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MASS-LOSS RATES OF HOT STARS

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Abstract. Methods of hot star mass-loss rates determination based on observations in ultraviolet, visual, infrared, and radio spectral regions are discussed and compared with values theoretically predicted by hydrodynamical calculations. The effect of wind inhomogeneities (clumping) on line formation calculations is discussed.

1. Introduction

In this paper we concentrate on O-type stars (with $T_{\rm eff} \gtrsim 30000\,{\rm K}$). These stars are luminous ($L \gtrsim 10^6\,{\rm L}_\odot$), massive ($M \gtrsim 8\,{\rm M}_\odot$), they live very shortly (about 10^6 years), and they end their lifes as supernova explosions. They are relatively rare, and they form only a small fraction of the stellar population. Hot stars may be seen even at large distances. They heat-up and ionize their surroundings, and enrich the interstellar medium with heavier elements (metals). They also provide kinetic energy to the interstellar medium via stellar winds and at the end of their existence via supernovae explosions. They also trigger, regulate and terminate star formation in stellar clusters (see, e.g., Cesaroni 2005, Bresolin 2008, and references therein).

The stellar wind is an outflow of material from the stellar surface. The rate at which the mass is being lost (the mass-loss rate, $\mathrm{d}M/\mathrm{d}t$) may reach values up to about $10^6\,{\rm M}_\odot\,{\rm year}^{-1}$. The wind terminal velocities can be up to about $3000\,{\rm km\,s}^{-1}$. The outflow from hot stars is accelerated by radiation, which interacts with the wind matter. Although the continuum opacity (electron scattering, bound-free and free-free) can supply a significant amount of momentum from radiation to the wind, it is not sufficient to drive the wind. One has to add the line opacity (dominantly by resonance lines of metals) to obtain radiation force which is able to overcome the gravity. Since the radiation force acting on hydrogen and helium is very small, necessary momentum is transferred from metals to hydrogen and helium by Coulomb collisions (see Krtička & Kubát 2007).

The most important quantity describing the wind is its mass-loss rate. It can be determined using observational data, however in combination with the theoretical background and sophisticated modelling.

2. Wind hydrodynamical models

Hydrodynamical models of the wind are usually calculated using several restricting assumptions. The models are assumed to be stationary, homogeneous, and spherically symmetric. This means that all variables depend only on the radius r. To calculate a hydrodynamical model of the stellar wind, one has to solve the continuity equation (which determines the density structure $\rho(r)$), the equation of motion (which determines the wind velocity $v(r)$), and the energy equation (determining the temperature structure $T(r)$). The radiation field has crucial influence on the wind structure and dynamics. The accelerating force caused by radiation in wind hydrodynamical models can be expressed as

$$g_{\mathrm{rad}} = \frac{\pi}{c\rho} \int_0^\infty \chi(\nu) F(\nu)\,\mathrm{d}\nu. \tag{1}$$

To evaluate this force, it is necessary to know the radiation flux $F(\nu)$ and the opacity $\chi(\nu)$ for all frequencies. To simplify the problem, the so-called force multipliers k, α, and δ (Castor, Abbott, & Klein 1975; Abbott 1982) can be used for evaluation of the radiative force. These free parameters have a physical interpretation, namely δ reflects the ionization balance, α corresponds to line distribution, and k describes the line strength.

Although many successful models have been calculated using this CAK approximation, detailed calculations of the radiative force are now available and should be preferred. To calculate opacities in detail, it is necessary to know correct (i.e. NLTE) atomic level populations of dominant absorbing ions causing the wind acceleration. Detailed calculations of the radiative force using NLTE occupation numbers have been done using the Monte Carlo method (Vink et al., 1999) or using detailed treatment of the equations of statistical equilibrium (Krtička & Kubát 2004), who included this evaluation of the radiative force into the construction of hydrodynamical wind models. In the latter method, the global stellar parameters are used as an input to the wind hydrodynamical models, namely the stellar radius (R_*), the stellar mass (M_*), the stellar luminosity (L_*), and the chemical composition of the star. Additional necessary input is the radiation flux $F(\nu)$ at the lower wind boundary, which is usually taken from some static photosphere model or it is simply assumed to have a blackbody distribution. The latter option is, however, not too exact.

