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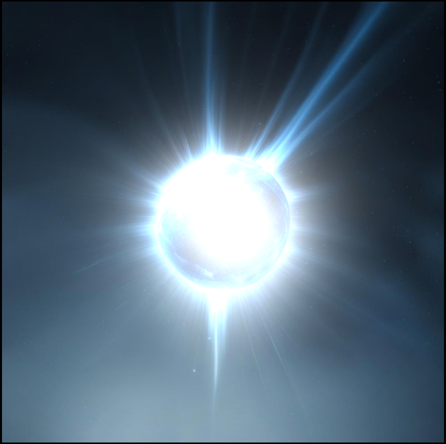

Roberto O. J. Venero

Institute of Astrophysics of La Plata (CONICET-UNLP)

Facultad de Ciencias Astronómicas y Geofísicas (FCAG)

La Plata National University (UNLP)

Argentina

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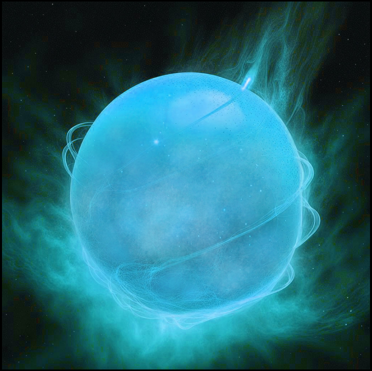
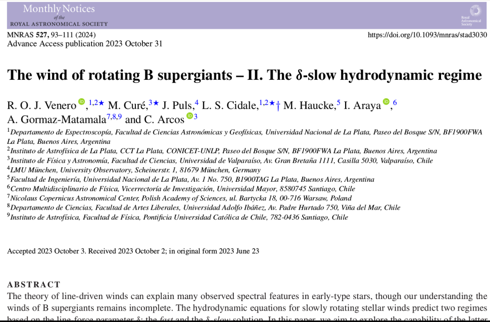
Stellar winds from B supergiant stars: Exploring the δ-slow hydrodynamic solution





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The wind of rotating B supergiants – II. The δ-slow hydrodynamic regime

R. O. J. Venero,[1,2★] M. Curé,[3★] J. Puls,[4] L. S. Cidale,[1,2★†] M. Haucke,[5] I. Araya,[6] A. Gormaz-Matamala[7,8,9] and C. Arcos[3]

[1] *Departamento de Espectroscopía, Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque S/N, BF1900FWA La Plata, Buenos Aires, Argentina*
[2] *Instituto de Astrofísica de La Plata, CCT La Plata, CONICET-UNLP, Paseo del Bosque S/N, BF1900FWA La Plata, Buenos Aires, Argentina*
[3] *Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Av. Gran Bretaña 1111, Casilla 5030, Valparaíso, Chile*
[4] *LMU München, University Observatory, Scheinerstr. 1, 81679 München, Germany*
[5] *Facultad de Ingeniería, Universidad Nacional de La Plata, Av. 1 No. 750, B1900TAG La Plata, Buenos Aires, Argentina*
[6] *Centro Multidisciplinario de Física, Vicerrectoría de Investigación, Universidad Mayor, 8580745 Santiago, Chile*
[7] *Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland*
[8] *Departamento de Ciencias, Facultad de Artes Liberales, Universidad Adolfo Ibáñez, Av. Padre Hurtado 750, Viña del Mar, Chile*
[9] *Instituto de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, 782-0436 Santiago, Chile*

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ABSTRACT
The theory of line-driven winds can explain many observed spectral features in early-type stars, though our understanding the winds of B supergiants remains incomplete. The hydrodynamic equations for slowly rotating stellar winds predict two regimes

B-type supergiant stars

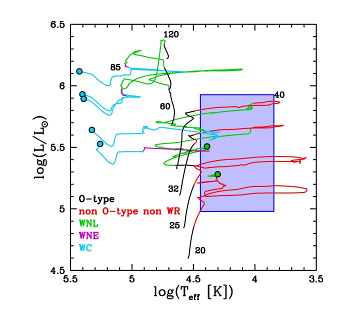
Main properties

- Heterogeneous group of stars.
- Diversity of evolutionary phases (blue region⇔red region of HR diagram).
- Photometric and spectroscopic variability.

Fundamental parameters

- $8\ M_\odot \lesssim$ Mass $\lesssim 50\ M_\odot$
- $10^{4,7}\ L_\odot \lesssim$ Luminosity $\lesssim 10^{5,6}\ L_\odot$
- $12\,000$ K $\lesssim T_{\rm eff} \lesssim 25\,000$ K
- $1.7 \lesssim \log g \lesssim 3$
- $20\ R_\odot \lesssim$ Radius $\lesssim 70\ R_\odot$
- $v \sin i \lesssim 100$ km s^{-1}

Region of the HR diagram occupied by B-type supergiant stars



(Georgy+,2017)

B-type supergiant stars

Wind Parameters

- Mass-loss rates:

  From $\dot{M} \sim 10^{-7}$ to 5×10^{-6} $M_\odot$ yr^{-1}

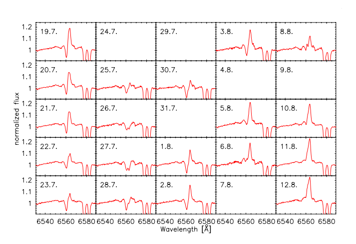
- Terminal velocities:

  From $v_\infty \sim 200$ km s^{-1}(late) to 1 500 km s^{-1} (early)

Optical depth invariant - Wind strength parameter

$$\begin{cases} Q_{res} = \dfrac{\dot{M}}{R_* v_\infty^2} & \text{Resonance lines} \\ Q_{rec} = \dfrac{\dot{M}}{(R_* v_\infty)^{1,5}} & \text{Recombination lines (H}\alpha\text{)} \end{cases}$$

Spectral variability



Hα line profiles of 55 Cygni (B3 Ia) from July to August 2013 (Haucke+,2016).

