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Rotational feature of Vega and its impact on abundance determinations

Y. Takeda, S. Kawanomoto and N. Ohishi

National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka,
Tokyo 181-8588, Japan (E-mail: takedayi@cc.nao.ac.jp)

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Abstract. In order to establish Vega's absolute rotational velocity ($v_{\rm e}$) separated from the inclination angle (i), while making use of the fact that information on rotation-induced gravity darkening is reflected in the characteristic spectral line shapes, we conducted a detailed profile study on a large number of weak lines based on the very high S/N spectrum data, and concluded that $v_{\rm e} \simeq 175$ km s^{-1} (with $i \simeq 7^{\circ}$) is the best solution. It also turned out that the conventionally derived abundances from Fe I lines by using classical model atmospheres tend to be overestimated by up to ~ 0.2 dex, though this effect is insignificant for Fe II lines. Such gravity-darkening corrections may have an appreciable impact on the Fe I/Fe II ionization equilibrium as well as on the determination of the microturbulence.

Key words: stars: abundances – stars: atmospheres – stars: early-type – stars: fundamental parameters – stars: rotation – stars: individual: Vega

1. Introduction

Although Vega (A0V) has long been well known for its sharp-line nature with a low projected rotational velocity ($v_{\rm e} \sin i \sim 20$ km s^{-1}), we now believe that it is not an intrinsically slow rotator but a rapidly rotating star seen nearly pole-on. This evidence came from studying the characteristic flat-bottom profiles of spectral lines, which were first discovered by Gulliver *et al.* (1991) based on the ultra-high S/N spectrum and successively analyzed in detail by Gulliver *et al.* (1994) and Hill *et al.* (2004) to determine ($v_{\rm e}$, i) separately, since they may contain information on rotation-induced gravity darkening (cf. Fig. 1). Furthermore, this fact has recently been confirmed also by interferometric observations (Peterson *et al.*, 2006; Aufdenberg *et al.*, 2006), by which the rotation-induced darkening on the stellar disk may be directly studied.

Unfortunately, from a quantitative point of view, consensus has not yet been reached regarding how fast Vega is actually rotating, since various ($v_{\rm e}$, i) results derived in the above-mentioned work are not in agreement with each other, diverging into high scale $v_{\rm e}$ ($\sim$ 250–270 km s^{-1}) and low scale $v_{\rm e}$ ($\sim$ 160–170 km s^{-1}). In order to shed light on this confusing situation while establishing its absolute rotational velocity independently by ourselves, we decided to carry out an extensive line profile study on a large number ($\sim$ 200) of weak lines

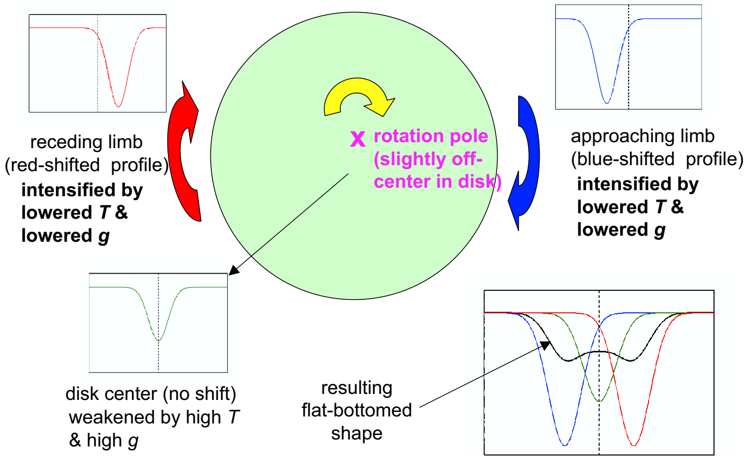

Figure 1. Schematic description of how the flat-bottom profile is produced in a gravity darkened rapid rotator seen nearly pole-on.

based on the very high-S/N ($\sim$1000–3000) and high-resolution ($R \sim 100\,000$) spectrum data we have recently published (Takeda *et al.*, 2007).

