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Hot star wind mass-loss rate predictions at low metallicity

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Abstract. Hot star winds are driven by the radiative force due to light absorption in lines of heavier elements. Therefore, the amount of mass lost by the star per unit of time, i.e., the mass-loss rate, is sensitive to metallicity. We provide mass-loss rate predictions for O stars with mass fraction of heavier elements $0.2 < Z/Z_\odot \leqslant 1$. Our predictions are based on global model atmospheres. The models allow us to predict wind terminal velocity and the mass-loss rate just from basic global stellar parameters. We provide a formula that fits the mass-loss rate predicted by our models as a function of stellar luminosity and metallicity. On average, the mass-loss rate scales with metallicity as $(Z/Z_\odot)^{0.59}$. The predicted mass-loss rates agree with mass-loss rates derived from ultraviolet wind line profiles. At low metallicity, the rotational mixing affects the wind mass-loss rates. We study the influence of magnetic line blanketing.

Keywords. Stars: winds, outflows, stars: mass-loss, stars: early-type, Magellanic Clouds, hydrodynamics, radiative transfer

1. METUJE global models

METUJE is a computer code for solution of hydrodynamic equations for stellar wind together with NLTE rate equations and consistent calculation of the radiation driving force. METUJE models predict wind structure from the basic stellar parameters, that is, the effective temperature, mass, radius, and metallicity. The model assumptions are decribed by Krtička & Kubát (2017) in detail:

- spherical symmetry, stationarity,
- stellar photosphere and wind treated in a global (unified) manner,
- we solve the same equations in the photosphere and in the wind,
- radiative transfer solved using the comoving-frame (CMF) radiative transfer equation taking into account transitions relevant in hot stars,
- ionization and excitation state derived from the statistical (kinetic) equilibrium (NLTE) equations using atomic data mostly from the Opacity and Iron Projects,
- bound-free radiative rates in NLTE equations derived from the CMF radiative field and bound-bound rates derived using Sobolev approximation,
- the line radiative force based on the solution of the CMF radiative transfer equation,
- the condition of radiative equilibrium used to derive the temperature in the photosphere, while the radiative cooling and heating terms derived using the electron thermal balance method (see Kubát *et al.* 1999) in the wind,
- the equations of continuity, motion, and energy are solved iteratively to obtain the photosphere and wind density, velocity, and temperature structure,
- the key output parameters are the wind mass-loss rate $\dot{M}$, terminal velocity v_∞, and emergent flux H_ν.

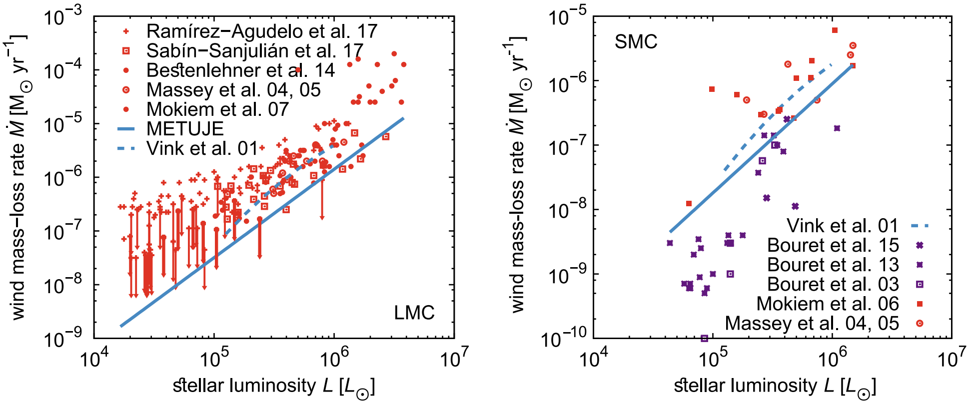

Figure 1. Dependence of mass-loss rates on the stellar luminosity for LMC and SMC stars. The predicted mass-loss rates are denoted using a blue line, the observational results corrected for clumping with violet symbols, and Hα mass-loss rates with red symbols.

