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Continuum Flux Excess in Be Stars Determined from Spectral Lines[1]

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Abstract. We study the continuum flux excess at λ4471 by comparing the observed He I λ4471 line profiles with non-LTE model line profiles. Assuming that emission of the Hγ line is formed nearly in the same regions of the circumstellar envelope as those where the visible continuum flux excess rises, we estimate the continuum opacity needed to account for the veiling of the He I λ4471 line. The flux excess so derived is then studied as a function of the stellar aspect angle in an attempt to determine the degree of incidence of the envelope geometry near the central star on the continuum flux of Be stars.

1. Introduction

For at least three different reasons, it is useful to determine the amount of flux excess (or flux deficiency) in the visible spectral range of Be stars as compared to the photospheric flux emitted by the central star without its circumstellar envelope (CE): (1) to derive the absolute magnitude, or energy distribution, of the central star to study the effects produced by stellar rotation; (2) to determine the statistical distribution of the flux excess (or deficiency) as a function of spectral type in stellar counts aiming at determining the mass distributions of these objects; (3) to give constraints to models of CE, as the flux excesses (or deficiencies) sought depend on the physical structure of CE and on their geometry.

In the present paper we study the incidence of CE geometry on V magnitude excess (deficiency).

2. The method of flux excess (deficiency) determination

For this study we used only spectral lines. We observed the He I 4471 line, one of the spectral transitions which seem to be least affected the by emissions or

[1]Data obtained at ESO-La Silla (Chile) and OHP (France)

absorptions in the line produced in the CE. The photospheric He I 4471 line can however be affected by veiling due to the continuum CE emission/absorption. Study of the veiling effect allows us to determine the flux excess sought.

It can readily be shown that for a photospheric absorption line whose optical depth $\tau_\lambda \simeq 0.0$ in the CE, the ratio $\Lambda_{\mathrm{HeI4471}}$ between the observed equivalent width, W^{obs}, and the photospheric one, W^*, is given by:

$$\frac{W^{\mathrm{obs}}}{W^*} = \Lambda_{\mathrm{HeI4471}} = \frac{\mathrm{e}^{-\tau_{\mathrm{V}}}}{1 + \frac{\Delta \mathrm{F_V}}{\mathrm{F_V^*}}} \tag{1}$$

where τ_{V} is the total optical depth of the continuum spectrum at $\lambda_{\mathrm{V}} = 0.56\mu$m, $\Delta\mathrm{F_V}$ is the flux excess ($\Delta\mathrm{F_V} \gtrsim 0$) or deficiency ($\Delta\mathrm{F_V} \lesssim 0$) produced by the CE at λ_{V}, and $\mathrm{F_V^*}$ is the photospheric flux corresponding to the underlying star without its CE. The equivalent width W^* is obtained from T_{eff} and log g derived using the stellar Balmer discontinuity component. The ΔV difference sought is then calculated as follows:

$$\Delta V = V(\mathrm{star} + \mathrm{CE}) - V(\mathrm{star}) = -2.5 \times \log(1 + \frac{\Delta F_V}{F_V^*}) \tag{2}$$

Hence, we then need to determine τ_{V} from observations and in a way which is as much CE-model independent as possible. To determine τ_{V}, we also observed the emission component of the Hγ line. Observations of this line were made at the same time as those of the He I 4471 line.

To derive relation (1) we used a simple equivalent slab representation of the CE to estimate the radiation flux produced by the CE-star system:

$$\mathrm{F}_\lambda = \mathrm{F}_\lambda^* \mathrm{e}^{-\tau_\lambda} + \gamma_\lambda[1 - f(\tau_\lambda)] \tag{3}$$

where $\gamma_\lambda = \frac{\Omega}{\Omega_*}\mathrm{S}_\lambda(1-\beta)$ and Ω/Ω_* is the ratio of the slab to the apparent stellar solid angle, which is a function of CE geometry (flattened or spheroidal); S_λ is the source function (line or continuum); β is a negligible function of the order of $(\Omega/\Omega_*)^{-1}e^{-\tau_\lambda}$; $f(\tau) = 2E_3(2\tau)$ for $\tau > 1$ (E_3 is the exponential integral of order 3), but $f(\tau)$ for $\tau < 1$ is different if we are dealing with lines or the continuum. For the continuum spectrum, the form of $f(\tau)$ depends on whether the continuum formation region is close to or far from the central star. For lines $f(\tau)$ depends on whether the line is collisional or radiation dominated.