2. Rotational characteristics of Vega

The modeling of a rapidly-rotating star was done mostly in the conventional way as has been adopted in a number of relevant studies so far, where we made the following assumptions:
(1) Point-mass approximation of gravitational potential (Roche model).
(2) Axially-symmetric uniform (i.e., non-differential) rotation.
(3) Stellar shape determined by the equipotential surface resulting as a combination of the gravity force and the centrifugal force.
(4) Local $T_{\rm eff}$ dependent upon g ($\equiv |\boldsymbol{g}_{\rm grav} + \boldsymbol{g}_{\rm cf}|$) as $T_{\rm eff} \propto g^{\beta}$, where we regarded the exponent β as a function of $T_{\rm eff}$ following Claret's (1998) calculation (though $\beta = 0.25$ essentially holds for most models in the present case).

A total of six model parameters are involved in our modeling: M (mass), [X/H] (metallicity), $v_{\rm e}$ (equatorial rotation velocity), i (inclination angle), $R_{\rm p}$ (polar radius), and $T_{\rm eff,p}$ (polar effective temperature). However, we could reduce the number of degrees of freedom to one (only $v_{\rm e}$) by adequately assuming M (2.3 $M_{\odot}$) and [X/H] (-0.5 dex), by the constraint of $v_{\rm e} \sin i = 22$ km s^{-1} (a reasonable value seen from recent determinations) and by the requirement of absolute spectral energy distribution (SED), which resulted in a sequence of candidate models [$i(v_{\rm e})$, $R_{\rm p}(v_{\rm e})$, $T_{\rm eff,p}(v_{\rm e})$] parameterized by $v_{\rm e}$.

Then, the observed profiles of 196 carefully selected, sufficiently weak lines, measured from the very high-S/N spectra of Takeda *et al.* (2007), were compared with the theoretical profiles (computed for various $v_{\rm e}$), and the best-fit $v_{\rm e}$ value was determined for each line. Since line profiles of ionized species turned out to be comparatively insensitive to $v_{\rm e}$, we focused on the solutions derived from 87 lines of neutral species, from which we concluded $v_{\rm e} = 175\,{\rm km\,s^{-1}}$ (with the standard deviation of $33\,{\rm km\,s^{-1}}$); and this gives $i = 7.^{\circ}2$, $R_{\rm p} = 2.52 R_{\odot}$, and $T_{\rm eff,p} = 9867\,{\rm K}$. Comparing these with the results of four previous studies (cf. Table 1), we see that our $v_{\rm e}$ solution ($175\,{\rm km\,s^{-1}}$) is rather near to Hill *et al.*'s (2004) value ($160\,{\rm km\,s^{-1}}$), while it is significantly discrepant from the conclusions of recent interferometric determinations ($\sim 270\,{\rm km\,s^{-1}}$). The complete procedures of our analysis and in-depth discussions of the results are described in Takeda *et al.* (2008), which may be consulted for more details.

Table 1. Parameters of rapidly-rotating Vega in comparison with other studies.

	$v_{\rm e}$ (${\rm km\,s^{-1}}$)	i (deg)	$T_{\rm eff}$ (K)	R ($R_{\odot}$)	$\log g$ (${\rm cm\,s^{-2}}$)	method
Gulliver *et al.*	245	5.1	9695	···	3.75	line
(1994)			9305	···	3.67	profile
Hill *et al.*	160	7.7	9602	···	3.94	line
(2004)			9252	···	3.88	profile
Peterson *et al.*	274	4.5	9988	2.31	4.07	interfero-
(2006)			7557	2.87	3.59	metry (opt.)
Aufdenberg *et al.*	270	4.7	10150	2.26	4.10	interfero-
(2006)			7900	2.78	3.64	metry (IR)
This study	175	7.2	9867	2.52	4.00	line
			8931	2.76	3.82	profile

Note. Regarding $T_{\rm eff}$, R, and $\log g$, the data in the upper and lower row correspond to the polar and equatorial value, respectively.

3. Gravity-darkening effect on abundance analysis

As a by-product of this study, we found that the strength of a line tends to be intensified in our final model as compared to the case of classical model of rigid-rotation (i.e., no gravity-darkening and no distortion), though the extent of this intensification differs from line to line (i.e., conspicuous especially for lines of neutral species such as Fe I, while lines of ionized species such as Fe II are comparatively inert), as shown in Fig. 2. This effect is closely connected with the profile shape; that is, the more conspicuous the peculiarity (flat-bottom profile) is, the more it is strengthened.

