Radiatively Driven Winds of OB Stars – from Micro to Macro

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Abstract. We review basic physics of line-driven stellar winds of OB stars. We discuss elementary processes due to which stellar winds are accelerated on a microscopic level. We show how these microscopic processes may enable the outflow and how they determine wind properties on a macroscopic level. We discuss shortcomings of present wind theories and future wind model improvements.

1. Introduction

Observations of many OB stars show that there exists an outflow of material from the stellar surface into the interstellar medium – the stellar wind. The theoretical study of hot star winds started few years after the discovery that electromagnetic radiation carries momentum that can be transferred to the matter in the process of light scattering. Milne (1923) and Johnson (1925, 1926) studied the possibility of the emission of high-speed atoms from stars. Milne (1926) in a beautifully written paper showed the importance of the Doppler effect for the line radiative acceleration. However, for the next few decades the radiatively driven hot star winds did not attract much attention. Modern studies of hot stars’ winds were stimulated mainly by UV observations of hot stars. Pioneering works of Lucy & Solomon (1970) and Castor, Abbott & Klein (1975, hereafter CAK) serve as a basis for present hot star wind theory.

Except a more general book by Lamers & Cassinelli (1999), Owocki (2001) provides an elegant introduction to the hot star wind physics, while Kudritzki & Puls (2000) or Owocki (2004) can be consulted for a more detailed review.

In this review we intend to answer two basic questions: First, what are the processes responsible for the acceleration of the stellar wind of OB stars? Second, what are the theoretical predictions of the wind structure?

2. Stellar wind of hot stars: micro-view

According to the theoretical studies of hot star winds, they are accelerated due to the light scattering in lines of heavier elements, and to a lesser extent due to scattering on free electrons. Hydrogen and helium are mostly inefficient for
wind driving. From the microscopic view of stellar wind in Fig. 1 it is clear that two basic processes are necessary to accelerate the bulk wind flow:

1. process that transfers momentum from the radiation field to heavier ions and electrons,
2. process that transfers momentum from heavier ions and electrons to the bulk flow (hydrogen and helium ions – mostly passive component).

2.1. How to transfer the radiation momentum to heavier ions?

To better understand transfer of the radiation momentum to heavier ions we shall generally discuss absorption and emission mechanisms. The photon frequencies before absorption and after emission are \( \nu \) and \( \nu' \), respectively (note that the case \( \nu' = 0 \) means pure absorption).

In the general case \( \nu \neq \nu' \) the transferred energy can be approximated as \( \Delta E = h(\nu - \nu') \approx h\nu \), the transferred momentum then about \( \Delta p \approx h\nu/c \). From this we can estimate the change of the kinetic energy as \( \Delta E_{\text{kin}} \approx \frac{1}{2}m_i (\Delta p/m_i)^2 = \frac{1}{2}h^2\nu^2/(m_ic^2) \). For a typical UV radiation \( \frac{1}{2}h^2\nu^2/(m_ic^2) \ll \Delta E \), and this means that most of transferred energy goes finally to heating (for \( \nu > \nu' \)) or cooling (for \( \nu < \nu' \)) of material and not to the macroscopic kinetic energy. This explains why the most common interaction of material and light results in heating or cooling. On the contrary, in the case \( \nu \approx \nu' \) most of transferred energy goes to the macroscopic kinetic energy and the irradiated material is accelerated (assuming isotropic emission).

Most effective processes for wind acceleration are those for which \( \nu \approx \nu' \). This condition is fulfilled for light scattering in lines and on free electrons. Both processes are important for the acceleration of hot star winds.

