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Hydrodynamics of stellar wind

1 Introduction

Since the foundation of the theory of radiatively driven stellar winds by Lucy & Solomon (1970) and Castor, Abbott & Klein (1975, hereafter CAK) many of the initial assumptions introduced by this authors were examined. To the most important ones belong the radial streaming approximation (Friend & Abbott 1986, Pauldrach et al. 1986), the wind stability (Abbott 1980, Owocki & Rybicki 1984), the limitations of the Sobolev approach (Poe et al. 1990, Owocki & Puls 1999), the thermal structure of the wind (Drew 1989) and many others.

Another important assumption, studied already at the dawn of the radiatively driven stellar wind theory by Castor, Abbott & Klein (1976) is the condition of the one-component flow. They discussed encounters which transfer momentum received by absorbing ions (typically C, N, O, etc.) to passive, nonabsorbing ions, mainly hydrogen and helium. They showed that for the high-density winds such encounters are not important for the overall dynamics of the wind and that high-density winds can be considered as one-component. However, for the low-density winds Springmann & Pauldrach (1992) showed that momentum transfer between absorbing and nonabsorbing plasma influences the wind thermal balance and even the wind dynamics. Thus, for the low-density winds the flow is essentially multicomponent. They proposed that the so-called ”ion-runaway” may occur. Based on the simplified theory of the multicomponent flow many of interesting results occurred. Porter & Drew (1995) re-examined model of wind-compressed disk in the presence of dynamical decoupling of absorbing ions and passive plasma, Porter & Skouza (1999) showed the possibility of formation of pulsating shells around stars with low-density radiatively driven wind, and Hunger & Groote (1999) explained the H/He abundance anomalies in Bp stars on the basis of helium decoupling.

First detailed numerical models of multicomponent radiatively driven stellar winds were presented by Babel (1995, 1996). However, Babel was concerned mainly in winds of main sequence A stars. Thus, an interesting domain of low-density winds of main sequence B stars was not thoroughly studied yet.

For low density winds, additional effect becomes important, so-called Doppler (Gayley-Owocki, GO) heating and cooling introduced in stellar wind domain by Gayley & Owocki (1994). This effect is a natural consequence of the dependence of the radiative force on the velocity gradient (via the Doppler effect) and physically it arises from the difference between absorption and emission frequency in the moving medium.

The main purpose of the thesis is a study of stellar wind hydrodynamic with special emphasis on the multicomponent nature of the wind and on GO heating. Both effects were not thoroughly modeled yet.

2 Basics of stellar wind theory

Basic theory describing multicomponent radiatively driven stellar winds of hot stars is summarized in the first part of the thesis. Multicomponent hydrodynamic equations for the plasma flow are derived directly from the Boltzmann equation. Special attention is paid to the proper treatment of the velocity dependent force term, which will be important for the derivation of GO heating term. Collisional terms are derived using Fokker-Planck approximation.

Similarly, the basic theory of the radiative transfer and of radiation-matter interaction is rewieved.

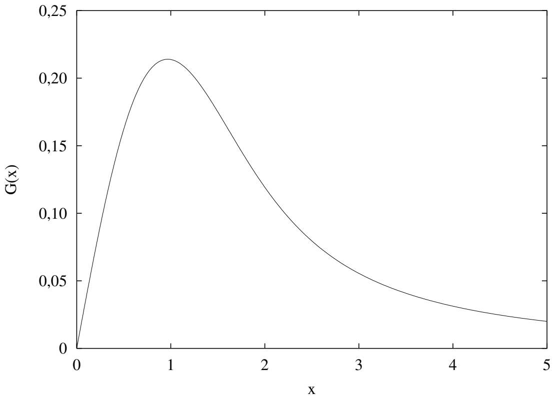


Figure 1: Chandrasekhar function $G(x)$. The frictional force depends on $G(u_{ab}/\alpha_{ab})$, whereas the frictional heating depends on $u_{ab}G(u_{ab}/\alpha_{ab})$.

