ON THE EFFECT OF ROTATION ON STELLAR ABSORPTION LINES

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Abstract. The effect of rapid uniform rotation on equivalent widths of spectral lines is studied in the case of a star seen pole-on. Contrary to the situation for the strong lines Mg II 4481 and Si II 4128, the effect may be significant for the weak ones, especially those of the Eu II-type. Because the mean atmospheric parameters of a rapidly rotating star seen pole-on are very similar to those of a non-rotating star of the same mass, this may cause significant errors in abundance determinations, especially for Eu-type elements. The aspect effect on the central intensity of two Eu II lines of different strengths is also studied.

1. Introduction

The effect of rapid uniform rotation on radiation from stars has been studied extensively, e.g., by Hardorp and Strittmatter (1968a, b). One of their results is that the pole-on cases (at least when $\omega \leqq 0.99$) show colors and spectral types differing very little from the values for non-rotating stars of the same mass. Also the mean atmospheric parameters θ_e and $\log g$ are very similar if deduced from the Balmer discontinuity and the width $D(0.2)$ of $H\gamma$. When these atmospheric parameters are used to determine the abundances for individual stars, errors may be caused if the star is rotating and seen pole-on. Since in the linear section of the curve of growth the abundance A is proportional to the equivalent width W, the error $\Delta \log A$ in the abundance, when weak lines are used, is equal to $\log W$(rotating and pole-on) $-$ $\log W$(non-rotating).

The results of Hardorp and Strittmatter (1968b) show that for Mg II 4481 the effect of rotation is small. In the present report we present our results for this same line and for the similar one Si II 4128 in the mass-range 1.55–3.55 solar masses, the star being viewed pole-on. Furthermore we have calculated the effect of rotation on weak lines of Fe II, Cr II and Eu II. In addition to abundance determinations generally, the results may be interesting in connection with the overabundances of peculiar stars. Aspect effects are not considered in the present communication in greater detail. Our preliminary result for the central intensity of the Eu II profile is presented. The visibility of the line is important from the point of view of the pole-on and fast-rotator hypothesis of peculiar stars.

2. Methods of Calculation

The physics involved is practically the same as that used by Hardorp and Strittmatter (1968a, b). The interior model of the rotating star was taken from Roxburgh *et al.* (1965), and the surface gravity calculated from the Roche model. The effective temperature is given by von Zeipel's law. The atmospheric parameters θ_e and $\log g$, as a

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function of latitude, thus depend only on the mass and a dimensionless parameter ω, representing the angular velocity in units of the break-up angular velocity. The radii and luminosities of the non-rotating stars were those given by Faulkner and taken from Hardorp and Strittmatter (1968b). The temperature and pressure at each latitude, as functions of the optical depth, were interpolated from the tables of Mihalas (1965). The corresponding opacity was interpolated from Bode's (1965) opacity tables. In the specific intensity

$$I_\nu(0, \mu) = \int_0^\infty S_\nu(\tau_\nu) \exp(-\tau_\nu/\mu) \, \mathrm{d}\tau_\nu/\mu$$

the Planck function was used as the source function. In the pole-on case the integration over the surface was finally performed using 11 latitude points. For the aspect effect 15 latitude and 17 longitude points with varying stepwidth were used.

To study the effect of rotation on weak lines, three singly ionized elements (Fe II, Cr II, Eu II) were chosen. The lines were calculated at 4000 Å for two different values of the excitation potential. In addition to zero, the values 3.25, 3.9 and 1.5 were used for Fe II, Cr II and Eu II, respectively. The latter values represent mean values in the spectrum of α^2 CVn between $\lambda\lambda$ 4950–3600, as taken from Burbidge and Burbidge (1955). The abundances and the oscillator strengths were chosen so that the lines were sufficiently weak, i.e. on the linear part of the curve of growth.

For comparison, the equivalent widths of the doublet Mg II 4481 and of Si II 4128.05, using the abundances $\log(A_{\mathrm{Mg}}/A_{\mathrm{H}}) = -4.0$ and $\log(A_{\mathrm{Si}}/A_{\mathrm{H}}) = -4.50$, were also calculated. The same values were used also by Hardorp and Strittmatter (1968b) and by Mihalas and Henshaw (1966). For Mg II 4481 $\log(gf\lambda)$ was put equal to 4.63 and for Si II 4128.05 equal to 4.18, as was done also by Mihalas and Henshaw (1966). The line profiles were assumed to be given by the Voigt profile and the damping constants calculated taking into account both radiation damping and collisional damping. The damping constants were calculated from the formulae given by Mihalas and Henshaw (1966).