Rotating radiation-driven winds

Equations for a rotating wind

1D symmetry in the equatorial plane.

Mass conservation: $F_m = 4\pi r^2 \rho v =$ constant

Momentum equation: $v\frac{dv}{dr} = -\frac{1}{\rho}\frac{dp}{dr} - \frac{G\,M_*(1-\Gamma)}{r^2} + \frac{v_\phi^2(r)}{r} + g^L\left(\rho, \frac{dv}{dr}, n_e\right)$

Energy equation $\rightarrow$ Isothermal wind

Centrifugal force

$$v_\phi^2/r = v_{\mathrm{rot}}^2\, R_*^2/r^3$$

v_{rot} is the equatorial rotation speed

Rotational rate Ω

$$\Omega = v_{\mathrm{rot}}/v_{\mathrm{crit}} \qquad 0 \leqslant \Omega < 1$$

$$v_{\mathrm{crit}} = \sqrt{\frac{2GM_*}{3R_*}}$$

Maeder & Meynet (2000).

Parameterization of the radiation force

Castor, Abbott, & Klein (1975)

$$g^L_{rad} = \frac{\sigma_e F}{c} \mathcal{M}(t)$$

Force multiplier

$$\mathcal{M}(t) = \sum_{lines} \frac{\Delta\nu_D F_\nu}{F} \frac{1}{t} (1 - e^{-\eta t})$$

$$\eta = \frac{\pi e^2}{m_e c} g_u \, f_{ul} \, \frac{n_l/g_l - n_u/g_u}{\rho \, \sigma_e \, \Delta\nu_D}$$

Force multiplier (Abbott,1982)

$$\mathcal{M}(t) = k \, t^{-\alpha} \left(\frac{n_e}{W(r)} \right)^{\delta}$$

with parameters k , α y δ

Interpretation of parameters

- k $\rightarrow$Effective number of contributing lines for momentum
- α $\rightarrow$Slope of line intensity distribution

  $dN(\nu, \kappa_L) = -N_0 \, f_\nu(\nu) \, \kappa_L^{\alpha-2} \, d\nu \, d\kappa_L$
- δ $\rightarrow$changes in ionization along the wind

Line-force parameters

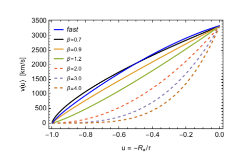
$T_{\rm eff}$ [K]	log g	k	α	δ	Fuente
10 000	1.5	0.36	0.54	0.05	A82
15 000	2.0	0.26	0.51	0.12	A82
20 000	2.5	0.32	0.56	0.02	P86
30 000	3.5	0.17	0.59	0.09	P86

A82: Abbott(1982) - P86: Pauldrach+(1986)

Hydrodynamic solutions

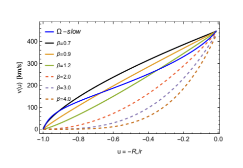
Fast Solution

- Classical (~m-CAK) solution
- High values of the terminal velocity
- $\Omega < 0.75$ (slow rotators)



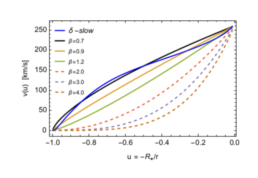
$\Omega_{\rm slow}$ solution

- Found by Curé (2004)
- $\Omega > 0.75$ (high rotators)
- Low terminal velocities and dense flows



$\delta_{\rm slow}$ solution

- Found by Curé et al. (2011)
- For high values of parameter δ (changes in ionization)
- Low terminal velocities and dense flows



Figures from Curé & Araya (2023)
O5V star with $T_{\rm eff} = 45\,000$ K,
$\log g = 4.0$, $R/R_\odot = 12$

Hydrodynamic solutions

β-velocity law

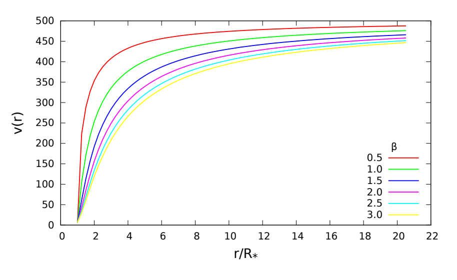
Approximation to the hydrodynamic solution

$$v(r) = v_\infty \left(1 - b\frac{R_*}{r}\right)^\beta$$

with

$$b = 1 - \left(\frac{v(R_*)}{v_\infty}\right)^{\frac{1}{\beta}}$$

This velocity law is commonly used with β values of 2, 3 or higher, particularly in B supergiants.



Questions to answer

What hydrodynamic solutions can we use to model the wind of supergiants B?

Most of B-type supergiants are not fast rotators ($\Omega \leq 0.6$)

i.e.: Howarth(2004),Hunter+(2008),Vink+(2010),de Burgos+(2023)

We can rule out the $\Omega_{\rm slow}$ solution

We can choose between *fast* and $\delta_{\rm slow}$ solutions

Questions

- In what cases does each solution appear? Can the domains of each solution be delimited in the space of the radiation force parameters?
- Can the wind of B-type supergiants be effectively modeled using $\delta_{\rm slow}$ solutions?
- Could the transition between one solution and another explain the variability observed in the spectrum?

