Slow hydrodynamic regime to model B supergiant winds

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Resumen / Las soluciones hidrodinámicas actuales para los vientos de las estrellas tempranas son obtenidas a partir de la teoría de estrellas rotantes con vientos impulsados por radiación. Estas soluciones están separadas en dos ramas principales: la solución *rápida* y las soluciones *lentas*. El primer conjunto de soluciones es la solución estándar CAK, mientras que el segundo conjunto corresponde a un grupo de soluciones cuyas propiedades son todavía poco conocidas. En este trabajo estudiamos las propiedades del régimen de viento lento obtenido para diferentes valores de los parámetros de la fuerza de línea, a través del cálculo de los perfiles de línea espectrales resultantes. Luego ajustamos nuestros perfiles de línea sintéticos a perfiles observados, con el objeto de evaluar la capacidad de la solución lenta para representar la variedad de características observadas en los perfiles de línea originados en los vientos. Encontramos que los vientos de las estrellas supergigantes B pueden ser representados adecuadamente por el régimen lento; un resultado que puede contribuir al progreso en la comprensión de la naturaleza de los flujos de materia emitidos por las estrellas tempranas.

Abstract / Current hydrodynamic solutions for the winds of early-type stars are obtained from the theory of rotating stars with radiation-driven winds. These solutions are separated into two main branches: the fast solution and the slow solutions. The first set is the standard CAK solution, while the second set corresponds to a group of solutions with still poorly known properties. In this work we study the properties of the slow wind regime derived for different values of the line force parameters, and compute the resulting line profiles. Then we fit our synthetic line profiles with observed ones, in order to evaluate the ability of the slow solution to represent the variety of features observed in line profiles originated along the winds. We find that the winds of B supergiants can be well-represented by the slow regime, a result that could give new insights into the true nature of the outflows in early-type stars.

Keywords / hydrodynamics — stars: early-type — stars: mass-loss — stars: winds, outflows

1. Introduction

In the spectra of B supergiants there are clear evidences that the strengths of the stellar winds show notable differences even in stars with the same effective temperatures. These winds are driven by the transfer of momentum from the radiation field in metal line transitions, a phenomenon which was first modelled successfully by Castor et al. (1975) in the so-called *CAK* theory. The hydrodynamic solution they found, named also the *fast* solution, is obtained by solving the momentum equations with a parameterization for the line-force (Abbott, 1982), which includes three parameters: k, α and δ. These parameters represent the effective number of lines driving the wind, the relative number of optically thin to optically thick lines, and the changes in the ionisation stratification, respectively.

Curé (2004) and Curé et al. (2011) discovered two new solutions in 1-D models confined to the equatorial plane of a rotating star. One solution is the Ω–*slow* solution which arises for stars with high values of Ω, the quotient between the equatorial rotational speed and the critical velocity. The other solution is the δ–*slow* solution, which is obtained for high values of parameter δ, i.e., different ionisation and recombination rates. The δ–*slow* solution exists even in a non-rotating case. Both kind of *slow* solutions lead to slower winds, with higher, similar, or even lower mass-loss rates ($\dot{M}$) in comparison with the case of the *fast* solution.

Recently Venero et al. (2016) explored the domains of these solution regimes and found a clear boundary between the domains of the *fast* and the *slow* regimes. This boundary consists in a well-defined gap in the δ parameter space, where no stationary solution is found. Venero et al. (2016) tested models inside this gap with the code Zeus-3D (Clarke, 2010), and found a non-stationary solution with a kink type structure as a consequence of the merge between both adjacent regimes. The location and width of the gap between stationary solutions, in a δ scale, strongly depend on the rotation rate.

In this work we present hydrogen line profiles computed for hydrodynamic models for B supergiants in the *slow* regime. The synthetic line profiles are calculated by mean of the NLTE model atmosphere code FASTWIND (Puls et al., 2005, and references therein). Our objective is to check the ability of this kind of solution to represent the wind of B supergiants, in order to obtain new insights on the physical conditions of the wind of early supergiants.