3. Results

The results are shown in Figures 1–3. The effective temperature and spectral class are given on the abscissa axis. The masses for which the calculations have been performed are also given. The ordinate is $\log W$ (rotating and pole-on) $-\log W$ (non-rotating). The possibility of using the effective temperature or the spectral class, the latter taken from Morton and Adams (1968), as the abscissae is based on the fact that these are practically the same for a non-rotating star and for a rotating star of the same mass when seen pole-on (at least when $\omega \leqq 0.99$, Hardorp and Strittmatter, 1968b).

Figure 1 shows the results for strong Mg II 4481 and Si II 4128 lines when $\omega = 0.99$. The effect of rotation is seen to be very small ($<10\%$). For comparison, the dashed line shows the results of Hardorp and Strittmatter (1968b) for Mg II 4481. Figure 2 represents the results for weak lines of Fe II, Cr II and Eu II when $\omega = 0.99$. The numbers in parentheses indicate the values of excitation potentials. The maximum

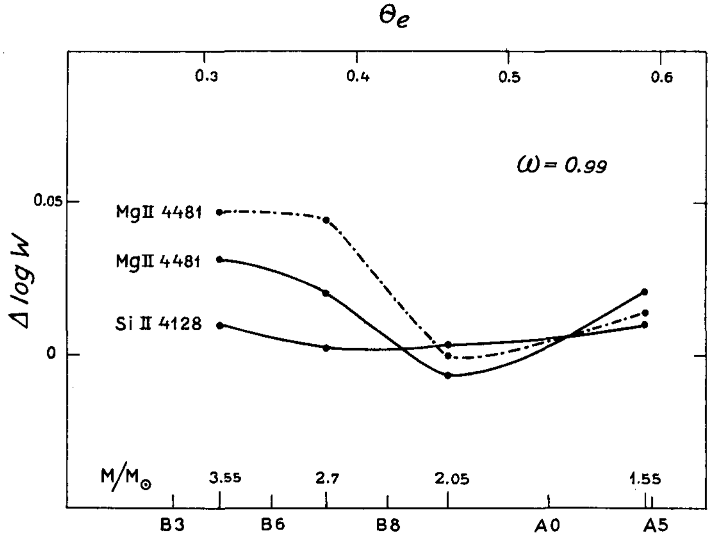

Fig. 1. Effect of rotation on the equivalent width (W) of Mg II 4481 and Si II 4128.05 as a function of spectral type (or effective temperature) when $\omega = 0.99$ and the stars are seen pole-on ($\Delta \log W = \log W$ (rot.) $- \log W$ (non-rot.)). The masses for which the computations have been performed are also given. The dash-dot line gives the results of Hardorp and Strittmatter (1968b) for Mg II 4481.

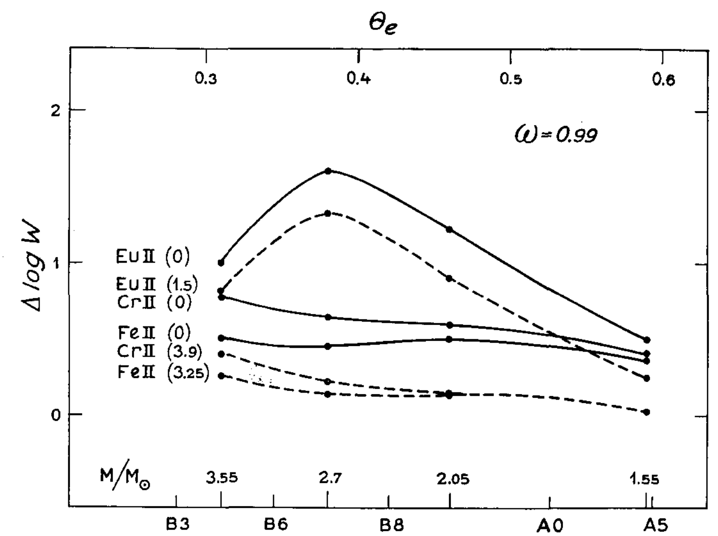

Fig. 2. The same as in Figure 1 but for weak lines of Fe II, Cr II and Eu II at 4000 Å for two different excitation potentials given in parentheses.

amplification occurs for Eu II at $\theta_e = 0.4$ and amounts to 40 for the zero excitation potential. There are also considerable differences between different elements, and clearly the rapid rotation significantly affects the abundance determinations from weak metallic lines, especially for elements like Eu and Sr, both having similar ionization