However, even line scattering may become less efficient. This is basically connected with the fact that frequencies of absorbed and emitted line radiation are slightly different. This effect, introduced in the domain of hot star wind theory by Gayley & Owocki (1994) is called Doppler or Gayley-Owocki heating/cooling. An example of this effect is given in Fig. 2. Let us have an artificial light source that emits radiation only in a very narrow wavelength interval corresponding only to the left (blue) part of the line-profile (see Fig. 2).
After the processes of absorption and emission the light from this source is redispersed over all wavelengths of a given line. Some part of the radiative energy has been thermalized, emitted radiation has lower energy, and the plasma can be heated by this process. On the other hand, let us have a light source that emits radiation with wavelengths corresponding only to the right (red) part of the line-profile. Again, the radiation is after the processes of absorption and emission redistributed over all wavelengths of the line. Clearly, after this, radiation has more energy that is taken from particle kinetic energy. Consequently, the plasma is cooler now. These processes are important for low-density winds (see Gayley & Owocki 1994; Krtička & Kubát 2001).

Figure 2. Schematic picture of Doppler (Gayley-Owocki) heating/cooling.

2.2. How to transfer momentum to the passive component?

Since hot star winds are ionised, the most efficient way to transfer acquired momentum from heavier elements to the passive component (H, He) is due to the Coulomb collisions. Frictional force on passive component (p) due to metallic ions (i) is given by

\[ f_{pi} \approx n_p n_i \frac{4\pi q_p^2 q_i^2}{kT} \ln \Lambda G(x_{ip}), \]  

(1)

where \( n_p, n_i \) are number densities of wind components, \( v_i, v_p \) are their radial velocities, and \( q_p, q_i \) their charges. The frictional force (1) depends on the velocity difference \( v_i - v_p \) via the so called Chandrasekhar function \( G(x_{ip}) \) (see Fig. 3), where

\[ x_{ip} = \frac{|v_i - v_p|}{\alpha_{ip}}, \]

\[ \alpha_{ip}^2 \approx 2kT \frac{m_i + m_p}{m_i m_p}. \]  

(2)

For very low velocity differences, \( x_{ip} \lesssim 0.1 \), the transfer of momentum between metallic and passive wind component is efficient. Wind is well-coupled in this case and it can be treated as one component. For higher velocity differences, \( x_{ip} \gtrsim 0.1 \), the frictional heating becomes important (Krtička & Kubát 2001). For even higher velocity differences \( x_{ip} \gtrsim 1 \), the Chandrasekhar function \( G(x_{ip}) \) is a decreasing function of the velocity difference. Consequently, the transfer of momentum between metallic and passive wind components is inefficient and wind components may decouple (e.g. Springmann & Pauldrach 1992).
3. Passing to macro: the radiative force

The radiative force is given by an integral

$$f_{\text{rad}} = \frac{1}{c} \int \chi_\nu F_\nu \, d\nu.$$  \hspace{1cm} (3)

Whereas the absorption coefficient $\chi_\nu$ depends explicitly only on local wind properties, the radiative flux $F_\nu$ is a non-local quantity and has to be obtained using the solution of the radiative transfer equation. Another complication for the calculation of the radiative force arises due to the Doppler effect. As the stellar wind is accelerated, the wavelength of a given line at which the wind absorbs the stellar radiation shifts to shorter wavelengths (in the reference frame of the star). Although this essentially enhances the radiative force since the wind is able to absorb stellar radiation that is unattenuated by the material below, this effect also significantly complicates consistent calculation of the radiative force. However, in the case of the stellar wind with relatively high velocity gradients both these effects may help to calculate the radiative force in an approximate way. This is the so called Sobolev (1947) approximation.

The radiative force due to optically thick line in the Sobolev approximation is given by

$$f_{\text{rad}, \text{thick}} \approx \frac{\nu F_\nu}{c^2} \frac{d\nu}{dv},$$  \hspace{1cm} (4)

where $F_\nu$ is the stellar flux at the frequency of a given line $\nu$ and $v$ is the wind velocity. Note that the radiative force in an optically thick line does not depend on line properties (e.g. the occupation numbers of corresponding levels or the line oscillator strength). This is one of the reasons why metals that have very low number density compared to hydrogen or helium (but a large number of optically thick lines) may be so important for the wind acceleration.