Interferometric observations of γ Cas (Stee et al. 1998) suggest that the region in the CE responsible for Hγ emission should be almost the same as that producing the visible continuum. The ratio Ω/Ω_* can then be assumed to be the same for both the Hγ emission line and the visible continuum, without any need to specify its analytical form. On the other hand, as from the photospheric radiation of a B star, the flux at the center of the Hγ absorption line is about the same as that at the continuum flux at $\lambda_{\mathrm{V}} = 0.56\mu$m: $\mathrm{F}_{\lambda_o}^{\mathrm{H}\gamma} \simeq \mathrm{F}_{\mathrm{V}}^{\mathrm{continuum}}$. We can then assume that for the line and the continuum source functions we have: $\mathrm{S}_{\lambda_o}^{\mathrm{H}\gamma} \simeq \mathrm{S}_{\mathrm{V}}^{\mathrm{continuum}}$, so that $\gamma_{\lambda_o}^{\mathrm{H}\gamma} \simeq \gamma_{\mathrm{V}}^{\mathrm{continuum}}$.

Once the factor γ_{V} is determined, from (1) and (2) written for the continuum, the optical depth τ_{V} and the flux excess ratio $\Delta\mathrm{F_V}/\mathrm{F_V^*}$ are obtained immediately.

Table 1. Program stars and CE parameters

Star	$\Lambda_{\mathrm{HeI4471}}$	γ_V	τ_V	ΔV mag	$V\sin i$ km s^{-1}	$\log T_{\mathrm{eff}}$
HD 28497	0.71±0.02	0.40±0.06	0.50±0.07	+0.174±0.080	216	4.380
HD 30076	0.81±0.00	0.47±0.03	0.26±0.01	+0.044±0.015	206	4.322
HD 37490	0.90±0.00	0.44±0.02	0.13±0.01	+0.022±0.006	146	4.290
HD 41335	0.69±0.02	0.68±0.04	0.32±0.02	−0.050±0.015	278	4.362
HD 44458	0.75	0.60	0.27	−0.016	229	4.407
HD 45725	0.99±0.00	0.48±0.05	0.01±0.00	+0.001±0.002	311	4.274
HD 48917	0.70±0.02	0.47±0.02	0.46±0.02	+0.102±0.020	159	4.322
HD 50013	0.71±0.02	0.65±0.04	0.32±0.02	−0.035±0.022	209	4.362
HD 54309	0.80±0.00	0.48±0.04	0.27±0.02	+0.043±0.025	163	4.334
HD 56139	0.79±0.01	0.50±0.06	0.27±0.03	+0.032±0.033	74	4.336
HD 58343	0.85±0.01	0.67±0.12	0.14±0.03	−0.030±0.028	54	4.217
HD 58978	0.87	0.40	0.19	+0.052	272	4.447
HD 60606	0.84±0.00	0.54±0.05	0.17±0.01	+0.003±0.022	250	4.262
HD 63462	0.64	0.52	0.52	+0.078	313	4.415
HD 66194	0.90±0.01	0.41±0.04	0.14±0.02	+0.034±0.016	204	4.318
HD 68980	0.60±0.03	1.11±0.08	0.30±0.02	−0.232±0.022	120	4.431
HD 77320	0.99	0.37	0.01	+0.002	321	4.279
HD 86612	0.88±0.00	0.57±0.03	0.12±0.01	−0.009±0.007	177	4.217
HD 86661	0.77±0.02	0.80±0.12	0.19±0.02	−0.078±0.026	225	4.334
HD 91465	0.98±0.00	0.49±0.04	0.21±0.00	+0.001±0.002	259	4.243
HD 105435	0.83±0.01	0.71±0.05	0.14±0.01	−0.044±0.010	216	4.334
HD 110432	0.47±0.02	0.79±0.00	0.67±0.00	−0.100±0.001	318	4.367
HD 112091	0.92	0.40	0.12	+0.030	190	4.176
HD 113120	0.81±0.01	0.69±0.05	0.17±0.01	−0.044±0.014	299	4.326
HD 124367	0.97±0.00	0.44±0.01	0.04±0.00	+0.005±0.001	286	4.204
HD 148184	0.63±0.01	0.74±0.13	0.40±0.07	−0.096±0.059	91	4.362