Calculation of wind models

Option 1

Self-consistent models

Input values

$T_{\rm eff}$, $\log g$, R_*, abundances, Ω.

Method

1) Solving hydrodynamic equations and radiation transport in moving media, including radiative acceleration calculated consistently with NLTE rates.

2) Generating the synthetic spectrum.

3) Comparison with observations.

4) Iterative refinement process.

Mostly for O-type and WR stars.

Pauldrach+(1994), Krtička & Kubát(2001, 2017), Sander+(2017), Sundqvist+(2019), Björklund+(2021), Poniatowski+(2021,2022).

Option 2

Partially consistent models

Input values

$T_{\rm eff}$, $\log g$, R_*, Ω, abundances, α, δ, k.

Method

1) Solving the hydrodynamic equations adopting a parameterization for the radiative acceleration.

2) Solving the radiation transport equation for moving media, using the hydrodynamic solution.

3) Generating the synthetic spectrum.

4) Comparison with observations.

5) Iterative refinement process.

Taresch+(1997), Pauldrach+(2001), Noebauer & Sim(2015), Lattimer & Cranmer(2021)

Option 3

Non-consistent models

Input values

$T_{\rm eff}$, $\log g$, R_*, Ω, abundances, β, $\dot{M}$, v_∞.

Method

1) Employing a β velocity law instead of solving the hydrodynamic equations.

2) Solving the radiation transport equation for moving media, using the β law.

3) Obtaining the synthetic spectrum.

4) Comparison with observations.

5) Process iteration.

Crowther+(2006), Markova & Puls(2008), Searle+(2008), Haucke+(2018)

Calculation codes

We choose option 2 because, currently, there are no self-consistent codes that produce the δ_{slow} solution.

Hydrodinamic equations

HYDWIND

Curé and collaborators (Univ. Valparaíso, Chile)

Basic features

- Input: Fundamentales parameters, Ω, k , α y δ .
- Spherical Symmetry - Equatorial plane
- Inner boundary condition adopted:

$$\int_{R_*}^{\infty} \sigma_e \rho(r) dr = 2/3 \text{ or } \rho(R_*) = \rho_*$$

- Execution time: few minutes.
- It gives *fast*, Ω_{slow} , or δ_{slow} solutions.
- Output: radial grid, velocities and densities for the wind.

Radiative transfer

FASTWIND

Puls and collaborators (LMU Munich)

Basic features

- Input: Fundamental parameters, hydro solution (or β, v_∞, $\dot{M}$).
- Spherical Symmetry.
- NLTE code considering *line blanketing*.
- Radiative transfer in Sobolev approximation and CMF.
- Unified model (photosphere + wind).
- Diagnostic range: optical.
- Execution time: 15 - 30 min.
- Output: continuum radiation distribution + line profiles (H, He, Si, C, N, O).

Most suitable δ values for B-type supergiants

Do values of δ higher than $\sim$0.25 exist in a stellar wind to achieve a δ_{slow} solution?

δ values for BSGs

Early calculations indicate $\delta \lesssim 0.12$ (Abbott, 1982; Pauldrach+. 1986).

Most recent non-LTE calculations for line-force parameters assume the material to be 'frozen in ionization' ($\delta = 0$), e.g. Noebauer & Sim(2015), Lattimer & Cranmer (2021), or are limited to O-type supergiants (Gormaz-Matamala+2019,2022).

Puls, Springmann & Lennon (2000) analytically derived $\delta \gtrsim 1/3$ for a medium composed of neutral hydrogen as a trace element.

Kudritzki (2002) demonstrated that $\delta \sim 1$ for winds of low optical depth and very low metalicity.

We postulate that BSGs have a different ionization structure compared with O-type stars.

Solution domains in δ and Ω space

First, we examine the distribution of solution domains based on the values of the line-force parameters (k , α , δ).

Model T19

$T_{\text{eff}} = 19$ kK

$\log g = 2.50$

$R_* = 40\ R_\odot$

S. Type: $\sim$ B2 I

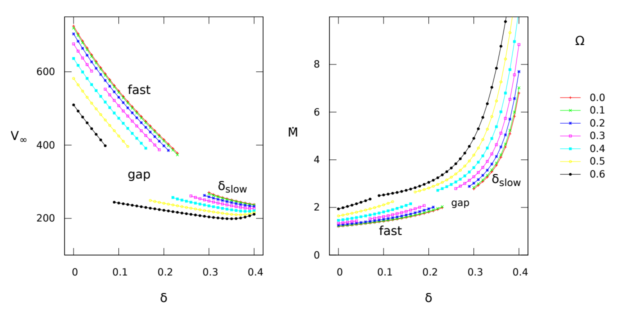
$\alpha = 0.5$

$k = 0.32$

$[\dot{M}] \equiv 10^{-6}\ M_\odot\ yr^{-1}$

$[v_\infty] \equiv$ km s^{-1}

Distribution of solutions



There exists a distinct **gap** between *fast* and δ_{slow} solutions. The HYDWIND code does not identify any stationary solution within the gap.

The gap is consistently present in all models, regardless of the values of T_{eff}, log g, or Ω .

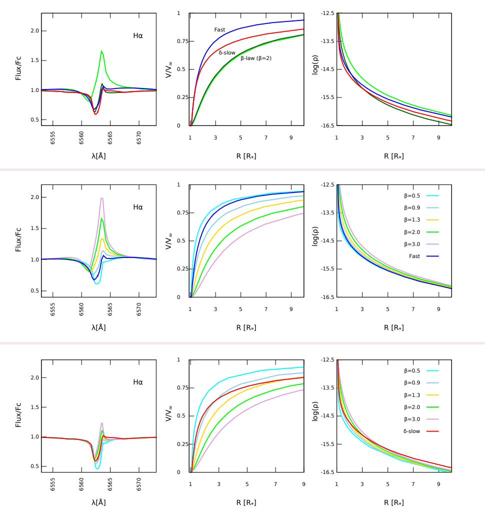
Line profiles from different wind regimes

Hα line profiles

Comparison of line profiles from *fast* and $\delta_{\rm slow}$ models with those from the β velocity law.