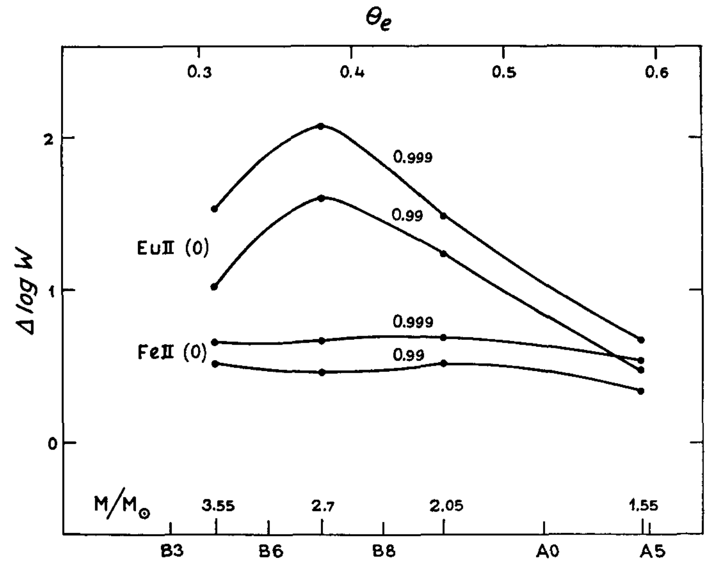

Fig. 3. The same as in Figures 1 and 2 for Fe II and Eu II lines with zero excitation potentials and two values of the rotation ($\omega = 0.99$ and 0.999).

TABLE I

Equivalent width W in mÅ and central intensity I_c in percent of Eu II for three inclinations and two line strengths. $M = 2.7\ M_\odot$, $\omega = 0.99$ and excitation potential = 0.

	$i = 0°$	$i = 30°$	$i = 60°$
W	13	15	27
I_c	12	0.17	0.26
W	92	99	128
I_c	65	1.3	1.4

potentials. In Figure 3 the results for the rotation $\omega = 0.999$ are shown together with those for $\omega = 0.99$, for the zero excitation lines of Eu II and Fe II. The maximum amplification for Eu II is now as great as two orders of magnitude. The reason for the behavior of the Eu II line follows from the powerful growth of the amount of Eu II ions with decreasing effective temperature. This growth attains its maximum at $\theta_e \approx 0.4$. This in turn follows mainly from the small (11.2 eV) second ionization potential.

Also it may be useful to remember that the present study is based on interior models in uniform rotation. Eu-type lines are very sensitive to effective temperature and gravity. Deviations from the Roche model can easily strengthen the lines greatly. In such a case, however, the equivalent width for a rotating star cannot be directly compared to the corresponding value of a non-rotating star of the same mass, but instead to the same spectral type. The reason is that the rotation may significantly change the mean atmospheric parameters and spectral types derived from observations. This may be true also for the case $\omega = 0.999$ in Figure 3.

Table I gives the central intensity of the profile of Eu II for two different strengths for the mass for which the amplification was greatest. Although calculated for three inclinations only, it can be clearly seen that the reasonably strong line ($W \approx 100$ mÅ) is also greatly flattened even when the inclination is relatively small.

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Discussion

Collins: What are the non-rotating values for Table I?

Tuominen: Table I was calculated only to demonstrate the aspect effect. The stronger line is no longer on the linear part of the curve of growth. To estimate the non-rotating value for that line we need in addition to Figure 2 also the curve of growth, which is different for a non-rotating and a rotating star.

Collins: Have you made any calculation of the models with a lower rotational velocity?

Tuominen: Not yet. These first calculations were done in order to find out how large an effect it is possible to obtain when the star is rotating uniformly.

Hardorp: These huge effects of rotation on the Eu II lines do not help us in explaining the peculiar A stars: as far as I remember the hypothesis that these stars are rapid rotators seen pole-on died four years ago at the conference on Magnetic and Related Stars. I am rather suspicious about the magnitude of the effects you found. They are in direct conflict to what Dr. Collins told us this morning.

Tuominen: Two of the objections against the pole-on hypothesis are that rotation can not produce spectral peculiarities and that these peculiarities should also be observed in stars with broader lines. What these results suggest is only that these two objections may not necessarily be correct.

Preston: How was the ionization equilibrium of Eu established? In particular, how did you determine the partition functions for successive stages of ionization as a function of temperature?

Tuominen: For Eu we have used the partition functions of La given by Aller (*Stars and Stellar Systems* **6**, 232) and by Allen (*Astrophysical Quantities*, 1958, p. 33). For curves like those in Figures 2 and 3 the influence of the partition functions is small. To test this we put all the partition functions of Eu equal to unity, and the resulting curves differed by less than 5% from those in Figures 2 and 3. In addition, for Sr II, whose partition functions are better known and whose ionization potentials are similar to those of Eu, the resulting curves were also within 5% of the curves of Eu.