.77 Å; C IV 1550.77 Å). For each pair of lines, we examine the flux ratio of the reference to the resonance line. Both lines are populated by collisions and de-populated by spontaneous radiative decays. The C IV and Si IV multiplets share the same lower level, but the two upper levels are closely spaced fine-structure levels which are populated according to their statistical weights. In statistical equilibrium the flux ratio will be the ratio of the collisional excitation rates. Under optically thin conditions, the escape probability of the photons is unity. Since the lower level is identical for each pair, the flux ratio will depend only on the ratio of collision strengths. The collision strength, $\Omega_{\rm ij}$, and oscillator strength, $f_{\rm ij}$, for a transition between levels i and j are related by the following equation (see Mariska 1992):

$$\Omega_{\rm ij} = \frac{8\pi}{\sqrt{3}} \frac{I_{\rm H}}{\Delta E_{\rm ij}} g \omega_{\rm i} f_{\rm ij} \qquad (2)$$

where $I_{\rm H}$ is the ionization energy for hydrogen, g the Gaunt factor, $\omega_{\rm i}$ the statistical weight of level i and $\Delta E_{\rm ij}$ the threshold energy for the transition. The ratio of collision strengths for two transitions of the same element, ionization stage and similar energy levels will be the ratio of the oscillator strengths. The observed line flux ratio will therefore be the ratio of their oscillator strengths reduced by the photon escape probability P, given by:

$$\frac{F_{\rm ref}}{F_{\rm res}} = \frac{P_{\rm ref}}{P_{\rm res}} \frac{f_{\rm ref}}{f_{\rm res}} \qquad (3)$$

where $F_{\rm ref}$ and $F_{\rm res}$ are the line fluxes, $P_{\rm ref}$, $P_{\rm res}$ the escape probabilities and $f_{\rm ref}$, $f_{\rm res}$ the corresponding oscillator strengths (Schmelz et al. 1997). The Si IV and C IV ratios show no density dependence over the 10^6 to 10^{14} cm^{-3} range (CHIANTI database; Dere et al. 1997). In optically thin conditions $P = 1$ and the ratio of the Si IV and C IV multiplets should simply be the ratio of their oscillator strengths (2:1). Any deviation from this value would imply that photons are scattered out of the line of sight and opacity has an effect on the observed line flux.

The escape probability is given by

$$P(\tau_0) = \frac{1}{\tau_0\sqrt{\pi}} \int_{-\infty}^{\infty} [1 - exp(-\tau_0 e^{-x^2})] dx \qquad (4)$$

where τ_0 is the optical depth at line center, x the dimensionless frequency variable $x = \frac{\nu-\nu_0}{\Delta\nu_{\rm D}}$ and $\Delta\nu_{\rm D}$ the half-width of the thermal Doppler line profile (Kastner & Kastner 1990). Values of $P(\tau)$ have been calculated numerically by Kastner & Kastner (1990) for optical depths in the range of $10^{-3} \leq \tau \leq 10^5$. The opacity ratios of Doppler broadened lines from common upper levels have also been evaluated. In the present paper we will use the opposite approach. We obtain values of the escape probabilities from the observed line ratios and use these to obtain τ for the quiescent and active phases of the star.

3. Observations and analysis

We have examined two sets of YZ CMi observations de-archived from the Hubble Space Telescope public data archive. The datasets were obtained with the Goddard High Resolution Spectrograph (GHRS) on board HST in December 1994 and April

Table 2. Line fluxes and ratios of the Si IV and C IV multiplets on YZ CMi. The fluxes are given in units of 10^{-14} erg cm^{-2} s^{-1} followed by the estimated error in brackets. The quiescent spectrum of the source was determined by co-adding spectra with fluxes within ≈ 50%. Note that the quiescent fluxes have been subtracted from the flares.