After solving the hydrodynamic equations we obtain the hydrodynamic wind model. The output from the calculations is the velocity structure $v(r)$, density structure $\rho(r)$, and temperature structure $T(r)$. This solution also gives basic global wind parameters. From the velocity profile we may determine the terminal wind velocity v_∞, which can then be measured from P-Cygni type profiles, and in combination with the density structure we can determine the mass-loss rate $\mathrm{d}M/\mathrm{d}t = \dot{M}$.

The radiative transfer in lines is solved using the Sobolev approximation in this method, while the continuum radiative transfer may be treated as in the static case. The method has been recently upgraded and the region close to the star is treated without assuming the Sobolev approximation, instead the so-called comoving frame method is used (see Krtička & Kubát 2010).

3. Mass-loss rate determination

The common way to determine mass-loss rates from observations is to use the fit of selected observed spectral features with the model prediction. The process is such that for *given* $v(r)$ and $\rho(r)$ (consequently $\mathrm{d}M/\mathrm{d}t$ and v_∞) we determine the emergent radiation, which is then compared with observations. Results of hydrodynamical model calculations are the most suitable models for this task. However, the density and velocity structures are often determined using very simplified wind models. Usually, the velocity law $v(r)$ is not taken as a result of hydrodynamic calculations. Commonly a simplifying assumption of the so-called β-velocity law,

$$v = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta , \tag{2}$$

is used. The velocity law of this form was first formulated by Milne (1926) and Chandrasekhar (1934) with $\beta = 0.5$.

Several different spectral regions are being used for mass-loss rate determination. Each of them has its strenghts, but also weaknesses.

Radio measurements Using radio emission is considered as the most reliable method for mass-loss rate measurements. It is based on detection of radiation coming from the outermost parts of the wind, where the wind velocity is nearly v_∞, i.e. it is almost constant. The outer wind is assumed to be spherically symmetric, fully ionized, and in local thermodynamic equilibrium. The dominant source of radiation at radio wavelengths in this region is the free-free emission, which is of a thermal origin. Consequently, the assumption of the local thermodynamic equilibrium is valid for this process. These assumptions allow to derive a simple expression of a mass-loss rate depending on the terminal wind velocity, measured radio flux, and the stellar distance (see Panagia & Felli 1975; Wright & Barlow 1975). Since the distance of the stars has to be known, this type of mass-loss rate determination is restricted to closest stars. Unfortunately, the radio radiation from hot stars is usually very weak, so we are restricted only to the brightest objects. In addition, the method gives reliable results if the radio radiation is thermal. The possible influence of non-thermal radio radiation may complicate situation.

Hα line profiles Contrary to radio radiation, the Hα emission originates in inner regions of the wind. In this method, observed profiles of the hydrogen Hα line are compared with the theoretical ones. Then the mass-loss rate corresponding to the model with the best fit is called the *observed mass loss rate*.

The calculations are often based on sophisticated NLTE wind models, which determine actual level populations and emergent radiation for a given density and velocity structure. The velocity dependence is usually described using the simple β-velocity law (2) and the core-halo approximation is assumed. This approximation artificially separates the photosphere and the wind, the photospheric radiation enters the wind, but there is no influence from the wind on the photosphere. There exist several computer codes, which are able to solve the problem of line formation in the wind, namely the CMFGEN code (Hillier & Miller 1998), the WMBasic code (e.g. Pauldrach et al., 2003, and references therein), the FASTWIND code (Santolaya-Rey et al. 1997, Puls et al. 2005), and the PoWR code (e.g. Hamann & Gräfener 2004).