The radiative force in an optically thin line is given by

$$f_{\text{rad}, \text{thin}} \approx \frac{\pi e^2}{m_e c^2} F_\nu g_i f_{ij} \left( \frac{n_i}{g_i} - \frac{n_j}{g_j} \right).$$  \hspace{1cm} (5)

Metals dominate also to the optically thin line force due to very high number of their lines and due to frequent complete ionization of hydrogen and helium.
The total radiative force is given by the sum of contributions of individual lines. The calculation can be simplified using two approaches. First, it is possible to use the line distribution function parameterised by the set of force multipliers $k$, $\alpha$ and $\delta$ to obtain the radiative acceleration in CAK approximation

$$g_{\text{rad}} \sim k \rho_{\text{el}}^\delta \left( \frac{1}{\rho} \frac{dv}{dr} \right)^\alpha,$$

where $\rho_{\text{el}}$ is electron density and $dv/dr$ is the velocity gradient. Another line-force parameterisation was introduced by Gayley (1995) using $\bar{Q}$ parameter,

$$g_{\text{rad}} \sim \bar{Q}^{1-\alpha} \rho_{\text{el}}^\delta \left( \frac{1}{\rho} \frac{dv}{dr} \right)^\alpha.$$

4. Macro view

4.1. Basic structure of 1D CAK models

We have understood how the stellar winds of hot stars are accelerated on a micro-level. Now we shall discuss the influence of the wind microscopic structure on the observable macroscopic properties.

To do so, we have to calculate at least approximate stationary spherically symmetric wind models in the CAK approximation. However, there is a problem because an extensive table of line-force parameters calculated by Abbott (1982) leads to overestimation of mass loss rates (e.g. Krtička & Kubát 2004a). On the other hand, for massive stars it is possible to use recent extended set of force parameters of Kudritzki (2002).

It is possible to show that wind mass loss rate scales with stellar luminosity

$$\dot{M} = 4\pi \rho(r)v(r)r^2 \sim L^{1/\alpha'}, \quad \alpha' = \alpha - \delta.$$

(Kudritzki & Puls 2000), where $\alpha$ and $\delta$ are usual CAK parameters. This means that wind mass loss rates depend mostly on the stellar luminosity. Mass loss rates are also significantly influenced by wind properties on a micro-level (e.g. metallicity, ionization structure) via the parameter $\alpha'$.

Wind terminal velocity $v_\infty$ depends mostly on the escape velocity

$$v_\infty = c(T_{\text{eff}})v_{\text{esc}}, \quad c(T_{\text{eff}}) \approx 1 - 3$$

(e.g. Lamers et al. 1995) and only slightly on wind properties on a micro-level.

It can be also shown that clever combination of the mass loss rate, the terminal velocity and the stellar radius in the form of

$$\dot{M}v_\infty (R_*/R_\odot)^{1/2},$$

that resembles wind momentum and is therefore called the modified wind momentum depends mostly on the stellar luminosity and only marginally on the stellar mass (e.g. Kudritzki & Puls 2000).

The approximation described above allows calculation of wind models. Derived velocity structure (e.g. Fig. 4) can be in many cases approximated by the so-called beta velocity law using parameter $\beta$ in the form $v(r) = v_\infty (1 - R_*/r)^\beta$.
4.2. Multicomponent effects

For low-density winds the transfer of momentum between metals and hydrogen or helium may become inefficient (see Sect. 2.2.). There are several types of flow with respect to the multicomponent effects (Krtíčka & Kubát 2004b).

Winds with negligible multicomponent effects  For stars with relatively dense winds (e.g. winds of Galactic O supergiants) the multicomponent effects can be neglected. Such stellar wind can be adequately treated as one-component.

Wind temperature influenced by frictional heating  For stars with lower-density winds or very low metallicity the transfer of momentum (and energy) between metals and passive (H, He) component becomes inefficient and part of transferred energy goes to heating (Curé 1992; Krtíčka et al. 2003).

