METUJE global hot star wind models

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Abstract. We describe our own global (unified) hydrodynamical models of expanding atmospheres of hot stars. The models solve hydrodynamic equations, kinetic equilibrium equations (NLTE), and comoving-frame radiative transfer equation consistently from the (nearly) hydrostatic photosphere to the supersonic wind. The model input parameters are the stellar effective temperature, radius, mass, and abundances of individual elements. For these stellar parameters, our code predicts the photosphere and wind structure and in particular the wind mass-loss rate and terminal velocity. The photospheric emergent flux and thermal structure nicely agree with the TLUSTY model atmospheres.

1. Introduction

Stellar winds of hot stars are accelerated mostly due to absorption or scattering of light by line transitions of heavier elements and due to light scattering on free electrons (see Puls et al. 2008, for a review). Standard wind models use the so-called core-halo approximation, that is, they treat the stellar wind separately from the stellar photosphere and the influence of the stellar photosphere is taken into account only by means of a lower boundary condition for wind radiation transfer. More advanced wind models describe both the supersonic wind and nearly hydrostatic photosphere in a global (unified) manner, i.e., they account also for the influence of the radiation scattered backwards from the stellar wind to the stellar atmosphere (Hillier & Miller 1998; Puls et al. 2005; Sander et al. 2017; see also the discussion by Sander et al. 2015). We describe our METUJE global wind models that heavily rely on numerous atomic data for the calculation of the radiative force and for the solution of the kinetic equilibrium (NLTE) equations (Krtička & Kubát 2017).

2. METUJE global wind models

Our models (Krtička & Kubát 2017) predict the wind structure from basic stellar parameters by iteration of structural equations (see Figure 1). The input parameters are the stellar effective temperature (i.e. luminosity), mass, radius, and abundances of individual elements. The models are assumed to be stationary and spherically symmetric. The stellar photosphere and the stellar wind are treated in a global (unified) manner, which means that we solve the same equations in the photosphere and in the wind. The radiative transfer equation is solved in the comoving frame (CMF). The ionization and excitation state is derived from the kinetic equilibrium (NLTE) equations. The radiative force which accelerates the wind is calculated using the flux calculated by the solution of the CMF radiative transfer equation. The temperature is derived using the condition of radiative equilibrium in the photosphere, while in the wind the electron thermal balance method is used. The equations of continuity, motion, and energy are solved iteratively to obtain the photosphere and wind density, velocity, and temperature structure. The most important output parameters are the wind mass-loss rate $\dot{M}$, the terminal wind velocity v_∞, and the emergent flux H_ν.

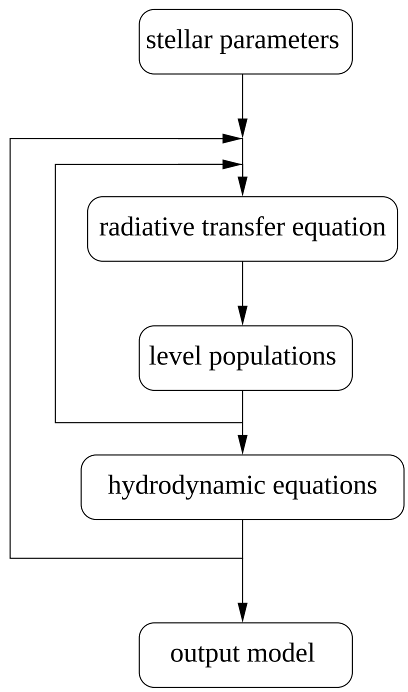

Figure 1. Procedure of the wind model calculation

3. CMF radiative transfer

The radiative transfer equation in lines is solved in the comoving-frame (Hubeny & Mihalas 2014)

$$\mu\frac{\partial I(\nu,r,\mu)}{\partial r}+\frac{1-\mu^2}{r}\frac{\partial I(\nu,r,\mu)}{\partial\mu}-\frac{\nu v_r}{cr}\left(1-\mu^2+\mu^2\frac{r}{v_r}\frac{\mathrm{d}v_r}{\mathrm{d}r}\right)\frac{\partial I(\nu,r,\mu)}{\partial\nu}$$
$$=\eta(\nu,r)-\chi(\nu,r)I(\nu,r,\mu). \quad (1)$$