The Sobolev theory is derived directly from the transfer equation. Finally, the quantitative description of the radiatively driven stellar winds is obtained in the framework of the so called CAK theory.

3 Model equations

In the most advanced case the multicomponent wind models are described by the density ρ_a, radial velocity $v_{r\,a}$ and temperature T_a of each component a of the flow. These quantities shall fulfill equation of continuity, momentum equations and energy equations for each component of the flow separately. In the case of steady spherically symmetric flow these equations take the form of (Burgers 1969)

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\rho_a v_{r\,a}\right) = 0, \tag{1a}$$

$$v_{r\,a}\frac{\mathrm{d}v_{r\,a}}{\mathrm{d}r} = \frac{1}{\rho_a}\sum_{b\neq a} K_{ab} G\left(\frac{u_{ab}}{\alpha_{ab}}\right)\frac{u_{r,ab}}{u_{ab}} - g_a - \frac{1}{\rho_a}\frac{\mathrm{d}}{\mathrm{d}r}\left(a_a^2\rho_a\right), \tag{1b}$$

$$\frac{3}{2}kv_{r\,a}\frac{\rho_a}{m_a}\frac{\mathrm{d}T_a}{\mathrm{d}r} + a_a^2\rho_a\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2 v_{r\,a}\right) = Q_a^{\mathrm{rad}} + \frac{1}{\sqrt{\pi}}\sum_{b\neq a} K_{ab}\frac{2k\left(T_b - T_a\right)}{m_a + m_b}\frac{\exp\left(-\frac{u_{ab}^2}{\alpha_{ab}^2}\right)}{\alpha_{ab}} + $$
$$+\sum_{b\neq a}\frac{m_b}{m_a+m_b}K_{ab}G\left(\frac{u_{ab}}{\alpha_{ab}}\right)u_{ab}, \tag{1c}$$

where g_a is a sum of forces (per unit of mass) acting on the component (ie. radiative, gravitational or electrical), a_a is sound velocity, $a_a^2 = kT_a/m_a$, m_a and m_b are masses of each particles and drift velocity $\boldsymbol{u}_{ab}$ and effective thermal speed α_{ab} are given by

$$\boldsymbol{u}_{ab} = \boldsymbol{v}_b - \boldsymbol{v}_a, \tag{2a}$$

$$\alpha_{ab}^2 = \frac{2k\left(m_b T_a + m_a T_b\right)}{m_a m_b}. \tag{2b}$$

The frictional constant K_{ab} depends on the product of densities of components,

$$K_{ab} = N_a N_b \frac{4\pi \ln\Lambda q_a^2 q_b^2}{kT_{ab}}, \tag{3}$$

where N_a, N_b, q_a, q_b are densities and charges of individual components, $\ln \Lambda$ is the Coulomb logarithm and the temperature T_{ab} is given by $T_{ab} = (m_a T_b + m_b T_a) / (m_a + m_b)$. Note, that the frictional force depends on the drift velocity u_{ab} via the the Chandrasekhar function $G(x)$ (see Fig.1). For low drift velocity the force depends on u_{ab} linearly, the higher drift velocity the higher frictional force. However, for higher drift velocities (for $u_{ab}/\alpha_{ab} \gtrsim 1$) the frictional force decreases with increasing drift velocity. This enables so called "decoupling" of individual flow components, or "ion-runaway" in the stellar wind domain.

The radiative force $g_{\mathrm{i}}^{\mathrm{rad}}$ acting on absorbing ions is taken in the CAK approximation. In the multicomponent stellar winds depends ion the ionic density and ionic velocity gradient via (Krtička & Kubát 2000)

$$g_{\mathrm{i}}^{\mathrm{rad}} \sim k \left(\frac{1}{\rho_{\mathrm{i}}} \frac{\mathrm{d}v_{r\mathrm{i}}}{\mathrm{d}r} \right)^{\alpha}. \tag{4}$$

Parameters k and α were taken from the Abbott (1982).