UV (resonance) line profiles Ultraviolet resonance lines may serve as a tool for determination of $\dot{M}q_i$, where q_i is the ionization fraction of the corresponding ion. If the ion is the dominant one (i.e. if the fraction is 1 or close to it), then the resonance lines give directly the mass-loss rate. However, the strongest ultraviolet resonance lines are often saturated. This happens, for example, for the case of C IV (1548, 1551 Å) or N V (1239, 1243 Å). In this case, these lines are almost insensitive to changes of $\dot{M}$, consequently they indicate only the lower limit of $\dot{M}$. On the other hand, the lines of less abundant elements are unsaturated, like it happens for the case of Si IV (1394, 1403 Å) or P V (1118, 1128 Å) resonance doublets. These lines are, consequently, more sensitive to changes of $\dot{M}q_i$, and may be used as useful mass-loss rates indicators. The importance of the P V resonance doublet 1118, 1128 Å was pointed out by Crowther et al. (2002). Careful analysis of a number of stars by Fullerton et al. (2006) resulted in disagreement between the derived mass-loss rates from the P V line and using other methods. It lead to a conclusion that either the P V mass-loss rates are wrong or the ionization fraction of P V is lower than 0.1. Subsequent NLTE calculations of Krtička & Kubát (2009, 2012) showed that the lower ionization fraction does not seem to be the solution to the disagreement, since neither additional X-ray nor XUV radiation are able to lower the ionization fraction of P V.

Comparison of measurement methods Different methods of mass-loss rate determination depend differently on the density. While the strength of the ultraviolet resonance lines depends linearly on the density, radio determinations are dependent on the square root of density (due to the collision nature of the free-free process). Since the Hα emission line is assumed to be formed predominantly by cascading of the atoms recombined to higher levels, the Hα diagnostics is also classified as density-squared dependent. All mass-loss rate determination methods should give the same result. However, different mass-loss diagnostics result in different mass-loss rates (e.g. Puls et al., 2008).

Comparison between observations and theory In addition to differences between mass-loss rates determined from different diagnostics tools, for some stars there is a significant difference between theoretical mass-loss rates (from hydrodynamical calculations) and those derived from observations. These stars are especially the cool O-type dwarfs, whose winds should be weaker than of hotter O-type stars, but they are even more weak than the mass-loss rates predicted from models. This is called the *"weak wind problem"*. This was demostrated by Bouret et al. (2003) and Martins et al. (2004) for the case of several SMC O-type dwarfs, and by Martins et al. (2004) and Marcolino et al. (2009) for Galactic O-type dwarfs. The short history of the weak-wind problem was summarized by Puls et al. (2009). Selected weak wind stars are listed in the Table 1.

It is not clear what is the exact reason for the existence of the weak wind problem. Several processes were discussed by Martins et al. (2005) and summarized by Puls et al. (2009). However, our recent results (in progress) show that the most probable

Table 1: Mass loss rates for selected "weak wind stars". Observational mass-loss rates are from: B – Bouret et al. (2003), M – Martins et al. (2005), W – Marcolino et al. (2009). Errors of observational determinations are not listed. The column "pred." lists values of predicted mass-loss rates from the observational references, which were calculated after Vink et al. (2000, 2001). The column shows the mass-loss rates from hydrodynamical calculations using the NLTE wind code by Krtička & Kubát (2004): K – Krtička (2006), X – Krtička & Kubát (2009).

star	$T_{\rm eff}$ [kK]	$\log g$ [g·cm^{-2}]	$\dot{M}$ [M$_\odot$ year^{-1}]				
			observations		pred.	hydro	
NGC 346 MPG 12	31	3.6	$1.0 \cdot 10^{-10}$	B	$4.0 \cdot 10^{-8}$	$1.7 \cdot 10^{-8}$	K
NGC 346 MPG 487	31	3.6	$3.0 \cdot 10^{-9}$	B	$7.9 \cdot 10^{-8}$	$3.0 \cdot 10^{-8}$	K
HD 326329	31	3.9	$6.0 \cdot 10^{-10}$	W	$4.2 \cdot 10^{-8}$		
HD 149757 (ζ Oph)	32	3.6	$1.6 \cdot 10^{-9}$	W	$1.3 \cdot 10^{-7}$	$4.7 \cdot 10^{-8}$	X
HD 34078 (AE Aur)	33	4.05	$3.2 \cdot 10^{-10}$	M	$4.2 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$	X
HD 38666 (μ Col)	33	4.0	$3.2 \cdot 10^{-10}$	M	$3.9 \cdot 10^{-8}$	$7.9 \cdot 10^{-9}$	X
HD 46202	33	4.0	$1.3 \cdot 10^{-9}$	M	$5.9 \cdot 10^{-8}$	$2.3 \cdot 10^{-8}$	X
HD 216532	33	3.7	$6.0 \cdot 10^{-10}$	W	$1.2 \cdot 10^{-7}$		
HD 93028	34	4.0	$1.0 \cdot 10^{-9}$	M	$1.3 \cdot 10^{-7}$		
HD 216898	34	4.0	$4.5 \cdot 10^{-10}$	W	$6.0 \cdot 10^{-8}$		
HD 66788	34	4.0	$1.2 \cdot 10^{-9}$	W	$1.1 \cdot 10^{-7}$		
HD 93146	37	4.0	$5.6 \cdot 10^{-8}$	M	$2.6 \cdot 10^{-7}$		
HD 42088	38	4.0	$1.0 \cdot 10^{-8}$	M	$6.8 \cdot 10^{-7}$	$3.1 \cdot 10^{-7}$	X
NGC 346 MPG 113	40	4.0	$3.0 \cdot 10^{-9}$	B	$1.3 \cdot 10^{-7}$	$4.8 \cdot 10^{-8}$	K