Decoupling in the wind  For stars with very low wind densities or with very low metallicities hydrogen and helium decoupling may occur in the wind (Springmann & Pauldrach 1992; Krtíčka & Kubát 2001). The stellar wind is not stable in this case (Owocki & Puls 2002; Krtíčka & Kubát 2002). This problem was studied using HD simulations (Porter & Skouza 1999; Votruba et al. 2006).

Decoupling of wind components in the atmosphere  Helium decoupling in the wind was proposed by Hunger & Groote (1999) as the explanation of the chemical peculiarity of He-strong stars. Due to its low charge, helium may decouple in the stellar atmosphere of cooler stars and a helium-free wind may exist in this case. For extremely low-density winds also hydrogen may decouple in the atmosphere and purely metallic stellar wind may exist (Babel 1996). For hot stars with lower luminosities the radiative force is not able to expel atoms out from stellar gravitational potential well, however the radiative force may cause chemical peculiarity (e.g. Michaud 2004).

The regions in HR diagram with different types of stellar wind are given in Fig. 5. Note, however, that NLTE models are necessary to study these effects in
5. Beyond classical CAK models

5.1. Influence of rotation

Rotation may cause significant deviations of wind structure from the spherical symmetry. Bjorkman & Cassinelli (1993) proposed that discs of rapidly rotating stars may be caused by the wind compression due to the stellar rotation. However, 2D hydrodynamic wind models (Owocki et al. 1996; Petrenz & Puls 2000) showed that due to the gravity darkening and nonnegligible non-radial component of the radiative force the wind density and mass loss rate at the equator are lower than at the poles.

5.2. Influence of magnetic fields

Also magnetic fields may cause significant deviations from spherical symmetry. They may be important for the correct explanation of the circumstellar activity of Bp stars (Babel & Montmerle 1997; Groote & Hunger 1997; Trigilio et al. 2004). According to MHD models of ud-Doula & Owocki (2002), the overall degree to which the wind is influenced by the magnetic field depends on the ratio between magnetic field energy density and wind kinetic energy density $\eta_*$,

$$\eta_* = \frac{B^2/(8\pi)}{\rho v^2/2}. \quad (11)$$

For a weak confinement ($\eta_* < 1$), the magnetic field is opened by the wind outflow. The structure of the circumstellar magnetic field is given mostly by the stellar wind and the influence of the magnetic field on wind is not a significant one. However, for strong confinement ($\eta_* > 1$) the situation is essentially opposite. The flow near the star is driven by the magnetic field. For B stars even a...
moderate magnetic field intensity \((B < 100 \, \text{G})\) causes strong confinement of the circumstellar environment by the magnetic field and is therefore very important for its structure. Note that for very strong magnetic fields some parts of the circumstellar envelope may be hydrostatic (Townsend & Owocki 2005).

Magnetic fields were used by Cassinelli et al. (2002) to explain the Be phenomenon. However, this is not supported by MHD simulations (ud-Doula 2006).

5.3. NLTE models
The "triplet" of parameters \((k, \alpha, \delta)\) or \((\bar{Q}, \alpha, \delta)\) gives only rough approximation to the radiative force. To solve this problem, it is possible to either

- introduce depth-dependent radiative-force parameters (e.g. Pauldrach et al. 2001; Kudritzki 2002), or to
- calculate the radiative force directly without any radiative-force parameters (e.g. Vink et al. 2001; Krtička & Kubát 2004a, and references therein).

NLTE approach is necessary in any case to obtain correct wind parameters (mainly mass loss rates).