The radiative heating/cooling term includes heating due to the free-free and bound-free transitions (calculated using output from model atmospheres of Kubát 2001) and the GO heating/cooling.

System of Eq. (1) shall be closed by eg. Maxwell equations for electrical field, by equations describing ionization balance etc.

4 Method of solution

Equations, which we solve (i.e. Eqs. (1)) together with the appropriate boundary conditions may formally be written as

$$\boldsymbol{P}\boldsymbol{\psi} = 0, \tag{5}$$

where $\boldsymbol{\psi}$ is a column vector of variables (which describes densities, velocities, temperatures etc. at each grid point) and $\boldsymbol{P}$ is a non-linear operator which describes numerical approximation of solved equations. To solve system of equations (5), we need a numerical method which is capable to solve a set of coupled nonlinear differential equations. We selected the Newton-Raphson method, which employs the iterative scheme

$$\mathsf{J}^n \delta\boldsymbol{\psi}^{n+1} = -\mathsf{P}^n \boldsymbol{\psi}^n, \tag{6}$$

where $\boldsymbol{\psi}^n$ is solution in the n-th iteration and J^n is the Jacobian in the n-th iteration,

$$J_{kl}^n = \frac{\partial P_k}{\partial \psi_l}. \tag{7}$$

To solve the system of equations (6) for $\delta\boldsymbol{\psi}^{n+1}$ we used the numerical package `LAPACK`, developed at the University of Tennessee.

5 Multicomponent wind models

The above mentioned theory is used for the description of multicomponent radiatively driven winds of hot stars. Firstly, the two-component isothermal winds are studied (Krtička & Kubát 2000). One of the components are absorbing ions, which receive all the radiative acceleration, the second component are nonabsorbing ions. It is shown that for the high-density winds the multicomponent effects are negligible. However, this is not the case in the low-density winds, where the multicomponent nature is important. However, contrary to the previous intuitive conclusions, the decoupling of absorbing component from the nonabsorbing component does not occur. It is shown, that this effect is a consequence

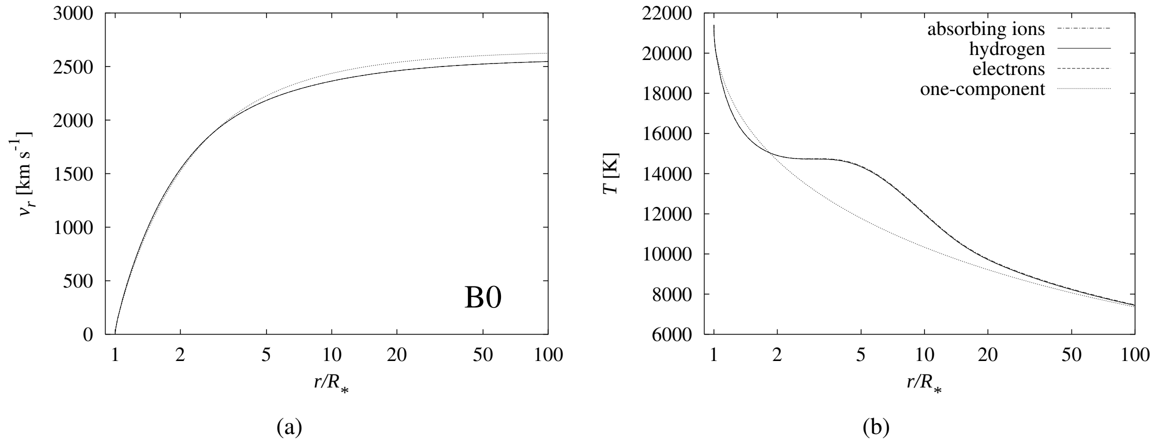


Figure 2: GO heating in the stellar wind. (a) Comparison of the radial wind velocity of one-component (dotted line) and three-component radiatively driven stellar wind models of an B0 star. Radiatively accelerated ions are denoted using dashed-dotted line, passive plasma with full line and electrons with dashed line. Notice that all three-component curves are very nearly the same. (b) Comparison of temperature stratification of one-component and three-component models. Assignment of all curves is the same as for velocity. Notice that the curves describing temperature of individual components of a three-component model coincide, which is not true if we compare one and three component models.

of the dependence of the radiative force on the velocity gradient in the CAK approximation. However, such models are not probably stable.