The models have nearly identical values of Q.

The Hα profiles generated by the *fast* and $\delta_{\rm slow}$ regimes are quite similar.



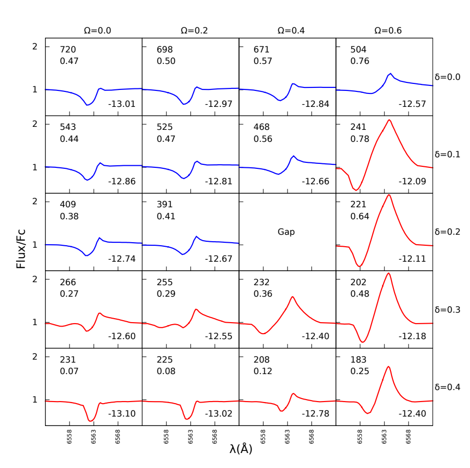
Hα line profiles

Dependence of Hα on Ω and δ

Sample of Hα line profiles for model T19.

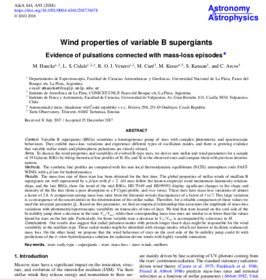
Terminal velocities and mass-loss rates [in units of $10^{-6} M_\odot\ yr^{-1}$]. The values of log Q are at bottom right.

Hα line profiles for different wind regimes (model T19)



Comparison with observations

Previous work by Haucke et al. (2018) Hα line profile fittings computed with β velocity laws.



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Astronomy & Astrophysics

Wind properties of variable B supergiants

Evidence of pulsations connected with mass-loss episodes*

M. Haucke[1,2], L. S. Cidale[1,2,3], R. O. J. Venero[1,2], M. Curé[3], M. Kraus[4,5], S. Kanaan[3], and C. Arcos[3]

[1] Departamento de Espectroscopía, Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque s/n, La Plata, Argentina
e-mail: mhaucke@fcaglp.unlp.edu.ar
[2] Instituto de Astrofísica de La Plata, CONICET-UNLP, Paseo del Bosque s/n, La Plata, Argentina
[3] Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Av. Gran Bretaña 1111, Casilla 5030, Valparaíso, Chile
[4] Astronomický ústav, Akademie věd České republiky v.v.i., Fričova 298, 251 65 Ondřejov, Czech Republic
[5] Tartu Observatory, Tõravere, 61602 Tartumaa, Estonia

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ABSTRACT

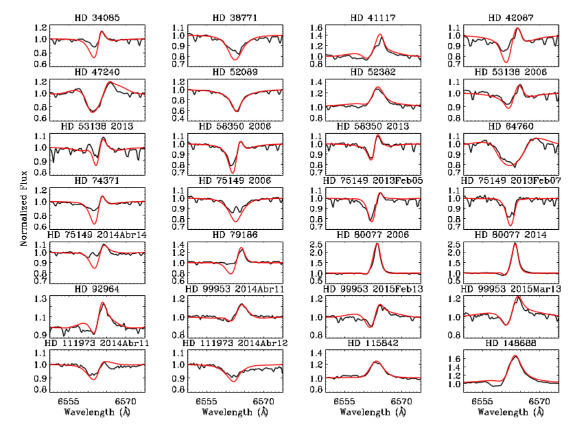
Context. Variable B supergiants (BSGs) constitute a heterogeneous group of stars with complex photometric and spectroscopic behaviours. They exhibit mass-loss variations and experience different types of oscillation modes, and there is growing evidence that variable stellar winds and photospheric pulsations are closely related.
Aims. To discuss the wind properties and variability of evolved B-type stars, we derive new stellar and wind parameters for a sample of 19 Galactic BSGs by fitting theoretical line profiles of H, He, and Si to the observed ones and compare them with previous determinations.
Methods. The synthetic line profiles are computed with the non-local thermodynamic equilibrium (NLTE) atmosphere code FASTWIND, with a β-law for hydrodynamics.
Results. The mass-loss rate of three stars has been obtained for the first time. The global properties of stellar winds of mid/late B supergiants are well represented by a β-law with $\beta > 2$. All stars follow the known empirical wind momentum-luminosity relationships, and the late BSGs show the trend of the mid BSGs. HD 75149 and HD99953 display significant changes in the shape and intensity of the Hα line (from a pure absorption to a P Cygni profile, and vice versa). These stars have mass-loss variations of almost a factor of 2.8. A comparison among mass-loss rates from the literature reveals discrepancies of a factor of 1 to 7. This large variation is a consequence of the uncertainties in the determination of the stellar radius. Therefore, for a reliable comparison of these values we used the invariant parameter Q_r. Based on this parameter, we find an empirical relationship that associates the amplitude of mass-loss variations with photometric/spectroscopic variability on timescales of tens of days. We find that stars located on the cool side of the bi-stability jump show a decrease in the ratio V_∞/V_{esc}, while their corresponding mass-loss rates are similar to or lower than the values found for stars on the hot side. Particularly, for those variable stars a decrease in V_∞/V_{esc} is accompanied by a decrease in $\dot{M}$.
Conclusions. Our results also suggest that radial pulsation modes with periods longer than 6 days might be responsible for the wind variability in the mid/late-type. These radial modes might be identified with strange modes, which are known to facilitate (enhanced) mass loss. On the other hand, we propose that the wind behaviour of stars on the cool side of the bi-stability jump could fit with predictions of the δ-slow hydrodynamics solution for radiation-driven winds with highly variable ionization.

