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Multicomponent stellar winds of He chemically peculiar stars

Krtička J.[1,2], Kubát J.[2]

[1] Ústav teoretické fyziky a astrofyziky PřF MU, Kotlářská 2, CZ-611 37 Brno, Czech Republic
[2] Astronomický ústav, AV ČR, CZ-251 65 Ondřejov, Czech Republic

Abstract. We calculate multicomponent stellar wind models with inclusion of a helium component applicable to He-rich and He-poor stars. We show that helium does not decouple from the stellar wind of He-rich stars due to its coupling to hydrogen and its ionized state. For He-poor stars helium may decouple from the stellar wind, however, this effect is unable to explain chemical peculiarity of these stars. We conclude that the explanation of the chemical peculiarity of these stars based purely on helium or hydrogen decoupling from the stellar wind is unlikely.

Key words: hydrodynamics – stars: mass-loss – stars: winds – stars: chemically peculiar

1 Introduction

Radiative force may have important influence on the structure of stellar atmospheres. Although no significant direct influence of the radiative force on the atmospheres of the coolest stars is not known, the radiative force may be dominant in the atmospheres of hot stars. The consequences of this influence are different. Mainly for A stars and white dwarfs, the radiative force may cause the radiative diffusion and subsequent elemental abundance anomalies (see Alecian (1995) or Vauclair (2003) for a review). On the other hand, the radiative force may accelerate a stellar wind mainly for O stars and WR stars (Kudritzki & Puls 2000). However, there exists a group of B stars, for which both effects of stellar wind and elemental diffusion in the stellar atmosphere are important. It is generally believed that in order to explain the elemental abundances of helium and some other elements in the atmospheres of He-rich stars, at least three different ingredients are necessary. These ingredients are stellar wind, elemental diffusion and magnetic field (e.g. Michaud et al. 1987).

However, there exists an alternative explanation of chemical peculiarity of He-rich and He-week stars. It was proposed by Hunger & Groote (1999, hereafter HG). They showed that for stars with effective temperatures $T_{\rm eff} < 25\,000\,{\rm K}$ helium may decouple from the stellar wind, fall back onto the stellar surface and create regions with enhanced abundance of helium if magnetic fields are present. Similarly, for stars with effective temperatures $T_{\rm eff} < 17\,000\,{\rm K}$ even hydrogen may decouple from the stellar wind, fall back onto the stellar surface and cause helium underabundance if magnetic fields are present. We decided to test this explanation of chemical peculiarity of He-rich and He-week stars using our multicomponent wind models. First preliminary calculations have already been performed by Krtička & Kubát (2001a), however, with artificially low helium charge and without ionization balance calculation.

2 Multicomponent stellar wind models

Stellar winds of hot stars are accelerated mainly by the absorption of radiation in the resonance lines of such elements as carbon, nitrogen, oxygen, or iron. However, these wind components have a much lower density than the rest of the stellar wind, which is composed mainly of hydrogen and helium. Thus, the process of acceleration of a stellar wind of hot stars has two different physical steps. At the first step, radiation is absorbed by low-density metals such as carbon, nitrogen, oxygen, or it is scattered by free electrons, and these wind components obtain momentum from the stellar radiation field. At the second step, the momentum obtained by these low-density components is transferred to high-density wind components via the Coulomb collisions between charged particles. Thus, stellar winds of hot stars have a multicomponent nature. For stars with a relatively high wind density (e.g. galactic O stars or WR stars) this multicomponent wind nature does not influence the wind structure, as has been discussed by Castor et al. (1976). However, for stars with a relatively low wind density (i.e. main-sequence B stars or stars with extremely low metallicity, see Krtička et al. 2003) the multicomponent wind nature becomes important for the wind structure itself because new effects occur, for example, frictional heating or decoupling of wind components (Springmann & Pauldrach 1992, Babel 1995, Krtička & Kubát 2001b, hereafter KKII).