Because the frictional heating and the effect of electrons may be important for the multicomponent stellar winds, three-component nonisothermal models (where the third component are free electrons) are computed (Krtička & Kubát 2001a). Similarly to the previous models, multicomponent effects are negligible for the high-density winds. For low density winds an important effect of frictional heating occurs. However, contrary to the previous models, the absorbing component does not decouple from the non absorbing component in the most of models due to the dependence of radiative force in the CAK parametrization on the temperature. The effect of the decoupling occurs only for the extremely low density winds, where the passive component falls back onto the stellar surface.

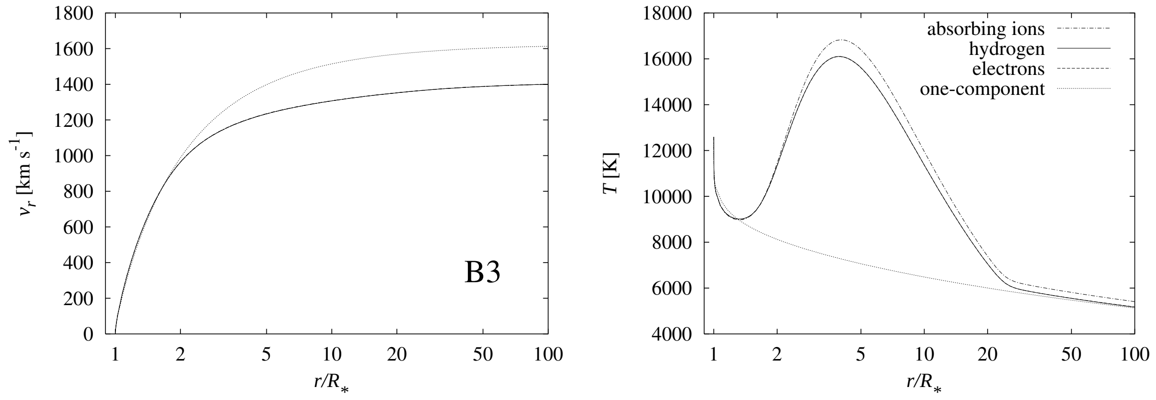
It is shown that GO heating term can be derived directly from the Boltzmann equation. If the force acting on the particle a depends on the particle velocity, then in the equation for the temperature occurs a new term

$$\int \mathrm{d}\boldsymbol{\xi}_a \xi_{a,h} f_{a,h} F_a, \tag{8}$$

which is equal to zero if the h-th component of force does not depend on the particle velocity $\xi_{a,h}$. Here F_a is the velocity distribution of a-particles. In the case of radiative force the integral (8) gives GO heating/cooling term in the energy equation (Krtička & Kubát 2001b).