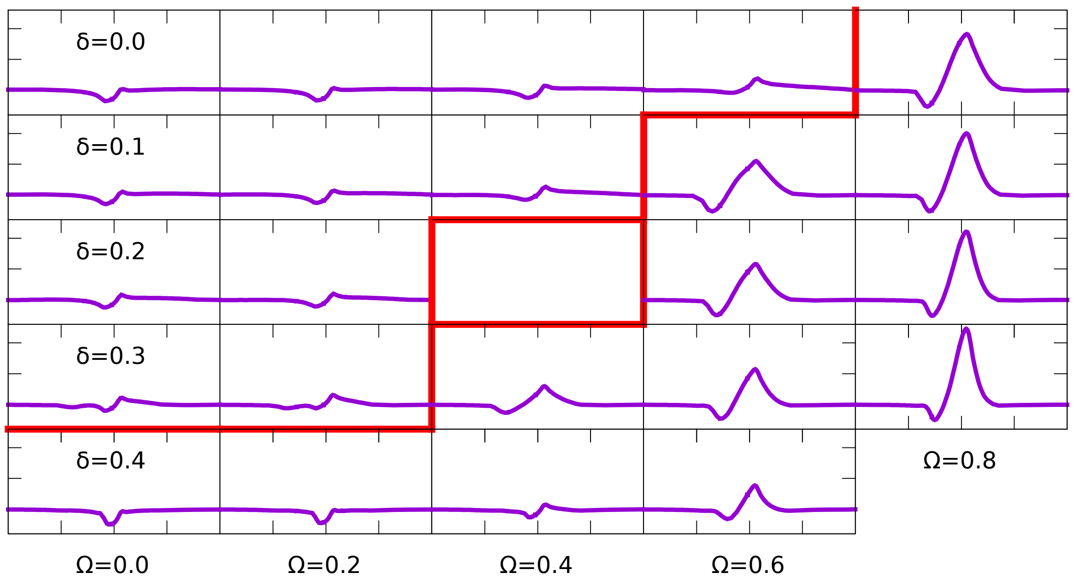

Figure 1: Hα line profiles computed for different values of the star rotation Ω (columns) and wind ionisation parameter δ (rows). The red line indicates the gap location, separating the *fast* regime (left and above) from the *slow* regime (right and down).

2. Results

Fig. 1 shows a sample of the computed Hα line profiles (normalised flux vs. wavelength in Å) obtained for an array of models with $T_{\rm eff} = 19\,000$ K, $\log g = 2.5$ and $R = 40$ $R_{\odot}$. The models are distributed in columns for different values of Ω and, in rows for different values of δ. For the parameters α and k, we adopted typical values given by the line-driven wind theory (Abbott, 1982). In this work we choose $k = 0.2$ and $\alpha = 0.5$, which represent a low number of contributing lines to the radiative acceleration, half of which are optically thick.

The red line in Fig. 1 approximately indicates the location of the gap between the *fast* domain (left and above) and *slow* domain (right and below). The line profile for a model placed just inside the gap (in the centre of Fig. 1) is not represented here.

Comparing the line profiles along a row of panels in Fig. 1 which correspond to a fixed low ionisation rate (i.e. a small value of δ), it is clear that there is a significant change in the shape of the line profiles at both sides of the gap. The *slow* regime generates stronger P Cygni line profiles than the *fast* counterpart. Exceptions are given when high ionisation rates are allowed (e.g., $\delta = 0.4$) where the *slow* regime almost always delivers pure absorption profiles. A rise in the rotation rate also pump up the emission components of the P Cygni profiles, as the density of the wind is increased and the mass-loss rate is considerably enhanced.

3. Line fittings

We test our models with observations of some B supergiants obtained with the REOSC spectrograph in crossed dispersion mode, attached to the Jorge Sahade 2.15 m telescope at the Complejo Astronómico El Leoncito (CASLEO), San Juan, Argentina. The spectral resolution R was around 12 600 in the Hα region. The spectra were obtained in different observation runs on 2006, 2013, and 2015.

Some of the line profile fittings to the observed Hα line profiles of B supergiant stars are shown in Fig. 2. Their corresponding main stellar parameters along with the wind parameters are listed in Table 1. The adopted values of the main parameters are very close to the published ones for *fast* regime models (actually, β–law models) in the literature (see the references in Table 1). The only exception is the poorly studied star HD 99953. Table 1 also includes the stellar and wind parameters computed with the β–law for the same set of observations (Haucke et al., 2017). Some stars, like HD 41117, present wind parameters in fairly good agreement with our values. The adopted line force parameters for each of the models are presented in Table 2. Our values for α are similar to those from the standard theory, while our values of k are considerably smaller. All the models presented here correspond to the δ–*slow* solution and are in good agreement with the observed features. However, it is evident that some of the derived wind features are quite different.