Here $I(\nu,r,\mu)$ is the specific intensity of radiation, $\eta(\nu,r)$ is the emissivity, and $\chi(\nu,r)$ is the absorption coefficient. The CMF radiative transfer equation is solved numerically after Mihalas et al. (1975) with all relevant bound-bound (from VALD line list, Kupka et al. 1999), bound-free, and free-free transitions. The CMF specific intensity is used to derive the radiative force

$$f_{\mathrm{rad}} = \frac{1}{c}\int_0^\infty \chi(\nu,r)F(\nu,r)\,\mathrm{d}\nu,$$

the bound-free radiative rates in NLTE equations, and the radiative field for the calculation of temperature.

4. Kinetic equilibrium (NLTE)

The number density of ions N_i in the state i is given by the kinetic equilibrium equation (Hubeny & Mihalas 2014)

$$\sum_{j\neq i} N_j P_{ji} - N_i \sum_{j\neq i} P_{ij} = 0. \tag{2}$$

Here $P_{ij} = R_{ij} + C_{ij}$ are rates for a transition from i to j (similarly P_{ji}), where R_{ij} stands for radiative rates (bound-bound – radiative excitation and deexcitation rates, bound-free radiative ionization and recombination rates) and C_{ij} denotes collisional rates. The bound-free radiative rates are calculated from the CMF radiative field, while the bound-bound rates are derived using the Sobolev approximation.

We account for all relevant ions in the NLTE calculations. The list of ions which are accounted for the NLTE calculations and for the calculation of the radiative force is given in Table 1. The model ions for the solution of the kinetic equilibrium equations were either adopted from TLUSTY model atmosphere input files (see Lanz & Hubeny 2007, for their description) or prepared by us using Opacity and Iron Project data (Seaton et al. 1992; Hummer et al. 1993) and data described by Pauldrach et al. (2001).

5. Hydrodynamics

To derive the wind density ρ, wind velocity υ_r, and temperature, we solve the continuity equation

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\rho\upsilon_r\right) = 0, \tag{3}$$

the equation of motion

$$\rho\upsilon_r\frac{\mathrm{d}\upsilon_r}{\mathrm{d}r} = f_{\mathrm{rad}} - \rho g - \frac{\mathrm{d}}{\mathrm{d}r}\left(a^2\rho\right), \tag{4}$$

and the energy equation

$$\frac{3}{2}\upsilon_r\rho\frac{\mathrm{d}a^2}{\mathrm{d}r} + \frac{a^2\rho}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\upsilon_r\right) = Q^{\mathrm{rad}}. \tag{5}$$

The equations account for the radiative driving and for radiative cooling and heating. Here Q^{rad} is the radiative heating calculated using the thermal balance of electrons method (Kubát et al. 1999). The hydrodynamical equations are solved using the Newton-Raphson iterations.

Table 1. Atoms and ions included in NLTE calculations with number of accounted levels. Here 'Level' means either an individual level or a set of levels merged into a superlevel.

Ion	Levels	Ion	Levels	Ion	Levels	Ion	Levels
H I	9	O II	50	Al II	16	Ar III	25
H II	1	O III	29	Al III	14	Ar IV	19
He I	14	O IV	39	Al IV	14	Ar V	16
He II	14	O V	14	Al V	16	Ar VI	11
He III	1	O VI	20	Al VI	1	Ar VII	1
C II	14	O VII	1	Si II	12	Ca II	16
C III	23	Ne II	15	Si III	12	Ca III	14
C IV	25	Ne III	14	Si IV	13	Ca IV	20
C V	11	Ne IV	12	Si V	15	Ca V	22
C VI	1	Ne V	17	Si VI	1	Ca VI	1
N II	14	Ne VI	11	P III	16	Fe III	29
N III	32	Ne VII	1	P IV	17	Fe IV	32
N IV	23	Na II	13	P V	21	Fe V	30
N V	13	Na III	14	P VI	14	Fe VI	27
N VI	15	Na IV	18	P VII	1	Fe VII	1
N VII	1	Na V	16	S II	14	Ni III	36
		Na VI	1	S III	10	Ni IV	38
		Mg III	14	S IV	18	Ni V	48
		Mg IV	14	S V	14	Ni VI	1
		Mg V	13	S VI	16		
		Mg VI	1	S VII	1		