2.1 Model equations

Equations used here for the calculation of four-component wind models are nearly the same as those of KKII. We assume a stationary and spherically symmetric stellar wind, which is composed of four components, namely, absorbing metallic ions, hydrogen, helium, and free electrons. For the calculation of wind models we solve the continuity equation, momentum equation, and energy equation for each component of the flow. The continuity equation has the form

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

where ρ_a is the density, r is the radius, and $v_{r\,a}$ is the velocity of component a. The momentum equation is

$$v_{r\,a}\frac{\mathrm{d}v_{r\,a}}{\mathrm{d}r}=g_a^{\mathrm{rad}}-g-\frac{1}{\rho_a}\frac{\mathrm{d}}{\mathrm{d}r}\left(a_a^2\rho_a\right)+\frac{q_a}{m_a}E+\sum_{b\neq a}g_{ab}^{\mathrm{fric}}, \tag{2}$$

where g_a^{rad} is the radiative force, E is the electric polarisation field, and g_{ab}^{fric} is the frictional force (Burgers 1969)

$$g_{ab}^{\mathrm{fric}}=\frac{1}{\rho_a}K_{ab}G(x_{ab})\frac{v_{r\,b}-v_{r\,a}}{|v_{r\,b}-v_{r\,a}|}, \tag{3}$$

where $G(x_{ab})$ is the Chandrasekhar function, and the frictional coefficient is

$$K_{ab}=n_a n_b\frac{4\pi q_a^2 q_b^2}{kT_{ab}}\ln\Lambda, \tag{4}$$

where the mean temperature $T_{ab}=\left(m_bT_a+m_aT_b\right)/\left(m_b+m_a\right)$ is calculated using temperatures T_a and T_b of individual wind components with atomic masses m_a and m_b. The radiative force in the CAK approximation (Castor et al. 1975, Friend & Abbott 1986, Pauldrach et al. 1986, see also KKII for generalization of CAK force for a multicomponent flow) due to line-absorption acts on metals and radiative force due to the Thomson scattering acts on free electrons.

The energy equation for each component of the flow is

$$\frac{3}{2}v_{r\,a}\rho_a\frac{\mathrm{d}a_a^2}{\mathrm{d}r}+\frac{a_a^2\rho_a}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2v_{r\,a}\right)=Q_a^{\mathrm{rad}}+\sum_{b\neq a}\left(Q_{ab}^{\mathrm{ex}}+Q_{ab}^{\mathrm{fric}}\right), \tag{5}$$

where the heat exchange is given by

$$Q_{ab}^{\mathrm{ex}}=\frac{1}{\sqrt{\pi}}K_{ab}\frac{2k\left(T_b-T_a\right)}{m_a+m_b}\frac{\exp\left(-x_{ab}^2\right)}{\alpha_{ab}}, \tag{6}$$

the frictional heating is

$$Q_{ab}^{\mathrm{fric}}=\frac{m_b}{m_a+m_b}K_{ab}G(x_{ab})|v_{r\,b}-v_{r\,a}|, \tag{7}$$

and Q_a^{rad} is the radiative heating calculated using the method of thermal balance of electrons (Kubát et al. 1999). We also take into account the Gayley-Owocki (1994) heating. The base flux, which is necessary for the calculation of the radiative heating term, is taken from H-He spherically symmetric NLTE model atmospheres (Kubát 2003).

The system of hydrodynamic equations is closed using the equation for the electric polarisation field and by equations of ionization equilibrium (we assume nebular approximation after Mihalas 1978, Eq. 5.46). For a more detailed description of the three-component variant of these models see KKII.

