Massive Stars Near and Far
Proceedings IAU Symposium No. 361, 2024
J. Mackey, J. S. Vink, & N. St-Louis, eds.
doi:10.1017/S1743921322002605

New self-consistent wind parameters to fit optical spectra of O-type stars

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Abstract. We perform spectral fittings for O-type stars based on self-consistent wind solutions, providing $\dot{M}$ and $v(r)$ directly derived from the initial stellar parameters. We introduce our two methods: m-CAK prescription and Lambert-procedure.

The Lambert-procedure allows the calculation of consistent $v(r)$ that reduce the number of free parameters when a spectral fitting using CMFGEN is performed, even without recalculation of the $\dot{M}$. Spectra calculated from our Lambert-solutions show significant differences compared to the initial β-law CMFGEN models. For m-CAK prescription, self-consistent solutions provide values for theoretical $\dot{M}$ on the order of the most recent predictions from other studies. Later, we find a global fit with the RT code FASTWIND. This is an important step towards the determination of stellar and wind parameters without using β-law. Our m-CAK prescription is valid for the O-type stars with $T_{\rm eff} \geq 30$ kK and $\log g \geq 3.2$.

We expect that solutions introduced here to be extended to numerous studies about massive stars in future.

Keywords. Early-type stars, Hydrodynamics, Stellar winds

1. The Lambert-procedure

Given the radiative acceleration $g_{\rm rad}(r)$ calculated by CMFGEN, we have the wind equation of motion

$$v\frac{dv}{dr} = -\frac{1}{\rho}\frac{dp}{dr} - \frac{GM_*}{r^2} + g_{\rm rad}(r)\,, \tag{1}$$

new velocity profile $v(r)$ is analytically calculated

$$\Rightarrow -\hat{v}^2 e^{-\hat{v}^2} = -\left(\frac{\hat{r}_c}{\hat{r}}\right)^4 \exp\left[-1 - 2\,\hat{v}_{\rm crit}^2\left(\frac{1}{\hat{r}} - \frac{1}{\hat{r}_c}\right) - 2\int_{\hat{r}_c}^{\hat{r}} \hat{g}_{\rm line}\,d\hat{r}\right] \tag{2}$$

by implementing the Lambert W-function as

$$\hat{v}(\hat{r}) = \sqrt{-W(x(\hat{r}))}\;. \tag{3}$$

This is iteratively implemented, until convergence is achieved. Mass-loss rate $\dot{M}$ is a free parameter for the Lambert-procedure, but it needs to be constrained to accurately satisfy the full equation of motion in CMFGEN, including clumping.

$$\left(v - \frac{a^2}{v}\right)\frac{dv}{dr} = g_{\rm rad} - \frac{GM_*}{r^2} + 2\frac{a^2}{r} + \frac{a^2}{f}\frac{df}{dr}\,. \tag{4}$$

Results of this procedure are shown in Table 1.

Table 1. Results for our modelled stars using the Lambert-procedure (Gormaz-Matamala et al. 2021)

	ζ-Puppis	**HD 163758**	**α-Cam**
$T_{\rm eff}$ [kK]	41	34.5	28.2
$\log g$	3.6	3.4	2.975
$R_*/R_\odot$	17.9	19.1	30.3
v_∞ [km s^{-1}]	2 740	2 400	2 650
$\dot M$ [$10^{-6} M_\odot$ yr^{-1}]	2.7	1.2	0.85
f_∞ [$1/D_\infty$]	0.10	0.05	0.05

Table 2. Stellar and wind parameters for HD 192639, obtained using the m-CAK prescription (Gormaz-Matamala et al. 2022a)

HD 192639			
$T_{\rm eff}$ (kK)	34.0	$(k, \alpha, \delta)_{\rm sc}$	(0.047,0.694,0.089)
$\log g$	3.25	$\log \dot M_{\rm sc}$ ($M_\odot$ yr^{-1})	$-5.783\pm.090$
$R_*/R_\odot$	19.8	v_∞ (km s^{-1})	$1\,460\pm160$
$M_*/M_\odot$	25.4	$f_{\rm cl}$	6.25
$L_*/L_\odot$	4.73×10^5	$v_{\rm rot}$ (km s^{-1})	100
[He/H]	0.10	$\log D_{\rm mom}$	28.83

2. The m-CAK prescription

Equation of motion is solved using the line-force parameters k, α and δ (Gormaz-Matamala et al. 2019)

$$v\frac{dv}{dr} = -\frac{1}{\rho}\frac{dp}{dr} - \frac{GM_{\rm eff}}{r^2} + g_{\rm es}(r)\, k\, t^{-\alpha}\left(\frac{N_{\rm e}}{W}\right)^{\delta} . \tag{5}$$

Line-force parameters (k, α, δ) are self-consistently calculated with the wind hydrodynamics, by means of the force-multiplier ($\mathcal{M}(t)$) which is defined as a function of the independent optical depth (t)

$$\mathcal{M}(t) = k\, t^{-\alpha}\left(\frac{N_{\rm e}}{W}\right)^{\delta} = \frac{g_{\rm line}}{g_{\rm es}} \text{ , with } t = \sigma_{\rm es} v_{\rm th}\, \rho(r)\left(\frac{dv}{dr}\right)^{-1} , \tag{6}$$

We generate a large grid with of solutions for the line-force parameters, for different values of effective temperatures and surface gravities. Self-consistent solution is delimited to a specific range of t, which depends on the hydrodynamic conditions such as incorporation of temperature structure $T(r)$. New self-consistent values for mass-loss rate ($\dot M_{\rm sc}$) and terminal velocity ($v_{\infty,\rm sc}$) are obtained, which are used to perform synthetic spectra and determine new stellar and wind parameters. Results for the star HD 192639 are shown in Table 2.

Because wind parameters $\dot M_{\rm sc}$ and $v_{\infty,sc}$ now depend on stellar parameters, we do our spectral fittings reducing the number of free parameters. Mass-loss rates derived from the m-CAK prescription can be applied for the generation of evolutionary tracks for massive stars (Gormaz-Matamala et al. 2022b, accepted in A&A).

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https://doi.org/10.1017/S1743921322002605 Published online by Cambridge University Press