4. The slow solution and the Wind-Momentum Luminosity relationship

Fig. 3 shows the location points of our modeled stars along with coloured lines obtained by adjusting a linear regression to the values of $\mathbf{D}_{\rm mom} = \dot{M} v_{\infty} (R/R_{\odot})^{0.5}$ measured for A/B supergiants of the solar neighbourhood, as function of luminosity (the so-called Wind-Momentum Luminosity relationship, WLR, Kudritzki & Puls, 2000). The parameters of our *slow* regime models adjust quite well the WLR for mid-B supergiants

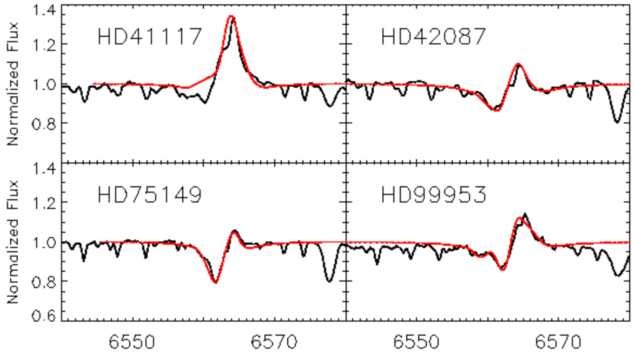

Figure 2: Some line profile fittings (red line) to observed Hα line profile of B supergiants (black line).

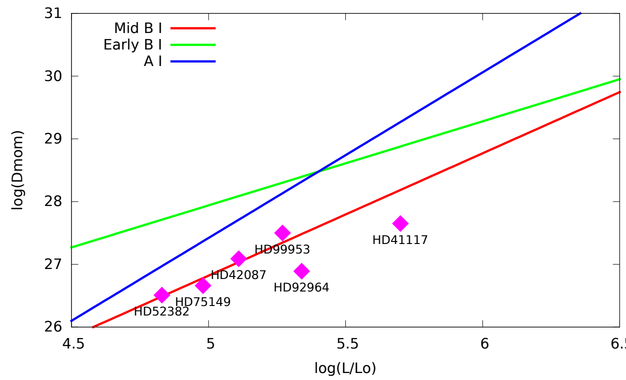

Figure 3: Location of our modelled stars relative to the empiric WLR.

Table 1: Main parameters and wind parameters adopted in our *slow* regime models, in comparison with previously published values. Effective temperatures ($T_{\rm eff}$) are in kK, radii (R) are in $R_\odot$, terminal velocities (v_∞) are in $\rm km\,s^{-1}$, and mass-loss rates ($\dot{M}$) are in units of $10^{-6}\times M_\odot\,\rm yr^{-1}$. References: - a: Kudritzki et al. (1999) - b: Searle et al. (2008) - c: Lefever et al. (2007) - d: Fraser et al. (2010) - h: Haucke et al. (2017) - e: This work.

Star	T.E.	$T_{\rm eff}$	log g	R	v_∞	$\dot{M}$	Ref.
HD 41117	B2 Ia	19.5	2.25	61.7	500	0.85	a
		19.5	2.25	61.7	280	0.44	h
		19.5	2.35	62	216	0.419	e
HD 42087	B2.5 Ib	18	2.5	36.6	630	0.2	b
		19	2.5	63	260	0.24	h
		18	2.5	37	222	0.14	e
HD 75149	B3 Ia	16	2.05	39	500	0.10	c
		16	2.5	39	350	0.10	h
		16	2.05	40	147	0.079	e
HD 99953	B1.5 Ia	16.8	2.15	49	...	...	d
		19	2.3	60	700	0.85	h
		19	2.5	40	268	0.3	e

(B1.5 to B3). Thus the well-known tight relationship between the stellar luminosity and the properties of the wind of the early-type stars hold still for this kind of solution.

5. Conclusions

Our analysis allow us to infer some preliminary conclusions:

- At both sides of the gap which separates *fast* and *slow* wind regimes, the Hα line profiles change significantly. A detailed study on the behaviour of the line profiles close to the gap would allow to figure out which kind of flow regime dominates the wind of B supergiants. This analysis could be performed from a careful examination of the line profiles.
- Most of the *slow* regime models produce stronger emission components when higher values of either Ω, k or α are considered. As B supergiants only exhibit mild P Cygni profiles, it is clear that these parameters should be kept at moderate values, in order to accurately represent the observed features.
- Many of our wind parameters are close to the values obtained with the β–law models fitting the same set of observations. This result shows that the *slow* wind regimes could give wind parameters in fair agreement with many of the published data.
- The observed line profiles can be fitted with the *slow* hydrodynamic solution, a regime which also meets the Wind-Momentum Luminosity relationship. These results encourage us to further explore on the potential of the *slow* regime.

Table 2: Adopted line force parameters.

Star	k	α	δ
HD 41117	0.15	0.49	0.38
HD 42087	0.23	0.50	0.33
HD 75149	0.13	0.50	0.31
HD 99953	0.20	0.50	0.29

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