physical process, which could be able to correct the disagreement is wind clumping. Consequently, the most promising way to correct the disagreement is to include clumping into both line formation calculations and hydrodynamic wind models.

4. Clumping in stellar winds

It is highly probable that stellar winds are not smooth, but that they form various condensations at different scales. There is indeed some evidence of such clumping. Observations of Eversberg et al. (1998) repeatedly showed differently travelling bumps at a series of difference spectra of the bright O-type star ζ Pup. These spectra were obtained within two single subsequent nights. These travelling structures in the line profiles could be interpreted as a consequence of absorption in random small-scale structures in both density and velocity, which were moving in the wind. The theoretical evidence of clumping follows indirectly from 1-D radiative hydrodynamic simulations (see, e.g., Runacres & Owocki 2002). As a consequence of the radiative-acoustic instability, structures in radial velocity $v(r)$ and density $\rho(r)$ profiles occur. However, full 3-D hydrodynamical simulations are still missing, so we assume that the 1-D structures represent the way how real 3-D structures may develop and look like.

Although it is commonly accepted that the stellar winds are clumped, details of clumping (clump distribution, clump shapes, their density and velocity) are largely unknown. To include clumping in wind modelling, a description of clumps using adjustable parameters is used together with further simplifying assumptions.

In many NLTE wind codes, where the emergent radiation is consistently determined with the atomic level occupation numbers, clumping is treated using single free parameter. *All* wind matter is assumed to be concentrated in clumps (i.e. clumps are in vacuum). Then it is possible to introduce the (volume) filling factor as a ratio of the volume occupied by clumps V_{cl} and the total volume of the wind V_{wind},

$$f = \frac{V_{\mathrm{cl}}}{V_{\mathrm{wind}}}. \tag{3a}$$

Alternatively, clumping may be described using the clumping factor ($\langle\rho_{\mathrm{cl}}\rangle$ is the average density inside clumps and $\langle\rho_{\mathrm{wind}}\rangle$ is the average wind density)

$$D = \frac{\langle\rho_{\mathrm{cl}}\rangle}{\langle\rho_{\mathrm{wind}}\rangle} = \frac{1}{f}, \tag{3b}$$

which is the inverse of the volume filling factor[1]. In addition, *all* clumps are assumed to be optically thin. This approach is usually referred to as the *microclumping*. The assumption of optically thin clumps allows to express the opacity in the wind as

$$\chi = \frac{1}{D}\chi_{\mathrm{cl}} \tag{4}$$

where χ_{cl} is the opacity of the material in clumps. Since $\rho_{\mathrm{cl}} = D\rho_{\mathrm{wind}}$ (note that $D > 1$, since $\rho_{\mathrm{cl}} = D\rho_{\mathrm{wind}}$), the actual effect of clumping depends on the physical process. For processes with opacities proportional to the density ($\chi \sim \rho$), like, e.g.,

[1] Alternatively, the clumping factor is sometimes denoted as C_c or f_{cl}.