Key words. stars: early-type – supergiants – stars: mass-loss – stars: winds, outflows

1. Introduction

Massive stars have a significant impact on the ionization, structure, and evolution of the interstellar medium (ISM). Via their stellar winds they release energy and momentum to their sur-

are mainly driven by line scattering of UV photons coming from the stars' continuum radiation. The standard stationary radiation-driven wind theory (Castor et al. 1975; Pauldrach et al. 1986; Friend & Abbott 1986) predicts mass-loss rates and terminal velocities as a function of stellar parameters (Abbott 1982; Vink



Comparison with observations

Star	Spectral type	$T_{\rm eff}$ (kK)	log g (dex)	R_* ($R_\odot$)	log $L/L_\odot$ (dex)	v sin i (km s^{-1})	$v_{\rm rot}$ (km s^{-1})	$v_{\rm mic}$ (km s^{-1})	$v_{\rm mac}$ (km s^{-1})
HD 47 240	B1 Ib	19.0	2.40	30	5.02	95	122	10	60
HD 99 953	B1/2 Iab/b	19.0	2.30	25	4.87	50	64	18	50
HD 41 117	B2 Ia	19.0	2.30	23	4.79	40	51	10	65
HD 80 077	B2 Ia + e	17.7	2.20	195	6.53	10	13	10	10*
HD 92 964	B2.5 Ia	18.0	2.20	70	5.67	45	58	11	40
HD 53 138	B3 Ia	18.0	2.25	46	5.30	40	51	10	80*
HD 75 149	B3 Ia	16.0	2.10	61	5.34	40	51	11	52
HD 42 087	B4 Ia	16.5	2.45	55	5.31	80	103	15	80
HD 58 350	B5 Ia	15.0	2.00	54	5.12	40	51	12	70
HD 79 186	B5 Ia	15.8	2.00	61	5.32	40	51	11	53
HD 74 371	B6 Iab/b	13.7	1.80	73	5.23	30	39	10	60
HD 34 085	B8 Iae	12.7	1.70	72	5.08	30	39	10	52

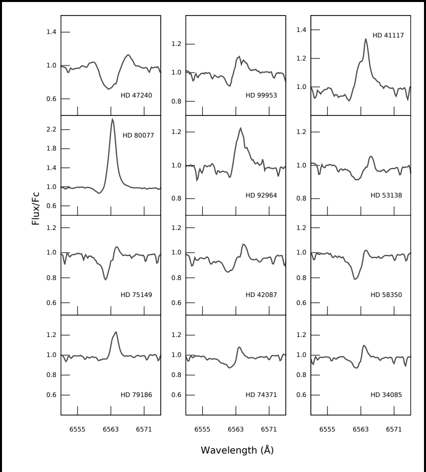
We adopt the stellar parameters from Haucke et al. (2018)

Comparison with observations

Hα line profiles

Observations were performed at CASLEO using the REOSC spectrograph (2005-2015).

A subsample of stars was selected based on the presence of emission in the Hα line profile.

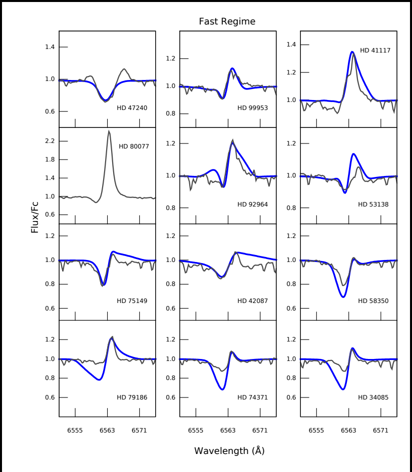


Comparison with observations

Hα line profiles

Fast regime fittings

When fitting the line profiles, we primarily focus on adjusting the emission component of the P Cygni profile.



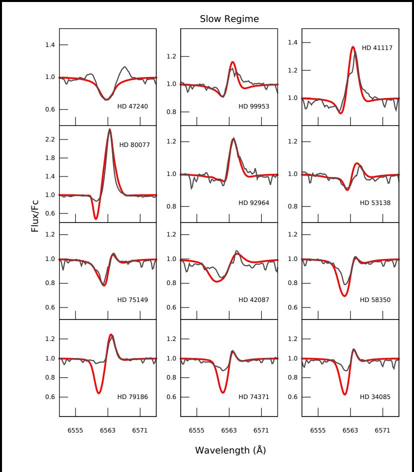
Comparison with observations

Hα line profiles

$\delta_{\rm slow}$ regime fittings

The wings appear slightly improved compared to the *fast* case.

However, many absorption components are still too deep.

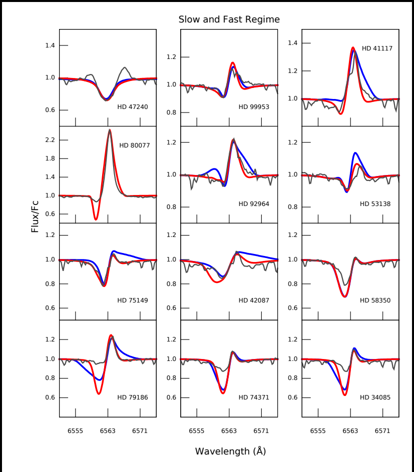


Comparison with observations

Hα line profiles

There are no significant differences between the Hα fittings for both the *fast* and δ_{slow} regimes.

