Self-consistent formulae for theoretical mass-loss rate and terminal velocity of O stars

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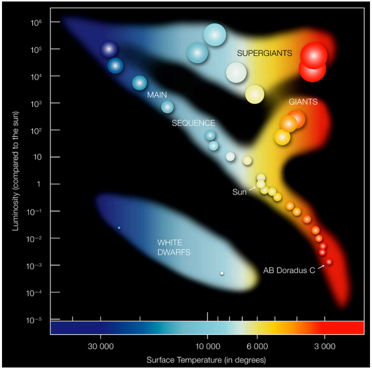
Introduction

What are massive stars?

Massive stars are stars with a mass typically higher than $8 - 10\ M_{\odot}$. Because of this, the physical characteristics of these stars present some of the most extreme conditions in the universe.

Due to the properties of these stars, we can observe:

- Rapid and extreme stellar evolution.
- **Strong winds** and mass-loss rates. ($\sim 10^{-6}\ M_{\odot}$ yr^{-1}).
- Terminal velocities between. $500 - 3000\ km\ s^{-1}$.



https://www.eso.org/public/images/eso0728c/

How can we describe the wind?

For a line-driven stellar wind, the m-CAK theory (Castor et al. 1975, Pauldrach et al. 1986, Friend & Abbot 1986) provides us of two main equations:

Equation of Momentum

$$v\frac{dv}{dr} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{GM_*(1-\Gamma_e)}{r^2} + g_{\text{line}} \tag{1}$$

Equation of Continuity

$$\dot{M} = 4\pi\rho(r)r^2v(r) \tag{2}$$

How can we describe the wind?

From Eq. (1), we can compute the line acceleration in terms of the electron scattering acceleration:

$$\frac{g_{\text{line}}}{g_{\text{es}}} = \mathscr{M}(t) = \sum_{\text{lines}} \Delta\nu_D \frac{F_\nu}{F} \frac{1 - e^{-\eta_{\text{line}} t}}{t} \tag{3}$$

where t is the optical depth for a moving medium: $t = \sigma_e \rho(r) v_{th} (dv/dr)^{-1}$. The force multiplier $\mathscr{M}(t)$ can be modeled as a power-law approximation:

$$\mathscr{M}(t) = k t^{-\alpha} \left(\frac{N_e \times 10^{11}}{W(r)} \right)^{\delta} \tag{4}$$

Therefore

$$(T_{\text{eff}}, \log g, R_*) \,\&\, (k, \alpha, \delta) \longrightarrow (\dot{M}, v_\infty) \tag{5}$$

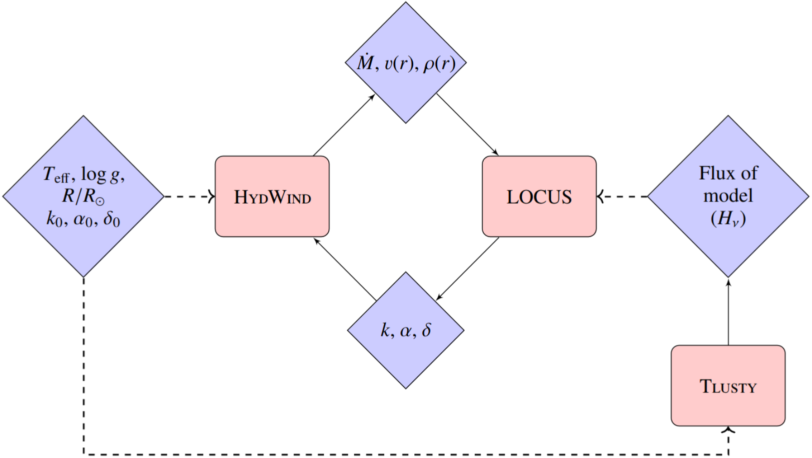
Method & Procedure

The m-CAK Procedure

First used in Gormaz-Matamala et al. (2019). Combines two codes to converge hydrodynamical solutions.