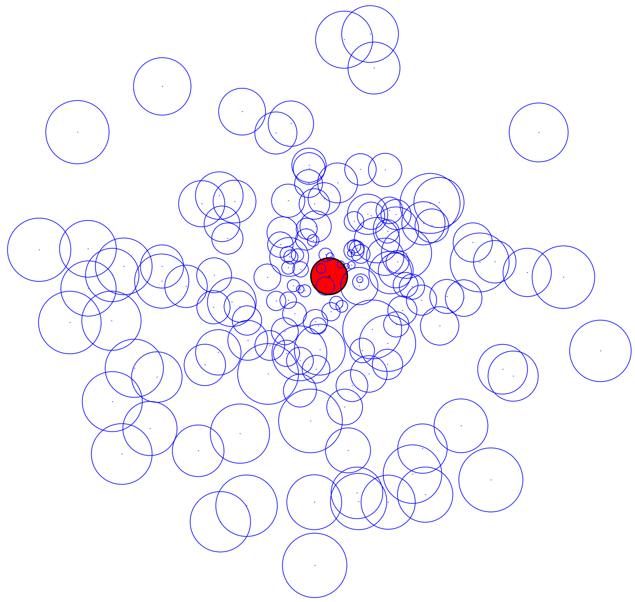

Figure 1: An example of wind clumping represented by randomly distributed spherical clumps. The picture was generated by a code developed by Šurlan (2012).

resonance line scattering, the opacity in the clumped wind is the same as in the smooth wind. For processes with opacities depending on the second power of density ($\chi \sim \rho^2$), like recombination or free-free transitions, the opacity is higher.

However, in reality we can not assume that all clumps are optically thin. Consequently, the influence of clumping can not be expressed as simply as in Equation (4). We have to take into account the fact that some clumps may be optically thick. This approach is referred to as the *macroclumping* (or porosity). Since the clumps may be optically thick in this approach, it may happen that they shield each other and, as a result, some matter is effectively excluded from the radiation-matter interaction. At the same time, more matter concentrated in clumps causes larger interclump medium (which is usually considered as void) and higher probablity that the photon does not interact with matter. The opacity dependence on the degree of clumping is more complicated and has to be taken into account in detail using multidimensional radiative transfer.

Modelling of wind clumping A method of handling macroclumping using a 3-D Monte Carlo radiative transfer code is described in Šurlan et al. (2012a). In this method several above mentioned assumptions are released. First, the optical thickness of clumps is calculated consistently based on the local clump density and its optical properties. Consequently, clumps may be optically thick, which allows to handle the above mentioned case of macroclumping. The interclump medium is allowed to be non-void, which is closer to reality. Clumps are assumed to have a spherical shape and they are distributed using the probability distribution derived from the velocity law. In the above mentioned paper pure resonance line scattering is taken into account. The transfer of radiation is solved using the Monte Carlo method. More details about this method may be found in Šurlan (2012) and Šurlan et al. (2012a).

Effect of the macroclumping on resonance line profiles Our results showed strong influence of the clumping factor on resulting line profiles. The profiles are shallower with higher clumping factor showing the effects of effective lowering opacity for optically thick clumps. Also velocity clumping (vorosity), non-void inter-clump medium, location of the onset of clumping influence the line profiles. All these effects influence the mass-loss rate determination based on such lines, as it was shown by Šurlan et al. (2012b).

5. Summary

Despite sophisticated theory of hot star winds, mass-loss rates are still not firmly determined. Multiwavelength observations are necessary for mass-loss rate determination. Line profiles in clumped wind strongly depend on clump properties. Observational study of clumping in bright stars winds is a suitable program for small class telescopes.