Hα dichotomy



Wind parameters from fittings

Fast regime

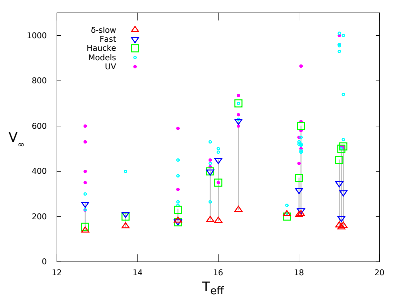
Star	Ω	v_{crit}	v_∞	$\dot{M}$	k	α	δ	$\log D_{mom}$
HD 47240	0.55	222.5	347.2	0.075	0.070	0.500	0.000	26.96
HD 99953	0.33	191.7	193.8	0.080	0.090	0.494	0.150	26.69
HD 41117	0.27	183.9	306.9	0.179	0.113	0.520	0.000	27.22
HD 80077	0.03	470.0	–	–	–	–	–	–
HD 92964	0.20	287.1	317.5	0.640	0.120	0.500	0.200	28.03
HD 53138	0.21	238.8	227.5	0.205	0.190	0.420	0.170	27.30
HD 75149	0.23	224.8	450.1	0.443	0.155	0.480	0.000	27.99
HD 42087	0.35	290.7	622.8	0.826	0.530	0.420	0.000	28.38
HD 58350	0.27	187.5	179.0	0.184	0.240	0.420	0.170	27.18
HD 79186	0.24	209.2	399.1	0.714	0.140	0.510	0.000	28.15
HD 74371	0.22	176.8	211.9	0.323	0.190	0.450	0.120	27.57
HD 34085	0.25	154.0	256.3	0.339	0.150	0.500	0.050	27.67

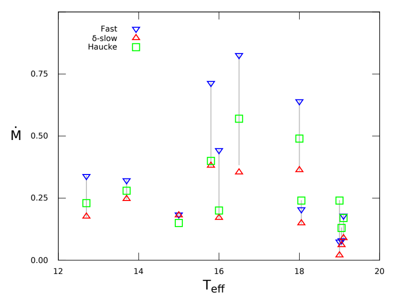
δ_{slow} regime

Star	Ω	v_{crit}	v_∞	$\dot{M}$	k	α	δ	$\log D_{mom}$	v_∞^{Hal8}	$\dot{M}^{Hal8}$	β^{Hal8}	$\log D_{mom}^{Hal8}$
HD 47240	0.55	222.5	161.3	0.020	0.090	0.500	0.300	26.04	450	0.24	1	27.57
HD 99953	0.33	191.7	152.5	0.061	0.080	0.530	0.320	26.47	500	0.13	2	27.33
HD 41117	0.27	183.9	160.0	0.089	0.095	0.510	0.240	26.63	510	0.17	2	27.38
HD 80077	0.03	470.0	211.0	6.379	0.606	0.300	0.295	29.07	200	5.4	3.2	28.86
HD 92964	0.20	287.1	207.0	0.363	0.130	0.505	0.350	27.60	370	0.49	2	27.98
HD 53138	0.21	238.8	211.2	0.149	0.090	0.550	0.320	27.13	600	0.24	2	27.79
HD 75149	0.23	224.8	181.6	0.171	0.185	0.480	0.310	27.18	350	0.2	2.5	27.54
HD 42087	0.35	290.7	230.4	0.354	0.452	0.480	0.405	27.58	700	0.57	2	28.27
HD 58350	0.27	187.5	182.5	0.181	0.120	0.550	0.290	27.18	233	0.15	3	27.21
HD 79186	0.24	209.2	185.3	0.381	0.110	0.550	0.300	27.54	400	0.4	3.3	27.90
HD 74371	0.22	176.8	157.6	0.247	0.163	0.501	0.270	27.32	155	0.23	2.6	27.22
HD 34085	0.25	154.0	138.5	0.176	0.180	0.500	0.280	27.11	155	0.23	2.6	27.22

Comparison with values from previous works

Comparison of terminal velocities and mass loss rates as a function of effective temperature.



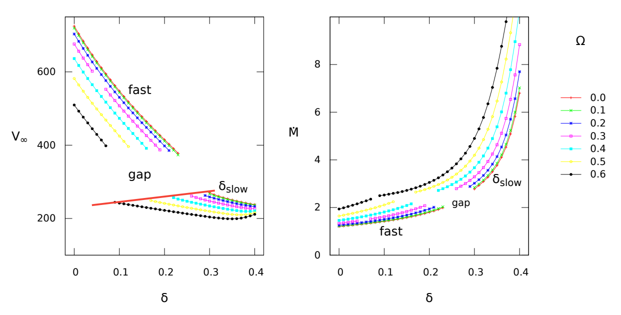


Models & UV points were taken from literature.

- Generally, the $\delta_{\rm slow}$ solution yields the lowest values for the wind parameters.
- The *fast* solution provides values greater than those predicted by the β law.
- The measured values of v_∞ (UV) exceed those obtained by all models.

Solution domains in δ and Ω space

Upper limit for terminal velocities in the δ-slow solution



The existance of a **gap** between *fast* and δ_{slow} solutions, puts an upper limit on the terminal velocities of the δ_{slow} solution.

Conclusions

Domains of hydrodynamic solutions

- We determined the domains of hydrodynamic solutions. The *fast* and $\delta_{\rm slow}$ regimes are separated by a gap where no stationary solutions were found using the available codes.
- Rotation affects the distribution of domains.