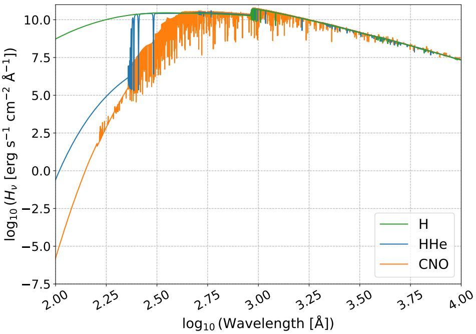
1. HydWind (Curé 2004): Code that solves the m-CAK equations providing a hydrodynamical profile from the stellar and line-force parameters, instead of approximating with β–law.
2. LOCUS (Gormaz-Matamala et al. 2019): Code that computes the force-multiplier from a hydrodynamical profile, providing the line-force parameters from a linear fitting of $\mathscr{M}(t)$.

The m-CAK Procedure



Our motivation: How to obtain a description of $\dot{M}$ & v_∞?

- Our main goal is to quantify the change of mass-loss rate and terminal velocity throughout the number of elements in $\mathscr{M}(t)$.
- As the number of lines increases, the total flux of the stellar atmosphere will be diminished.
- We converged several hundred models for three different grids: H, H-He, & H-He-C-N-O.



Results

Number of Models

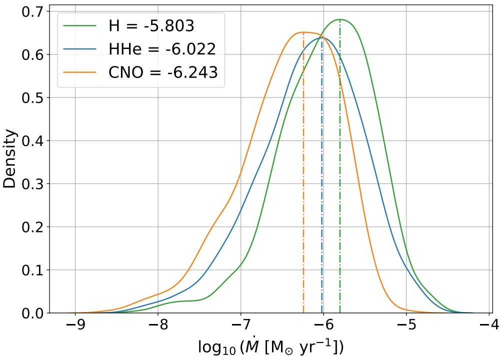
The converged models can be seen in the table below. Each one of them, fulfilled the following conditions:

- $T_{\rm eff} = 30000 - 50000$ K, each 1000 K
- $\log g = 2.9 - 4.3$ dex, each 0.1 dex
- $R_* = 7 - 70\ R_\odot$, each $1.5\ R_\odot$
- No rotation
- Solar abundance

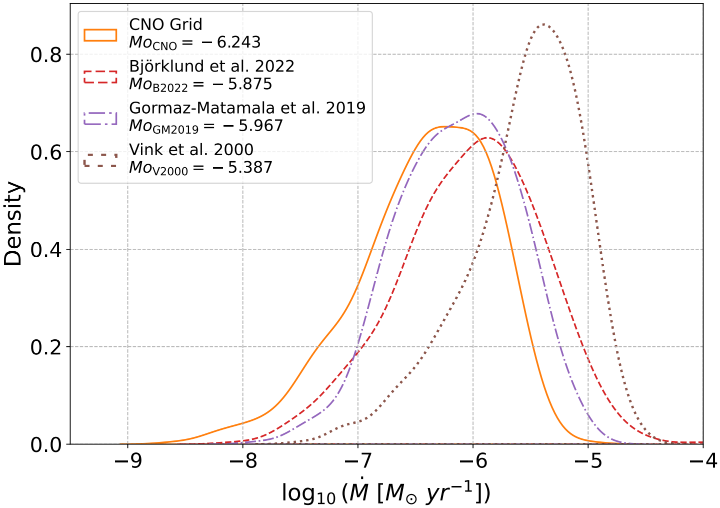
Grid	Chemical Composition	Number of Models
H	H	911
HHe	H-He	913
CNO	H-He-C-N-O	617

Distribution of $\dot{M}$

- Along the number of elements increases, the mass-loss rate shifts to lower values.
- Higher-value mass-loss rates will be less common, where CNO have almost no models with $\dot{M} \sim 10^{-4}$.
- An excess on lower values will appear, becoming an explanation for *weak winds*.



How different is our sample from other works?



Recipe for $\dot{M}$

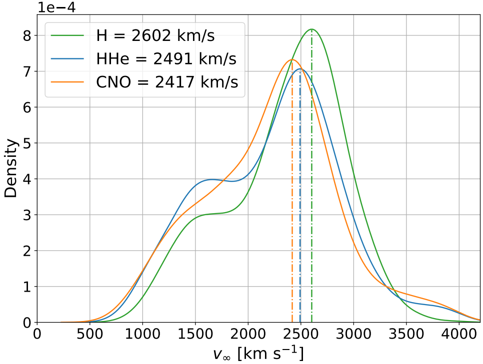
For each different grid, a linear bayesian fitting was made using a modified form of Gormaz-Matamala et al. (2019). The general formula for our recipes can be written as:

$$\log \dot{M} = A \cdot \log\left(\frac{T_{\text{eff}}}{1000\ \text{K}}\right) + B \cdot \log g + C \cdot \log\left(\frac{R_*}{R_\odot}\right) + D \quad (6)$$