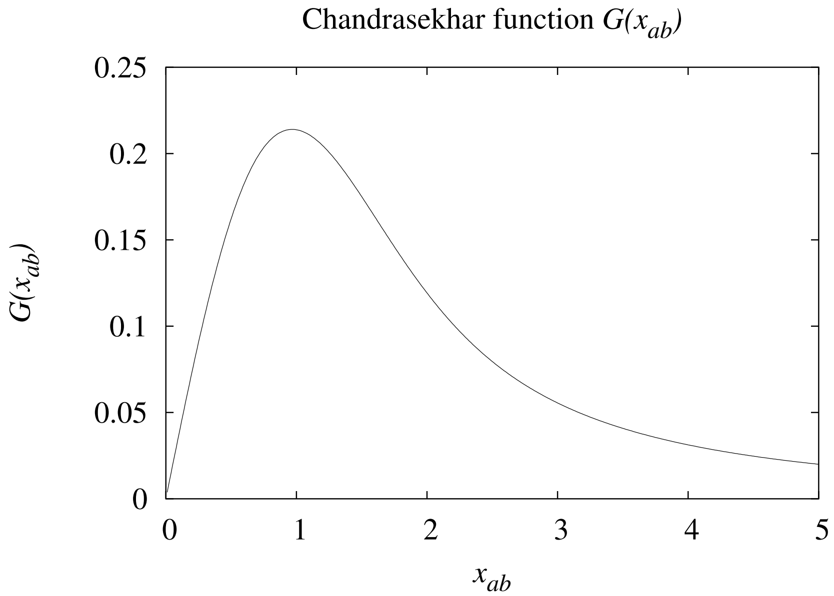

Figure 1: *The run of Chandrasekhar function.* Note that Eq. (9) yields $x_{ab} \sim \Delta v_{ab}$, where Δv_{ab} is the velocity difference between wind components. If the flow is well coupled, $x_{ab} \lesssim 1.0$, $G(\Delta v_{ab}) \sim \Delta v_{ab}$. If the drift velocity is large, $x_{ab} \gtrsim 1.0$, $G(\Delta v_{ab}) \sim \Delta v_{ab}^{-2}$, and the wind may decouple. Note that the point $x_{ab} \approx 1.0$ corresponds to the maximum of G.

2.2 The possibility of wind decoupling

The frictional force Eq. (3) between two components depends on the velocity difference between these two components via the so-called Chandrasekhar function,

$$G(x_{ab}) = \frac{1}{2x_{ab}^2}\left[\Phi(x_{ab}) - x_{ab}\frac{\mathrm{d}\Phi(x_{ab})}{\mathrm{d}x_{ab}}\right], \tag{8}$$

where the non-dimensional velocity difference x_{ab} is given by

$$x_{ab} = \frac{|v_{rb} - v_{ra}|}{\alpha_{ab}} = \frac{\Delta v_{ab}}{\alpha_{ab}}, \tag{9}$$

where α_{ab} is the mean thermal speed, $\alpha_{ab}^2 = 2k\left(m_a T_b + m_b T_a\right)/\left(m_a m_b\right)$. The plot of the Chandrasekhar function is given in Fig.1. For relatively low velocity differences, $\Delta v_{ab} \lesssim \alpha_{ab}$, the Chandrasekhar function is an increasing function of the velocity difference Δv_{ab} and components a and b are well coupled. However, for higher velocity differences, $\Delta v_{ab} \gtrsim \alpha_{ab}$, the Chandrasekhar function is a decreasing function of velocity difference and the decoupling of components may occur.

2.3 Solution using Newton–Raphson method

Multicomponent wind equations (1, 2, 5) can be formally written as

$$\mathsf{P}\boldsymbol{\psi} = 0, \tag{10}$$

where the vector describing the solution has the form

$$\boldsymbol{\psi} = \left(\boldsymbol{\psi}_1, \boldsymbol{\psi}_2, \ldots, \boldsymbol{\psi}_{\mathrm{NR}}\right)^{\mathrm{T}}, \tag{11}$$

where

$$\boldsymbol{\psi}_i = \left(\left(\rho_{a,i}, v_{ra,i}, T_{a,i}, z_{a,i}\right)_{a=\mathrm{i,\,p,\,e}}, E_i, \Delta v_{r,i}\right). \tag{12}$$