Since almost all abundance studies for Vega have been done by using the classical model atmosphere, this trend must have some effect on abundance de-

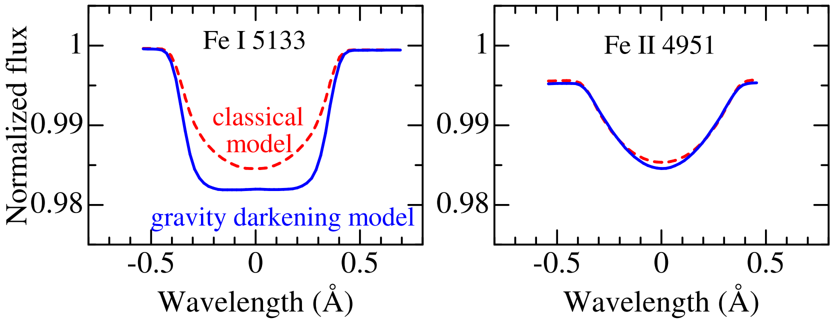

Figure 2. Line profile/strength difference between the classical model (dashed line) and the gravity-darkening model (solid line), shown for the two representative cases of Fe I 5133 line ($\chi_{\rm low}$ = 4.18 eV; left) and Fe II 4951 line ($\chi_{\rm low}$ = 10.31 eV; right).

terminations. It is thus interesting to examine how much gravity-darkening (GD) correction ($\Delta \log \epsilon_{\rm GD}$; to be added to the conventionally derived value to obtain the true abundance) is expected and how it depends on the line parameters. Fig. 3 shows the behavior of $\log(W_{\rm GD}/W_{\rm cl})$, which is the ratio of realistically computed equivalent width by including the gravity darkening effect ($W_{\rm GD}$) to the conventionally computed one with a classical model ($W_{\rm cl}$) and is related to the GD correction as $\Delta \log \epsilon_{\rm GD} \simeq -\log(W_{\rm GD}/W_{\rm cl})$ in the present case of weak lines. The following characteristics are seen:
—(a) Fe I lines show systematically higher $\log(W_{\rm GD}/W_{\rm cl})$ (0.1–0.2 dex) than Fe II lines (0.00–0.05 dex), the difference amounting up to ~ 0.2 dex.
—(b) For the case of Fe I lines, $\log(W_{\rm GD}/W_{\rm cl})$ tends to decline progressively with an increase in the line strength ($w^{\rm obs}$).
—(c) Meanwhile, $\log(W_{\rm GD}/W_{\rm cl})$ shows a decreasing trend as $\chi_{\rm low}$ becomes higher for Fe II lines.
We would remark that these trends may be related to the long-standing problems involved with abundance analyses of Vega.

The first issue concerns the Fe I/Fe II ionization equilibrium. It is known that lines of Fe I (trace species) suffer an appreciable non-LTE weakening due to the over-ionization of Fe I caused by the excess of UV photoionizing radiation over the Planck function, while those of Fe II (dominant stage) are hardly affected. According to Gigas (1986), expected non-LTE corrections are $\sim +0.3$ dex (Fe I) and ~ 0.0 dex (Fe II). However, it has been embarrassingly known that almost consistent Fe I and Fe II abundances are obtained even under the assumption of LTE and an application of non-LTE corrections evidently deteriorates this consistency (cf. Fig. 4a), as Adelman (1993) remarked "*... but I am disturbed that the discrepancy between the abundances from Fe I and Fe II lines increases when NLTE corrections are applied.*" In our opinion, the apparent agreement between Fe I and Fe II observed in the LTE abundances is nothing but a result of