2. Adopted model stars

We calculated a grid of global wind models for stellar parameters corresponding to O stars in the effective temperature range 30 000 − 45 000 K. Stellar masses and radii were derived using relations of Martins *et al.* (2005) for main sequence stars, giants, and supergiants. We calculated wind models for three different metallicities, corresponding to our Galaxy (with solar mass fraction of heavier elements, $Z = Z_\odot$), Large Magellanic Cloud (LMC, $Z = 0.5\,Z_\odot$), and Small Magellanic Cloud (SMC, $Z = 0.2\,Z_\odot$). The solar abundances were taken from Asplund *et al.* (2009).

3. Mass-loss rates: prediction

The predicted mass-loss rates can be fitted as a function of stellar luminosity L and mass-fraction of heavier elements Z as (for details see Krtička & Kubát 2018)

$$\log\left(\frac{\dot{M}}{1\,\mathrm{M}_\odot/\mathrm{yr}}\right) = -5.70 + 0.50\log\left(\frac{Z}{Z_\odot}\right) + \left[1.61 - 0.12\log\left(\frac{Z}{Z_\odot}\right)\right]\log\left(\frac{L}{10^6 L_\odot}\right). \tag{3.1}$$

From this equation it follows that with decreasing metallicity not only does the mass-loss rate decrease due to weaker line force, but also the luminosity dependence becomes steeper. The steeper luminosity dependence at low metallicity is caused by weaker blocking of the flux by the wind, especially for frequencies $\nu \gtrsim 7\times10^{15}\,\mathrm{s}^{-1}$. The average metallicity dependence predicted by our models $\dot{M} \sim Z^{0.59}$ is less steep than that derived by Vink *et al.* (2001) because the wind blanketing effect is weaker at low metallicity.

4. Mass-loss rates: observations

The predicted mass-loss rates in Fig. 1 agree with observational results corrected for clumping. Stars with a low luminosity ($L < 2\times10^5\,L_\odot$) show too low mass-loss rates in comparison with theory (this is so-called weak wind problem (e.g. Bouret *et al.* 2015). The clumping factor of $C_\mathrm{c} = 8 - 9$ is needed to reconcile the Hα mass-loss rates with theoretical predictions. Our estimates are by a factor of $2 - 5$ lower than the predictions of Vink *et al.* (2001). The main reasons for the difference are a more precise calculation of the radiative force in the CMF and the blocking of the radiative flux for $\nu \gtrsim 7\times10^{15}\,\mathrm{s}^{-1}$ in global models.

5. Magnetic line blanketing

Fraction of hot stars posses strong magnetic fields that channel their radiatively driven outflows. We studied the influence of line splitting in the magnetic field (Zeeman effect) on the wind properties. For typical magnetic field strengths found on the surfaces of hot stars (of order of few tens of kilogauss) the magnetic splitting is weaker than the thermal line broadening. As a result of this, the Zeeman splitting has a negligible influence on the line force and therefore on the wind mass-loss rates and terminal velocities. Neither we have found any strong influence of Zeeman splitting on the emergent fluxes. Therefore, the rotationally modulated flux variability due to the magnetic line blanketing is very weak (of the order of 10^{-4} mag).

6. Rotational mixing

The rotational mixing brings CNO-cycle processed material to the stellar surface. This affects the mass-loss rates because the radiative force depends on the abundance of individual elements. For a mass-fraction of heavier elements $Z/Z_\odot \gtrsim 0.1$ the change of chemical composition does not significantly affect the wind mass-loss rates. However, for a very low-mass fraction of heavier elements $Z/Z_\odot \lesssim 0.1$ the rotational mixing significantly affects the wind mass-loss rates (for details see Krtička & Kubát 2014).

7. Conclusions

We describe results of our hydrodynamical hot star wind code which provide consistent wind models suitable for quantitative study of stars at low metallicity.

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