We do not use Equation (5) to derive the temperature in the stellar photosphere. Instead, we use the the so-called differential form of the radiative equilibrium equation deep in the photosphere (Hubeny & Mihalas 2014)

$$\frac{\sigma T_{\text{eff}}^4}{4\pi}\frac{R_*^2}{r^2} = H(r) = -\int_0^\infty \frac{1}{q_\nu \chi_\nu}\frac{\mathrm{d}\,(q_\nu f_\nu J_\nu)}{\mathrm{d}r}\,\mathrm{d}\nu, \tag{6}$$

where q_ν and f_ν are sphericity and Eddington factors (Auer 1971), R_* is the stellar radius, σ is the Stefan-Boltzmann constant, and $H(r)$ is the frequency-integrated Eddington flux derived from the CMF solution. Equation (6) also employs the effective temperature (T_{eff}) of the star. In the upper layers of the photosphere, we use integral form of the radiative equilibrium

$$\frac{1}{r^2}\frac{\mathrm{d}(r^2 H(r))}{\mathrm{d}r} = 0 = \int_0^\infty (\eta_\nu - \chi_\nu J_\nu)\,\mathrm{d}\nu. \tag{7}$$

We update fluxes within the Newton-Raphson iteration step to fullfill the flux conservation (left-hand sides of Equations (6) and (7)), while the right-hand sides are used to derive the derivatives of fluxes with respect of flow variables.

6. Model results

The predicted mass-loss rates $\dot{M}$ can be fitted as a function of the stellar luminosity L and mass fraction of heavier elements Z via

$$\log\left(\frac{\dot{M}}{1\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}}\right) = -5.70 + 0.50\log\left(\frac{Z}{Z_\odot}\right) + \left(1.61 - 0.12\log\left(\frac{Z}{Z_\odot}\right)\right)\log\left(\frac{L}{10^6 L_\odot}\right). \quad (8)$$

The equation was derived from the wind models corresponding to our Galaxy (with abundances from Asplund et al. 2009), and Large and Small Magellanic Clouds with metallicities $Z/Z_\odot = 0.5$ and $Z/Z_\odot = 0.2$, respectively.

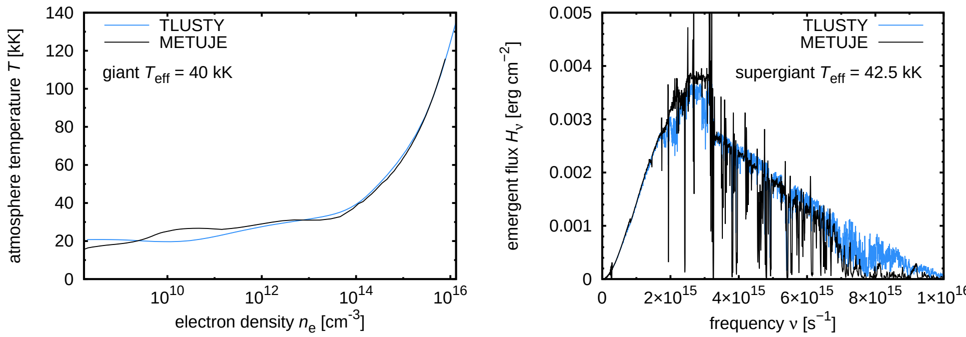

Figure 2. Comparison of the derived results with TLUSTY model photospheres. *Left:* Temperature structure. *Right:* Emergent flux.

The photospheric temperature structure derived from our METUJE models nicely agrees with TLUSTY (Lanz & Hubeny 2007) static planparallel model atmospheres (see Figure 2). For lower frequencies (for $\nu \lesssim 7\times10^{15}\,\mathrm{s}^{-1}$) also the emergent flux nicely agrees with results of TLUSTY (Lanz & Hubeny 2007) model atmospheres (Figure 2). Stellar wind blocks part of the emergent flux in the far UV region (for $\nu \gtrsim 7\times10^{15}\,\mathrm{s}^{-1}$).

7. Conclusions

We describe our own global models of expanding atmospheres of hot stars. The models derive the structure of the wind and wind parameters from the basic stellar parameters. The models strongly rely on the atomic data for the solution of kinetic equilibrium equations and for the calculation of the radiative force.

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