Ion	Si IV	Si IV	Ratio	$\tau_{1393.8}$	C IV	C IV	Ratio	$\tau_{1548.2}$
(Å)	1393.8	1402.8			1548.2	1550.8		
Quiescent 1994	3.9 (0.07)	2.1 (0.06)	1.86 (0.08)	0.2	–	–	–	–
Flare 1994	4.2 (0.18)	3.6 (0.17)	1.17 (0.11)	1.8	–	–	–	–
Quiescent 1996	5.2 (0.15)	2.9 (0.13)	1.79 (0.13)	0.3	20.0 (0.68)	11.0 (0.6)	1.82 (0.16)	0.3
Flare 1996	19.0 (0.64)	13.0 (0.60)	1.45 (0.11)	1.0	46.0 (2.1)	29.0 (1.9)	1.57 (0.17)	0.7

1996. The December 1994 dataset consists of 11 spectra covering the wavelength range 1150–1435 Å, whereas the April 1996 observations consists of 5 spectra between 1380–1660 Å. Each spectrum had an exposure time of approximately 40–45 minutes. The observations were carried out with the G140L grating thus providing a spectral resolution of $\frac{\lambda}{\Delta\lambda} \approx 1000$. A preliminary analysis of the December 1994 dataset has been presented by Robinson et al. (1996). A major flare was detected in each of the two datasets. Both flares are detected as strong enhancements in chromospheric and transition region lines as well as in the continuum. YZ CMi was in a continuous state of low-level variability throughout the HST observations. Spectra with line fluxes within approximately 50%, were co-added to create the *quiescent* spectrum of the source for each observing period. Ten spectra were used for this purpose in the December 1994 dataset and 4 in the April 1996. Line fluxes were determined by gaussian fits to the observed line profiles. The results are listed in Table 2 where the line fluxes of Si IV and C IV are followed by the ratio of the multiplets. The flare fluxes have been integrated over an ≈ 40 minute period, whereas the average of the co-added spectra was used for the quiescent state. In the case of the flares, the line fluxes constitute a lower limit to the true flare fluxes. The O IV (1401.2 Å) line flux was also determined from the fitting process.

4. Results and discussion

The Si IV and C IV flux ratios indicate the presence of detectable opacity. In the quiescent state of YZ CMi the line ratios show marginal deviations from their optically thin values, whereas significant deviations occur during the flares. In the solar transition region, the C IV and Si IV line ratios are at the optically thin limit, except at heights near the limb where they reach values as low as 1.5 (Doschek et al. 1976). The same effect has been observed in some active regions (Feldman & Doschek 1978). On the same basis, Linsky et al. (1995) have presented indications that these lines may be moderately optically thick in the transition region of the RS CVn binary Capella.

Here we assume that the deviations of the line ratios from the optically thin values are due to opacity. The observed over theoretical line ratios should therefore be equal to the ratio of the escape probabilities (Eq. 3). Kastner & Kastner (1990) evaluate the escape probabilities for a homogeneous distribution of emitters and absorbers as well as for spatially separated emitters and absorbers (inhomogeneous case). By dividing the observed line ratio with the oscillator strengths, the ratio of escape probabilities can be found. The optical depths are then estimated from the ratio of escape probabilities and the Kastner & Kastner (1990) tables (Fig. 2). The optical depths derived are also listed in Table 2.

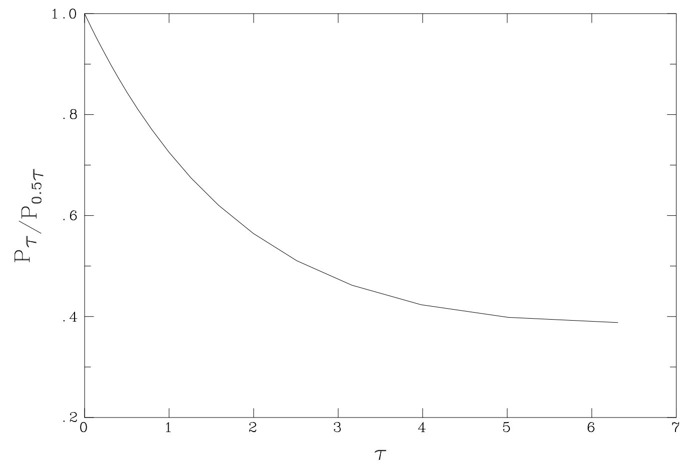

Fig. 2. The ratio of escape probabilities as a function of optical depth, for an inhomogeneous distribution of emitters and absorbers.