We obtained three sets of adjusted parameters using the converged models of our grids. The table below shows the results:

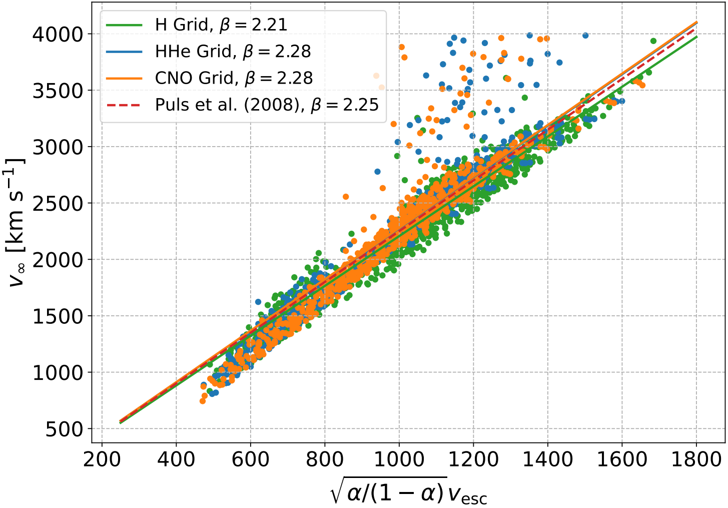
Grid	A	B	C	D	R^2
H	8.86 (±0.09)	-1.66 (±0.05)	1.82 (±0.05)	-16.2 (±0.09)	0.9486
HHe	12.6 (±0.17)	-2.23 (±0.05)	1.75 (±0.04)	-20.3 (±0.18)	0.9734
CNO	13.2 (±0.25)	-2.25 (±0.07)	1.78 (±0.05)	-21.3 (±0.24)	0.8893

Distribution of v_∞



- In contrast with the mass-loss rate, the distribution of terminal velocity doesn't have a significant shifting.
- Our results show an unusual and asymmetrical distribution compared with the mass-loss rate.

Distribution of v_∞



Recipe for v_∞

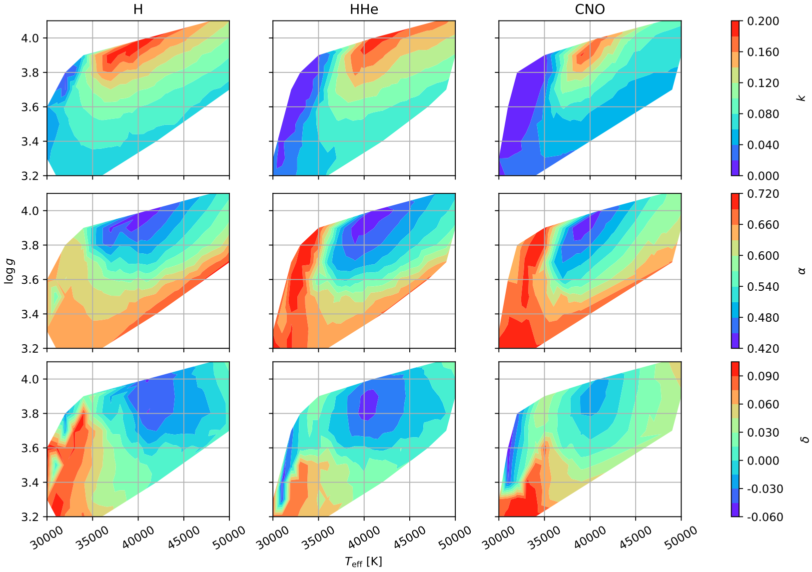
The process of the mass-loss rate fitting was repeated for the terminal velocity. We want to describe the wind in terms of stellar parameters.

$$\log v_\infty = A \cdot \log\left(\frac{T_{\rm eff}}{1000\ \rm K}\right) + B \cdot \log g + C \cdot \log\left(\frac{R_*}{R_\odot}\right) + D \tag{7}$$

Here we also obtained three sets of adjusted parameters, one for each grid. The table below shows the results:

Grid	A	B	C	D	R^2
H	-0.81 (±0.06)	0.58 (±0.02)	0.58 (±0.02)	1.81 (±0.08)	0.8838
HHe	-1.93 (±0.09)	0.76 (±0.02)	0.57 (±0.02)	2.96 (±0.10)	0.8405
CNO	-1.23 (±0.13)	0.62 (±0.03)	0.56 (±0.03)	2.33 (±0.14)	0.7457

Mapping of the Line-Force Parameters



Conclusions & Future Work

Conclusion

- Mass-loss rate is greatly affected by the number of elements. Along the number of lines increases, the estimation of the mass-loss rate will decrease, going to more realistic results.
- Our mass-loss distributions can show an excess on lower values, where the weak winds locate. This could explain the formation of this phenomenon.
- The terminal velocity, compared with the mass-loss rate, shows an asymmetric distribution. Nevertheless, the adjusted parameters show very good correlation.
- Because of the number of converged models, we could map the distribution of line-force parameters in the $T_{\rm eff} - \log g$ diagram, where there is a specific zone with negative δ values.

Future Work

- The number of lines' effect is shown to be significant, yet we only used CNO elements. We are currently working on the use of the OSTAR2002 Grid by Lanz & Hubeny (2003). This will change the values of the mass-loss rate and show the effect of **metallicity**.
- Because of the range of temperature, we can't use the descriptions for B or A-type stars. We have planned to expand this study for **lower** temperatures between $20 - 30$ kK (B-type stars).

¡Muchas gracias por la atención!

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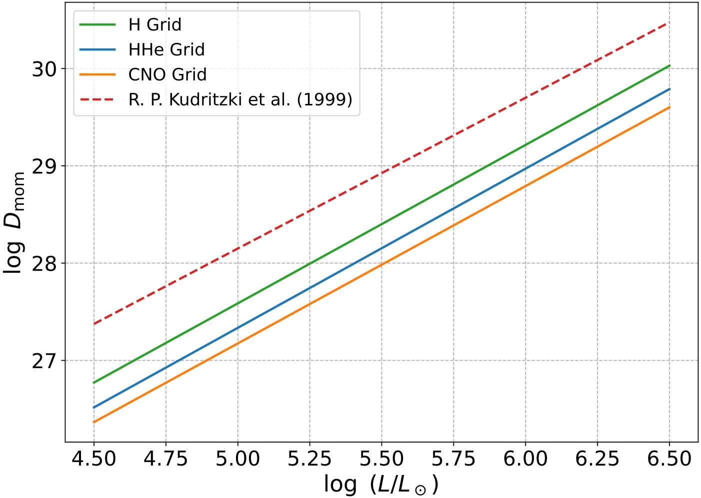
1. We developed three self-consistent grids for this work, changing the number of elements used in the stellar atmosphere models (H, H-He, & H-He-C-N-O).
2. The grids converged several hundred models, with self-consistent parameters of the wind (k, α, δ, $\dot{M}$, $v(r)$ & $\rho(r)$).
3. We accomplished the description of both the mass-loss rate and the terminal velocity of the wind using only the stellar parameters. These results were obtained with a high R^2 value and were consistent with the literature.
4. Additionally, we recovered the approximation from Puls et al. (2008) for the terminal velocity and the escape velocity, providing a good validation for our models.
5. Finally, we were able to map the line-force parameters in the $T_{\rm eff} - \log g$ diagram, showing different zones of interest where the values of k, α and δ take extreme conditions.

Calibration of the Wind Momentum - Luminosity Relationship



Calibration of the Wind Momentum - Luminosity Relationship

Because of the lower values of mass-loss rates, the WLR is affected by shifting to lower values in $\log D_0$, but mantaining the slope.

Grid	$\log D_0$	x	α_{eff}	R^2
H	19.4 ($\pm$0.12)	1.63 ($\pm$0.02)	0.614 ($\pm$0.008)	0.8761
HHe	19.2 ($\pm$0.12)	1.64 ($\pm$0.02)	0.611 ($\pm$0.007)	0.8790
CNO	19.1 ($\pm$0.14)	1.62 ($\pm$0.03)	0.618 ($\pm$0.008)	0.8761
Kudritzki et al. (1999)	20.4 ($\pm$0.85)	1.55 ($\pm$0.15)	0.65 ($\pm$0.06)	–