Line profiles

- For the first time, we have fitted synthetic line profiles computed with the hydrodynamic solution $\delta_{\rm slow}$ to observed ones for B supergiant stars.
- Hα line profiles can be fitted with both *fast* and $\delta_{\rm slow}$ models.
- The $\delta_{\rm slow}$ solution could be suitable for modeling the winds of certain B supergiants.
- However, this solution is constrained by the maximum terminal velocity. Consequently, it cannot account for the measured (or estimated) v_∞ values in the UV for B supergiants.

Future work

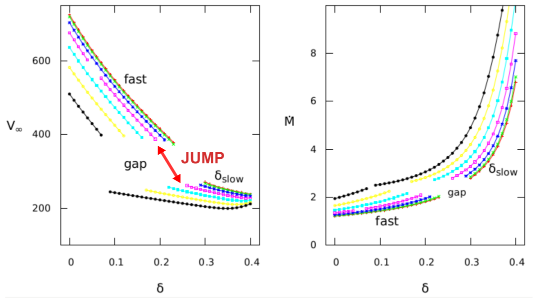
- Hα may not be the most suitable line for determining the most appropriate wind regime. A multiwavelength analysis is required.
- This study analyzed only 12 stars. A larger sample is needed.
- Since the only hypergiant B in the sample was fitted exclusively with the $\delta_{\rm slow}$ solution, a sample of hypergiants B should be studied.

Discussion

The gap and the variability

- A change in wind regime can occur as a result of variations in δ.
- A higher rotational rate Ω reduces the required change in δ to transition between regimes.
- Could these changes in regime be due to binaries or stellar pulsations?

Jumping the gap

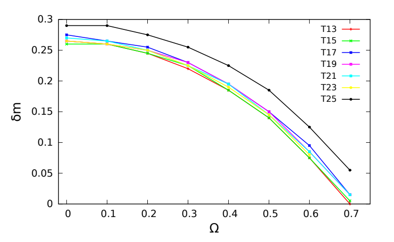



Muito Obrigado!

The End

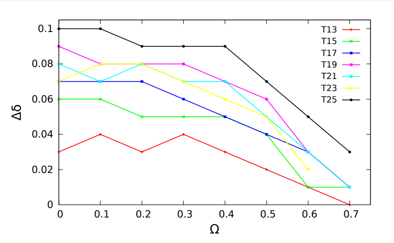
Gap Properties

Gap location



- δ_m represents the average value of δ across the edges of the gap.
- The location of the gap is almost independent of $T_{\rm eff}$.
- For B supergiants exhibiting higher rotation rates, the gap is located at small values of δ .

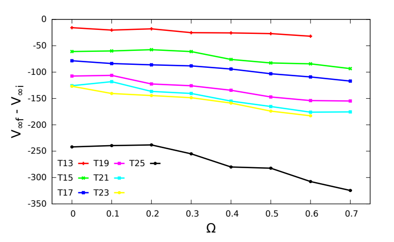
Gap width



- $\Delta\delta$ is the width of the gap in δ values.
- The width decreases as Ω increases.
- Gaps are narrower in models with lower $T_{\rm eff}$.

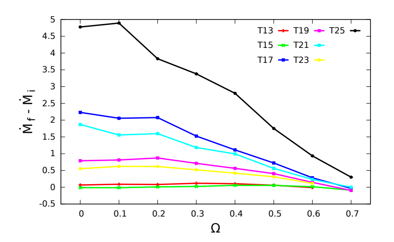
Gap Properties

Jump in v_∞



- There is little to no change in v_∞ for low T_{eff}.
- The jump increases in magnitude for faster rotators.

Jump in $\dot{M}$



- The jump in $\dot{M}$ is smaller for larger rotators.
- $\dot{M}$ can double its value if changes in δ result in crossing the gap.

Interaction between k and δ, and the wind parameters

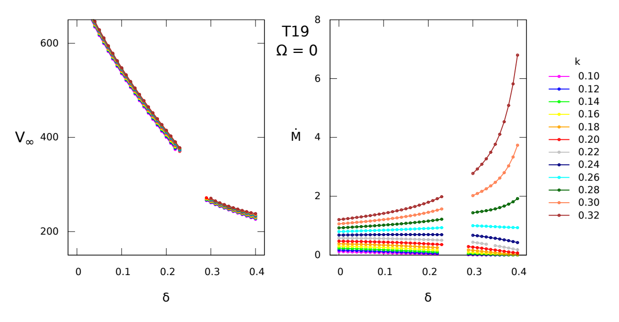
Model T19

$\alpha = 0.5$
$\Omega = 0$

The value of v_∞ remains unchanged when different values of k are considered.

There is no change in the position or width of the gap (in δ space).

Dependence of solutions on the parameter k

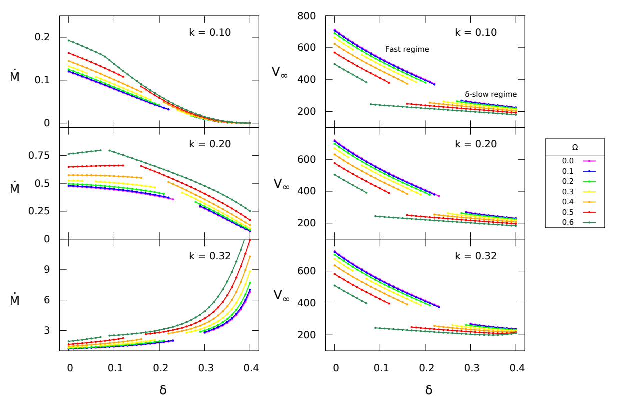


Interaction between k and δ, and the wind parameters

Model T19

The change in the slope of $\dot{M}$ as a function of $\delta_{\rm slow}$ for $k = 0.1$, 0.2, and 0.32. In contrast, the slope in v_∞ does not change.