In the quiescent state of YZ CMi the line ratios show marginal deviations from their optically thin values, whereas significant deviations occur during the flares. During the 1996 observations, where both the Si IV and C IV lines have been measured, the optical depths have similar values (Si IV is only marginally higher than C IV). At the temperature of maximum formation, log $T_{\rm SiIV}$ = 4.8 and log $T_{\rm CIV}$ = 5.0, the ionic fractions are similar for both ions $\frac{n_{\rm SiIV}}{n_{\rm Si}} \approx \frac{n_{\rm CIV}}{n_{\rm C}} = 0.35$ (Arnaud & Rothenflug 1985). The elemental abundances are $\frac{n_{\rm Si}}{n_{\rm H}} = 1.3\times10^{-4}$, $\frac{n_{\rm C}}{n_{\rm H}} = 3.9\times10^{-4}$ (Feldman 1992) whereas the atomic masses are $M_{\rm Si} = 28.1$, $M_{\rm C} = 12.01$. The above values, combined with the higher oscillator strengths of the Si IV transitions, explain the similarity in the optical depths derived from the two ions (assuming that $n_{\rm e}l$ is the same for both ions). As the optical depth is proportional to the electron density and the line of sight path length, the values of τ combined with an independent estimate of the electron density will allow us to determine the thickness of the emitting region.

The most accurate methods for estimating electron densities in the solar and stellar atmospheres are based on line ratio techniques. These can involve lines of the same multiplet or of different multiplets within the same ion. Due to the lack of any suitable line ratios in the present spectra, we estimate the electron density from the emission measure (EM). This method, based on the best fit of a density sensitive line to an existing emission measure, is applied to the April 1996 flare. Note that as we use lines of different elements, our estimated values can be effected by abundance and/or ionization equilibrium uncertainties. We use the observed flux of the intersystem line of O IV at 1401.2 Å (logT = 5.2). This is calculated to be density-sensitive, varying by more than one order of magnitude in the 10^{10}–10^{12} cm^{-3} density range (Doyle & Keenan 1992). An EM = 2×10^{27} cm^{-5} is determined using the C IV line (1550.1 Å; logT =5.0) which, given its relatively low oscillator strength, is less susceptible to opacity. The EM of O IV is assumed to be the same as for C IV. We believe that the assumption that both lines have the same EM is reasonable, as they are formed at a very similar temperature close to the minimum of the solar EM distribution (Griffiths & Jordan 1998, O'Shea et al. 1999). The best agreement of the O IV (1401.2 Å) line flux with the EM is obtained for an electron density of $\approx 10^{11.5}$ cm^{-3}. Finally, we substitute in Eq. 1 the electron density, ionization fraction, elemental abundance, atomic weight and temperature of line formation, to derive a line of sight path length of $\approx$ 5 km. This value is consistent with the optical depths of both C IV and Si IV. The derived path length is in very good agreement with the semi-empirical modelling of Houdebine & Doyle (1994), who concluded that the observed line profiles of an active stellar atmosphere can only be re-produced if the transition region is very thin and at a high column mass.

5. Conclusions

In optically thin conditions the flux ratios of the Si IV and C IV resonance lines in the UV is equal to the ratio of their oscillator strengths (2:1). We have presented strong evidence for opacity effects in the transition region of the active M-type dwarf YZ CMi. The deviations of the line ratios from their optically thin values are most pronounced during increased atmospheric activity (flares). In the cases were the Si IV and C IV lines are detected simultaneously, the derived optical depths have similar values. This can be interpreted as the higher oscillator strength, atomic mass and reduced temperature of the Si IV lines, balances the effect that the increased C IV abundance has on the optical depth. Using the best fit of the O IV 1401.2 Å intersystem line flux to the emission measure, we estimate an electron density of $\approx 10^{11.5}$ cm^{-3} for the April 1996 flare. This density combined with the optical depth allows us to to derive line of sight path lengths of $\approx$ 5 km in the transition region. Opacity can therefore be used as a powerful diagnostic to determine linear dimensions in upper stellar atmospheres.

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