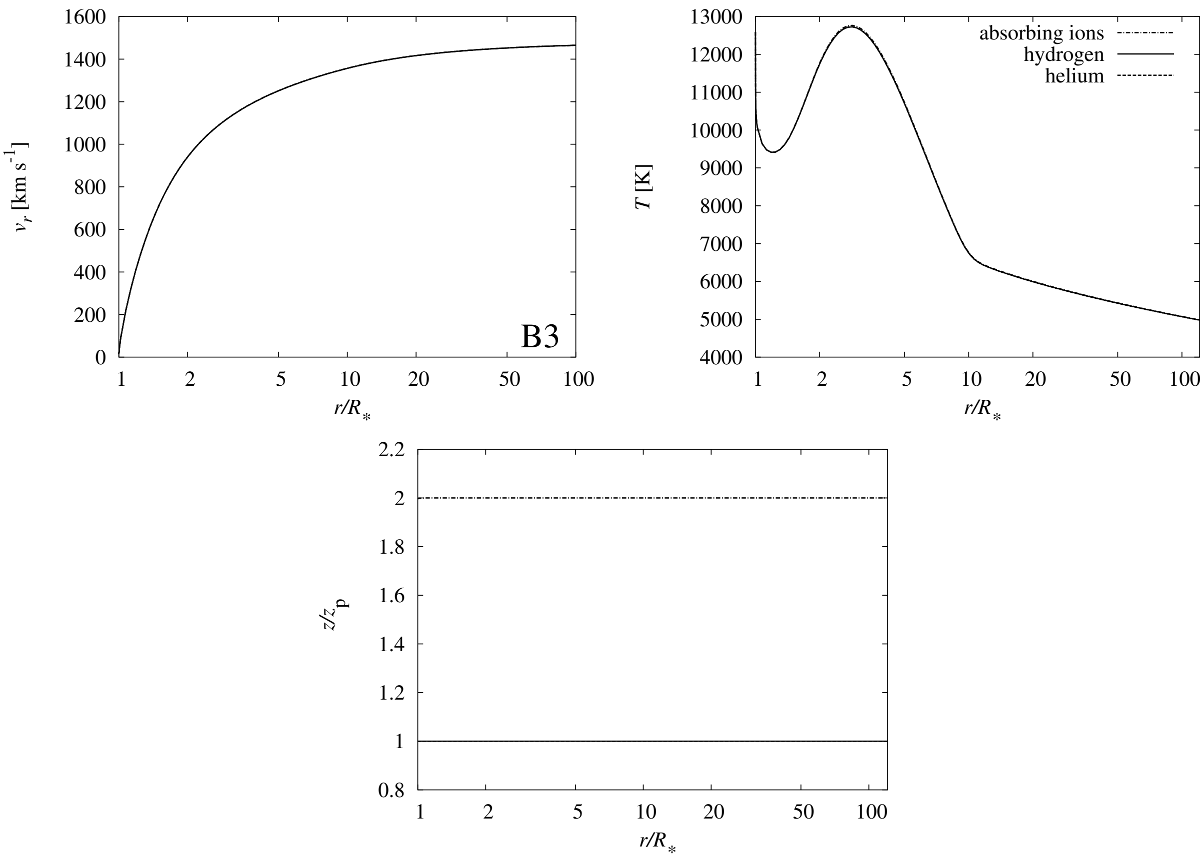

Figure 2: *Four-component wind model of a main-sequence B3 star. Upper left panel:* Wind velocities of wind components. Note that velocities of all wind components are nearly the same. *Upper right panel:* Temperatures of wind components. Temperatures of all wind components are close to each other. Note slight heating according to Gayley & Owocki (1994) and frictional heating. *Lower panel:* Charges of wind components.

The velocity difference $\Delta v_{r,i}$ was taken as an additional independent variable to improve convergence properties. The solution can be obtained using the iteration scheme

$$\mathsf{J}^n \delta \boldsymbol{\psi}^{n+1} = -\mathsf{P}^n \boldsymbol{\psi}^n, \tag{13}$$

where the Jacobi-matrix is

$$J^n_{kl} = \frac{\partial P_k}{\partial \psi_l}. \tag{14}$$

More details about the solution procedure can be found in Krtička (2003).

3 Calculated models

We have calculated four-component stellar wind models (i.e. models consisting of absorbing ions, hydrogen, helium, and free electrons) to test the explanation of helium chemically peculiar stars proposed by HG. Here we present two stellar wind models of B3 and B6 main-sequence stars. Spectral type of helium-rich stars is close to B3, for which HG predicted helium decoupling from the stellar wind. On the other hand, spectral type of helium-poor stars is close to B6. For these stars HG predicted hydrogen decoupling from the stellar wind.