Concerning the Hγ emission line analysis, we are interested only in the value of $\gamma_{\lambda_o}^{H\gamma}$. We thus used relation (3) to fit the equivalent width and the width at the half intensity of the emission component normalized to the underlying photospheric absorption. We did not further pursue any details concerning the physics of the line emission formation. For this reason, we used a gaussian representation of the line optical depth $\tau_\lambda = \tau_o e^{-x^2}$, where the total "Doppler" width is only a fitting parameter which statistically takes into account all velocity fields in the CE, as done by Höflich (1988) in his models of CE for Be stars.

3. Results

Fig. 1a shows some line profiles obtained from (3), which was used to fit observed Hγ line emission profiles normalized to the underlying photospheric component. Table 1 presents the studied stars and the CE mean parameters obtained from several observational dates. In this study we give the results for the first 26 Be stars (encompassing 58 observations) of a program which concerns 73 Be stars for which we obtained 127 spectra.

1. Despite a non-negligible mean opacity in the continuum $<\tau_V> = 0.27 \pm 0.16$, emission and absorption in the visible continuum produced in the studied Be stars compensate each other, so that on average we have $\Delta V \sim 0$ ($<$absorption$> \sim e^{-\tau_V} \sim 0.76$; $<$emission$> \sim \gamma(1-e^{-2\tau_V}) \sim 0.24$). Only those objects where $\gamma \gtrsim <\gamma>$ show $\Delta V \lesssim 0$ (flux excess); other stars have $\Delta V \gtrsim 0$ (flux deficiency) or $\Delta V \simeq 0$.

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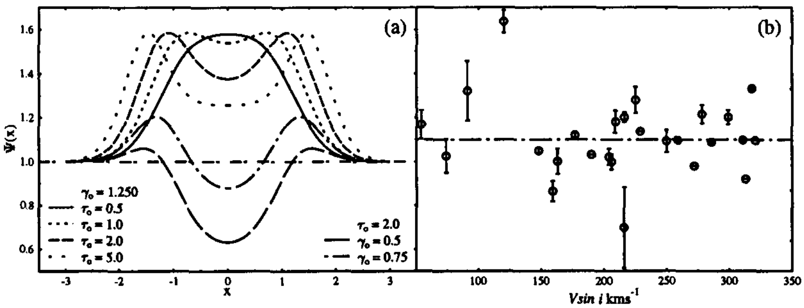

Figure 1. (a) Examples of line profiles obtained from (3) that were fitted to the observed Hγ emission line profiles. (b) Visual magnitude excess ΔV obtained from (2) as a function of $V \sin i$.

2. From Table 1 we can see that there is some flux excess ($\Delta V \lesssim 0$) for Be stars where $T_{\rm eff} \gtrsim 20000$ K, and that this flux excess tends to be slightly higher as the stars are hotter.

3. In Fig. 1b we show ΔV as a function of $V \sin i$. No systematic trend as a function of the aspect angle is detected. If circumstellar envelopes had a regular flat geometrical structure, ΔV would necessarily tend to be more negative for smaller $V \sin i$. We see however:

— that the stronger ΔV observed is only for the hottest Be stars of our sample;

— on average the same flux excess or deficiency is detected whatever the $V \sin i$;

— the stronger flux deficiencies observed are just for stars with intermediate values of $V \sin i$, but not for the highest;

— there may be $\Delta V < 0$ even for stars with $V \sin i \sim 300$ km s^{-1} where flattened structures would more likely produce $\Delta V > 0$.

4. Conclusion

The region of the CE near the central star where the visible continuum is produced cannot have regular and strongly flattened geometrical shapes. If these regions have some mean flattening to explain the small polarization observed, they probably have quite irregular density distribution or they are clumpy, so that whatever the viewing angle, the effect on ΔV of CE geometry is the same.

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