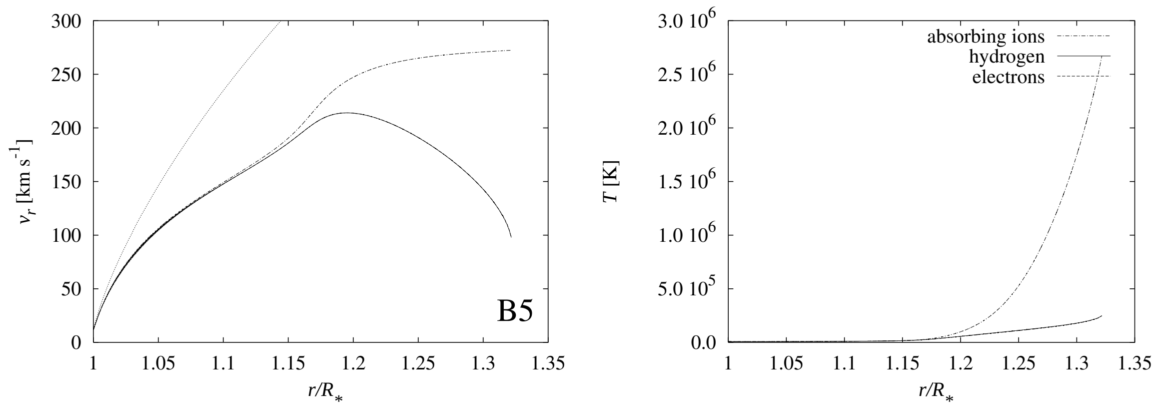
The most advanced models include the GO heating effects and the possibility of different temperatures of each component (Krtička & Kubát 2001b). Such models are given in the Figs. 2, 3, 4. Near the star the wind of main-sequence B0 star (see Fig. 2) is slightly cooled by the GO cooling compared to the model without GO heating/cooling effects. On the other hand, in the outer parts of the wind GO heating dominates. At the outermost parts of the wind the temperatures of models with and without GO heating are again nearly the same mainly due to the lowering of a stellar angular diameter. For this model the frictional heating is negligible.

For stars with a lower density wind GO heating and GO cooling are much more evident. Moreover, for such stars the frictional heating is also important and individual wind components have different



(a) (b)

Figure 3: The same as Fig.2 for a B3 star. The wind is heated by both frictional and GO heating in the outer parts of the wind. The temperatures of absorbing ions and electrons are nearly the same whereas the ionic temperature slightly differs mainly in the outer parts of the wind.



(a) (b)

Figure 4: The same as Fig.2 for a B5 star. The passive component decouples just above the stellar surface and subsequently falls back onto the star. Note that the temperature of the ionic component reaches the value of the order of 10^6 K. The temperatures of absorbing ions and electrons are nearly the same.

temperatures (see Fig. 3). To maintain the common flow, a sufficient amount of momentum must be transferred to the nonabsorbing component. Near the stellar photosphere, the wind is relatively dense. From inspection of the frictional force (in the Eq. (1b), see also Eq. (3)), it follows that the drift velocity between absorbing ions and nonabsorbing ions can be low compared to the thermal speed α_{ab}. Consequently, frictional heating can be neglected in this region and the temperature structure is set mainly by the radiative processes and the temperatures of individual components are nearly the same. However, this is not valid in the outer parts of the wind. The wind is heated by frictional and GO heating there. At the outer parts of the wind the density decreases. Since the frictional force depends on the product of densities, the drift velocity should increase to accelerate the nonabsorbing ions. Consequently, frictional heating increases. The velocity profile is affected by changes in the temperature structure. The higher the temperature, the greater the thermal speed and the lower the radiative acceleration. Consequently, the wind terminal velocity decreases.

In the case of the wind with the lowest densities the absorbing ions are not able to accelerate sufficiently the passive component of the wind. Thus, the passive component is not dragged out of the

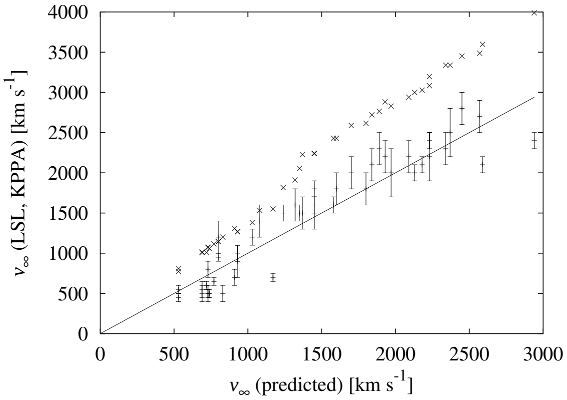


Figure 5: Comparison of predicted and observational (taken from LSL) values of terminal velocities. Vertical lines denote uncertainty of observed values. Straight line is one-to-relation. For comparison, we plotted theoretical terminal velocities computed by LSL using "cooking formula" of KPPA (crosses).

atmosphere and falls back onto the stellar surface (see Fig.4 for a model of a B5 star wind). Decoupling of velocities of absorbing and passive components is accompanied by decoupling of temperatures of these components (see Fig.4). Note, that the absorbing component attains temperatures sufficient to produce X-rays.