3.1 Models suitable for He-rich stars

We have selected a main-sequence B3 star as a representative example of He-rich stars. Stellar parameters are taken according to Harmanec (1988) and force multipliers are after Abbott (1982). The plot of velocities,

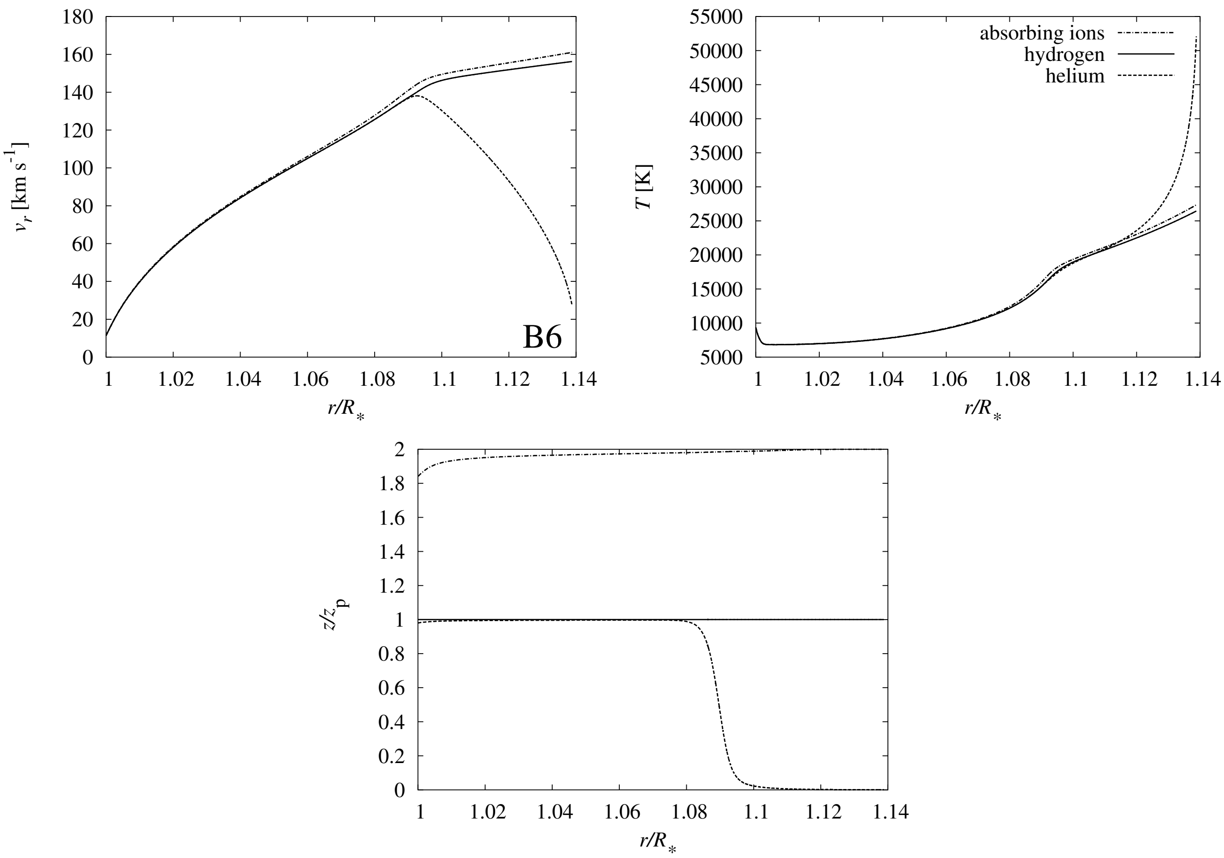

Figure 3: *Four-component wind model of a main-sequence B6 star. Upper left panel:* Wind velocities of wind components. Note that helium decouples from the stellar wind and subsequently decelerates. Helium velocity is lower that the escape velocity. Thus, helium may fall back onto the stellar surface. *Upper right panel:* Temperatures of wind components. Stellar wind is heated mainly due to the frictional heating in the outer parts of the wind. *Lower panel:* Charges of wind components. Note that helium recombines in the outer model region.

temperatures and charges of individual wind components is given in Fig. 2.