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References

Abbott, D. C. : 1982, *Astrophys. J.*, **259**, 282.
Bouret, J.-C., Lanz, T., Hillier, D. J., et al. : 2003, *Astrophys. J.* **592**, 1182.
Bresolin, F., Crowther, P. A., & Puls, J. (eds.) : 2008, *Massive Stars as Cosmic Engines, IAU Symposium* **250**, Cambridge University Press.
Castor, J. I., Abbott, D. C., & Klein, R. I. : 1975, *Astrophys. J.*, **195**, 157.
Cesaroni, R. : 2005, *Astrophys Space Sci.*, **295**, 5.
Chandrasekhar, S. : 1934, *Mon. Not. Roy. Astron. Soc.* **94**, 522.
Crowther, P. A., Hillier, D. J., Evans, C. J., et al. : 2002, *Astrophys. J.*, **579**, 774.
Eversberg, T., Lépine,S., Moffat, A.F.J.: 1998, *Astrophys. J.*, **494**, 799.
Fullerton, A. W., Massa, D. L., & Prinja, R. K. : 2006, *Astrophys. J.*, **637**, 1025.
Hamann, W.-R., & Gräfener, G. : 2004, *Astron. Astrophys.*, **427**, 69.
Hillier, D. J. & Miller, D. L. : 1998, *Astrophys. J.*, **496**, 407.
Krtička, J. : 2006, *Mon. Not. Roy. Astron. Soc.*, **367**, 1282.
Krtička, J., & Kubát, J. : 2004, *Astron. Astrophys.*, **417**, 1003.
Krtička, J., & Kubát, J. : 2007, *in Active OB-Stars: Laboratories for Stellar & Circumstellar Physics, eds. S. Štefl, S. P. Owocki, & A. T. Okazaki*, ASP Conf. Ser. **361**, p. 281.
Krtička, J., & Kubát, J. : 2009, *Mon. Not. Roy. Astron. Soc.*, **394**, 2065.
Krtička, J., & Kubát, J. : 2010, *Astron. Astrophys.*, **519**, A50.
Krtička, J., & Kubát, J. : 2012, *Mon. Not. Roy. Astron. Soc.*, **427**, 84.
Marcolino, W. L. F., Bouret, J.-C., & Martins, F., et al. : 2009, *Astron. Astrophys.*, **498**, 837.
Martins, F., Schaerer, D., Hillier, D. J., & Heydari-Malayeri, M. : 2004, *Astron. Astrophys.*, **420**, 1087.
Martins, F., Schaerer, D., Hillier, D. J., et al. : 2005, *Astron. Astrophys.*, **441**, 735.

Milne, E. A. : 1926, *Mon. Not. Roy. Astron. Soc.*, **86**, 459.
Panagia, N., & Felli, M. : 1975, *Astron. Astrophys.*, **39**, 1.
Pauldrach, A. W. A. : 2003, *Rev. Mod. Astron.*, **16**, 133.
Puls, J., Urbaneja, M. A., Venero, R. et al. : 2005, *Astron. Astrophys.*, **435**, 669.
Puls, J., Vink, J. S., & Najarro, F. : 2008, *Astron. Astrophys. Rev.*, **16**, 209.
Puls, J., Sundqvist, J. O., Najarro, F., & Hanson, M. M. : 2009, *in Recent Directions in Astrophysical Quantitative Spectroscopy and Radiation Hydrodynamics, I. Hubeny, J. M. Stone, K. MacGregor & K. Werner eds., AIP Conf. Proc.* **1171**, p. 123
Runacres, M. C., Owocki, S. P. : 2002, *Astron. Astrophys.*, **381**, 1015.
Santolaya-Rey, A. E., Puls, J., & Herrero, A. : 1997, *Astron. Astrophys.*, **323**, 488.
Šurlan, B. : 2012, PhD thesis, Univerzita Karlova Praha.
Šurlan, B., Hamann, W.-R., Kubát, J., Oskinova, L. M., & Feldmeier, A. : 2012a, *Astron. Astrophys.*, **541**, A37.
Šurlan, B., Hamann, W.-R., Kubát, J., Oskinova, L. M., & Feldmeier, A. : 2012b, *in Four Decades of Research on Massive Stars, eds. C. Robert, N. St-Louis & L. Drissen*, ASP Conf. Ser. **465**, 134.
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. : 1999, *Astron. Astrophys.*, **350**, 181.
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. : 2000, *Astron. Astrophys.*, **362**, 295.
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. : 2001, *Astron. Astrophys.*, **369**, 574.
Wright, A. E., Barlow, M. J. : 1975, *Mon. Not. Roy. Astron. Soc.*, **170**, 41.