Dependence of solutions on the parameter k



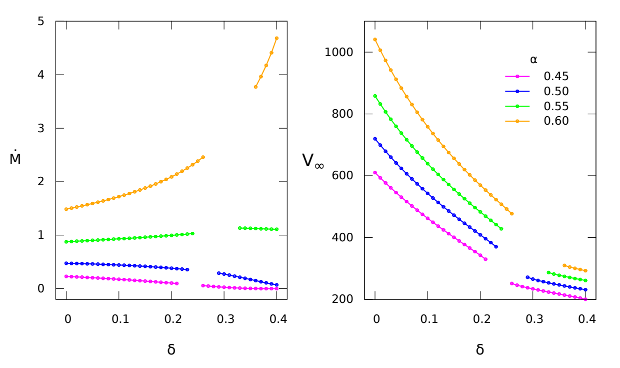
Interaction between α and δ, and the wind parameters

Model T19

In contrast to the parameter k, α completely modifies the terminal velocities.

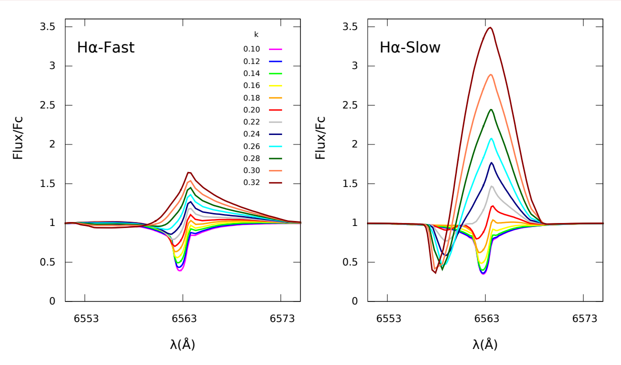
$\dot{M}$ is also highly sensitive to this parameter.

Changing the value of α also alters the gap in δ.



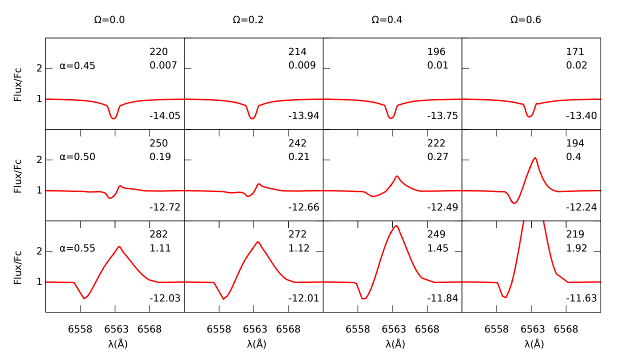
Hα line profiles

Hα line dependence on the parameter k



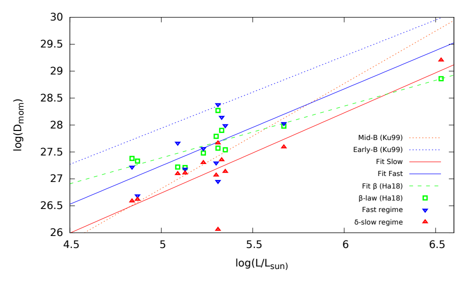
Hα line profiles

Hα line dependence on the parameter α



Discussion

Wind momentum - Luminosity relation



- The WLR based on the $\delta_{\rm slow}$ solution models is close to the empirical behaviour of the mid-B supergiants (Kudritzki+,1999).
- The WLR based on the *fast* solution is in better agreement with the results from Haucke+(2018) using a β-law.
- Both relations show a considerable dispersion.

Linear regressions

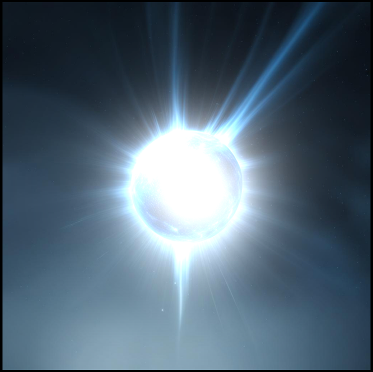
$\delta_{\rm slow}$ regime

$$\log\ D_{\rm mom} = 1{,}48\ \log\ L/L_{\odot} + 19{,}30$$

fast regime

$$\log\ D_{\rm mom} = 1{,}43\ \log\ L/L_{\odot} + 20{,}11$$

Stellar winds from B supergiant stars: Exploring the δ-slow hydrodynamic solution



Roberto O. J. Venero

IALP (CONICET-UNLP) - FCAG (UNLP) - Argentina

B-type supergiant stars are a heterogeneous group of objects with strong stellar winds. The hydrodynamic equations for rotating radiation-driven winds predict three kinds of solutions. In this presentation, we evaluate the "δ-slow" solution for the first time, in predicting the Hα line profile for B supergiants.

The observed Hα line can be reproduced by both "fast" and "δ-slow" hydrodynamic wind regimes with similar precision. These findings raise a dichotomy, because mass-loss rates and terminal velocities for each solution are quite different.

However, the "δ-slow" solution predicts maximum values for v_∞ that are systematically lower than those measured in the ultraviolet. Multiwavelength analyses and a larger sample of stars are needed to reach a definitive conclusion.