Contrary to the predictions of HG, helium does not decouple from the main wind. The reason for this behaviour is neglect of helium coupling to hydrogen by HG. They assumed that helium is accelerated mainly due to the collisions with metal (absorbing) ions. The frictional force $f_{\mathrm{He,i}} = \rho_{\mathrm{He}} g_{\mathrm{He,i}}$ is proportional to (see Eqs. (3, 4))

$$f_{\mathrm{He,i}} \sim n_{\mathrm{He}} n_{\mathrm{i}},$$

where n_{He} and n_{i} are number densities of helium and metal ions. However, the frictional force due to the collisions between helium and hydrogen atoms is

$$f_{\mathrm{He,H}} \sim n_{\mathrm{He}} n_{\mathrm{H}},$$

where n_{H} is the number density of hydrogen atoms. Since $n_{\mathrm{H}} \gg n_{\mathrm{i}}$, the frictional force due to hydrogen atoms may be important for the acceleration of helium atoms, and, consequently, can not be neglected.

We conclude that helium does not decouple from the stellar wind of He-rich stars. Thus, the explanation of the helium overabundance in chemically peculiar stars by the helium decoupling in their stellar wind is questionable.

3.2 Models suitable for He-poor stars

We have selected a main-sequence B6 star as a representative for He-poor stars. Again, stellar parameters are taken from Harmanec (1988) and force multipliers are after Abbott (1982). The plot of velocities, temperatures and charges of individual wind components is given in Fig. 3.

Apparently, in the outer model region helium atoms recombine. Because the frictional acceleration depends on the square of helium atomic charge (see Eqs. (3, 4)), the frictional acceleration is not able to support helium atoms any more and helium decouples from the flow. The decoupling is accompanied by large frictional heating. The helium velocity is lower than the escape velocity, thus helium may fall back onto the stellar surface and create helium overabundance in the stellar atmosphere. However, this spectral type corresponds to He-poor stars, thus even in this case the four-component models are not able to explain their chemical peculiarity.

4 Conclusions and discussion

We have calculated four-component wind models (i.e. models with absorbing ions, hydrogen, helium, and free electrons) applicable to helium chemically peculiar stars. We used our models to test the explanation of helium chemically peculiar stars by helium and hydrogen decoupling in the stellar winds of these stars. For hot B stars (in the parameter range of He-rich stars) helium is coupled not only to metals but also to hydrogen atoms, and it is ionized. Consequently, helium does not decouple from the stellar wind of He-rich stars. We conclude that the explanation of chemical peculiarity of He-rich stars (HG) based on helium decoupling is questionable.

On the other hand, for cool B stars (in the parameter range of He-poor stars) helium may recombine and consequently fall back onto the stellar surface. However, this decoupling can not explain chemical peculiarity of He-poor stars, since it may produce a surface overabundance of helium, not an underabundance, as anticipated by HG.

However, there are two effects which are still unclear. First of all, the mass-loss rates of B stars are highly uncertain. Our test calculations showed that due to lower mass-loss rate, *both* hydrogen and helium may fall back onto the stellar surface in the case of He-rich stars. However, this effect can not help to explain the chemical peculiarity of these stars since hydrogen and helium are well coupled even in this case. Another problem is the calculation of the wind ionization structure. From the theoretical point of view, as shown by Krtička & Kubát (2001), the helium decoupling is possible for artificially lowered helium charge. However, our simplified ionization calculations (based on a nebular approximation) do not predict such low helium charge. We think that our calculated ionization structure is roughly correct, but we shall perform tests using more detailed calculations. Both these effects, i.e. correct mass-loss rates and ionization structure, will be incorporated in our NLTE wind code. The first results obtained using our code are currently under way (Krtička & Kubát 2003).

We point out that helium diffusion superimposed with the multicomponent stellar wind may explain chemical peculiarity of He-rich stars (Michaud et al. 1987). On the other hand, mechanism of launching of He-free wind proposed by HG may possibly work for some cooler stars, however probably not for He-rich stars (see also Kubát & Krtička 2004).

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