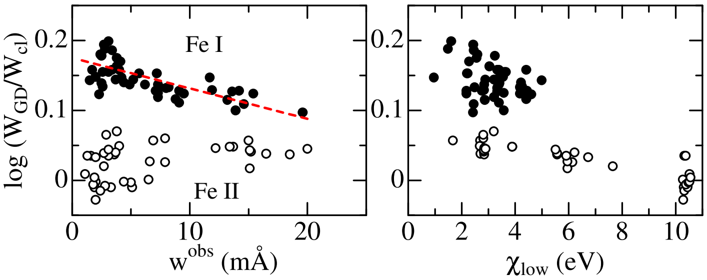

Figure 3. Dependence of the $W_{\rm GD}/W_{\rm cl}$ ratio of Fe lines upon $w_{\rm obs}$ (observed equivalent width, left) and $\chi_{\rm low}$ (lower excitation potential, right), which is related to the gravity-darkening correction for the conventionally derived abundance as $\Delta \log \epsilon_{\rm GD} \simeq -\log(W_{\rm GD}/W_{\rm cl})$ in the present case of weak lines. Filled and open symbols correspond to Fe I and Fe II lines, respectively. Note the systematic $w_{\rm obs}$-dependence of this ratio seen in Fe I lines (indicated by the dashed line).

fortuitous cancellation, because both the non-LTE correction ($\sim +0.3$ for Fe I, ~ 0.0 for Fe II) and the gravity-darkening correction (~ -0.2 for Fe I, ~ 0.0 for Fe II at the weak-line limit; cf. Fig. 3) act in the “opposite” direction.

The second question is the problem of the microturbulent velocity ($v_{\rm t}$). Most of the spectroscopic analyses of Vega done so far derived $v_{\rm t}$ values around $\sim 2\,{\rm km\,s^{-1}}$ consistently with each other (especially before 1990; cf. Fig. 4b). However, an appreciably lower $v_{\rm t}$ has been sometimes reported such as that of Adelman and Gulliver (1990) who derived the smallest-ever $v_{\rm t}$ of $0.5\,{\rm km\,s^{-1}}$ by including very weak Fe I lines based on their high-S/N Reticon spectrum. We suspect that the reason why they obtained such a low $v_{\rm t}$ may be related to the $w^{\rm obs}$-dependence of $\log(W_{\rm GD}/W_{\rm cl})$ seen in Fe I lines (Fig. 3; left panel). That is, the effect of gravity-darkening intensification for Fe I lines becomes more pronounced as the line strength decreases. Then, if one tries to compensate this trend within the framework of classical analysis (where the abundances of very weak lines are essentially invariant), there is no other choice than to raise the abundances of comparatively stronger lines by decreasing $v_{\rm t}$.

These two arguments evidently suggest the necessity of properly including the gravity-darkening correction ($\Delta \log \epsilon_{\rm GD}$) in a gravity-darkened pole-on rapid rotator such as Vega, when one tries to pursue fairly precise abundance studies using weak lines. While it is often believed as a fundamental assumption of stellar spectroscopy that “invoking fairly weak lines measured on a spectrum of high quality is the royal road to accurate and reliable abundance determinations (because they are free from various uncertain factors such as the microturbulence or damping constants)”, there may be a pitfall in placing too much confidence on this guideline.

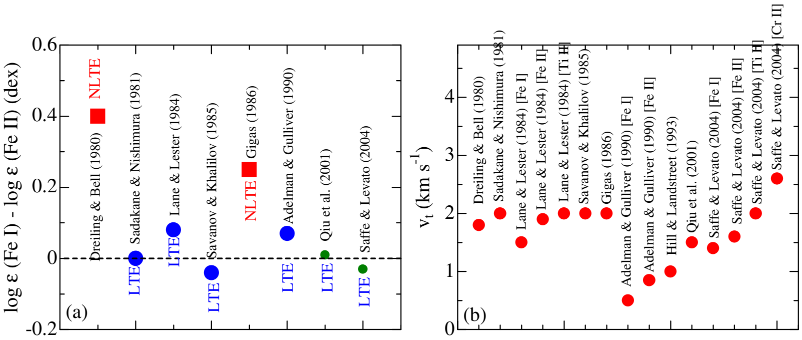

Figure 4. (a) Difference of Vega's Fe abundances derived from Fe I and Fe II lines (a measure of how the ionization equilibrium is accomplished) taken from various literature. Circles and squares correspond to the cases of LTE and non-LTE, respectively. Note that the latest two studies *postulated* the LTE ionization equilibrium as a presumption to determine T_{eff} and $\log g$; yet, we included them for a reference purpose because their resulting atmospheric parameters are similar to others. (b) Comparison of the literature values of Vega's microturbulent velocity (v_{t}).

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