6 Applications and experimental verifications of multicomponent models

Among the most important consequences of the discussed models belongs the frictional and GO heating of the stellar wind (cf. Figs. 2, 3). The higher wind temperature causes the lowering of the terminal velocity v_∞ of the stellar wind. This effect can proffer self-consistent explanation of the low terminal velocity of τ Sco. Moreover, higher wind temperature can influence observed stellar UV flux. This provides an alternative explanation for the observed UV excesses of stars ε CMa and β CMa.

Cohen et al. (1997) showed, that for stars later than B2 the observed X-ray radiation cannot be produced by wind-shock mechanism. They concluded that X-ray emission in mid- and late-type B stars can be produced by coronal mechanism. From our models we conclude that X-ray radiation of such stars can be produced by decoupling of absorbing and nonabsorbing components of the flow and subsequent backfalling of nonabsorbing component on the star (see Fig. 4).

Hunger & Groote (1999) proposed that peculiar chemical composition of He-rich and He-poor star Bp stars can be caused by decoupling of helium from the main flow and by his backfalling. However, four-component wind models with proper treatment of helium ionization showed that helium is ionized and thus such reaccreation does not occur. Clearly, the theory of Hunger & Groote (1999) was not confirmed by our models. However, some of this stars seems to exhibit circumstellar clouds (Smith & Groote 2001). Such clouds can be explained by the decoupling of passive and active components.

7 A new view on the low density stellar winds

For high density stellar winds the multicomponent and GO heating effects can be neglected. This conclusion was verified by the comparison of terminal velocities for large sample of stars (Krtička & Kubát 2001b). The systematic difference between observed (Lamers et al. 1995, hereafter LSL) and theoretical (Kudritzki et al. 1989, hereafter KPPA) terminal velocities has been removed (see Fig. 5).

For stars later than main sequence spectral type O6 the effect of GO heating/cooling becomes important for the temperature structure of the wind (see Fig. 2). Although the GO heating/cooling deposits energy directly to the absorbing ions, the temperature of all components is essentially the same. Other multicomponent effect are not also important.

Besides the GO heating/cooling the frictional heating alters the temperature structure for the stars later than main sequence spectral type B3 (see Fig. 3). Higher wind temperature lowers the radiative force and this causes lowering of the wind terminal velocity v_∞. Higher wind temperature can influence UV excess of such stars. However, contrary to the previous assumptions the decoupling of wind components does not occur.

In the extremely low density stellar wind the decoupling of absorbing and nonabsorbing components occurs (see Fig. 4). Absorbing component reaches temperatures of order 10^6 K which allows for emission of X-rays (see Fig. 4). The passive component falls back on the stellar surface or creates shells or clouds around the star (Porter & Skouza 1999).

Moreover, for many of cooler stars the common wind of passive and active components does not exists (Dworetsky & Budaj 2000). Such stars can have purely metallic wind (Babel 1996). This case was not studied in this thesis.

8 Future work

Models described in this thesis carries the multicomponent nature of the wind and the GO heating into the realm of quantitative modeling. However, the models are not still fully satisfactory. Especially the radiative force shall be computed consistently using proper atomic data. Similarly can be improved radiative heating/cooling term. Moreover, the approximation of one-type absorbing ions with parameters which are not rigidly given may lead to some misunderstanding. Nevertheless, the present models describe the basic picture of multicomponent phenomenon in the low density stellar wind and can be improved during the future work.

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