The introduction of a more realistic radiative force based on the appropriate level occupation numbers enables detailed study of wind parameter variations. Pauldrach & Puls (1990) found high sensitivity of calculated wind parameters of P Cyg on its stellar parameters – the bi-stability. Vink et al. (1999) found the bi-stability jump at around \(T_{\text{eff}} \approx 25,000 \, \text{K}\) for normal supergiants. Using terminal velocity measurements of Lamers et al. (1995) they concluded that for stars cooler than the temperature corresponding to the bi-stability jump the mass loss rate \(\dot{M}\) increases \(5 \times\), whereas the terminal velocity \(v_{\infty}\) decreases \(2 \times\). The bi-stability jump is caused by an increase of the line acceleration due to Fe \(\text{III}\) lines close to the stellar surface. These calculations slightly overestimate the correct temperature location of the bi-stability jump, which occurs roughly at \(T_{\text{eff}} \approx 21,000 \, \text{K}\) according to the results of Lamers et al. (1995). Jump properties have still to be tested against observations since results of Trundle & Lennon (2005) show a different picture of the jump for SMC stars (c.f. Searle et al. 2006).

5.4. Radiative force – more exact approximations
Inclusion of higher order approximations to the radiative force leads to the wind instabilities (Feldmeier 1998). Resulting wind shocks may (at least partly) explain the observed X-ray emission of hot stars. Detailed discussion of this problem can be found e.g. in a review of Owocki (2004).

6. Open questions
There are many open questions connected with the stellar wind of OB stars. Here we discuss only those that seem to as to be especially appealing nowadays.

6.1. Influence of instabilities and clumping
Observed hot star wind properties show signatures of spatially organised structures – clumping (e.g. Antokhin et al. 1988; Martins et al. 2005). As noted
above, the radiative driving is unstable and may cause generation of shocks (e.g. Owocki 2004). The relation between instabilities and clumping is still unclear, although clumping parameter is ofted used as an additional free parameter of wind models.

6.2. Winds close to $\Omega \Gamma$ limit

During the stellar evolution some stars may come close to the $\Omega \Gamma$ limit (Maeder & Meynet 2000). However, it is not clear what sets the mass loss rate in this case. The radiatively-driven wind cannot drive outflow with an arbitrary mass loss rate (Owocki & Gayley 1997). It is possible that to estimate these mass loss rates it is necessary to calculate "unified" models of stellar interior and envelope.

6.3. What are wind mass loss rates?

Reliable theoretical predictions of the mass loss rate are still insufficient. One of the reasons is that detailed (NLTE) wind models are necessary to predict mass loss rates. As the consequence, reliable predictions (for OB star domain) are available only for O-stars and luminous B-stars (e.g. Pauldrach et al. 2001; Vink et al. 2001; Krtička & Kubáč 2004a) and for hot horizontal branch stars (Vink & Cassisi 2002). Note that even frequently used predictions of Vink et al. (2001) suffer from many simplifications like neglect of "line branching" (Sim 2004), wind instabilities and clumping or X-ray radiation (MacFarlane et al. 1994). Whereas there is a relatively good agreement between theoretically predicted mass loss rates and mass loss rates derived from observations for individual hot OB stars, there is a significant disagreement between these values for cooler B supergiants (Vink et al. 2000). Although part of this discrepancy may be due to observations, some part of this discrepancy is likely due to model simplifications.

Even worse, for many stars (e.g. for many main-sequence B stars) there are no reliable predictions of mass loss rate available. The problem is that there are several processes that may influence the mass loss rate of these stars, e.g.

- multicomponent wind structure (Springmann & Pauldrach 1992; Curé 1992; Babel 1995; Krtička & Kubáč 2001),
- GO (Doppler) heating (Gayley & Owocki 1994),
- thin-wind effect (Owocki & Puls 1999).

Low-density stellar winds are also very difficult to observe. However, some indirect wind indications may be available, e.g. due to certain chemical peculiarities (Landstreet et al. 1998; Dworetsky & Budaj 2000) or due to wind magnetic braking of stellar rotation (Mikulášek et al. 2006; Oksala & Townsend 2006).

There is an increasing observational evidence that hot star winds are clumped. Martins et al. (2005) studied winds of several Galactic O-stars in detail and concluded that mass loss rates derived assuming clumped winds may be $2 \times - 5 \times$ lower than those derived assuming smooth winds (Fig. 5). Finally, for some stars with low luminosities the wind mass loss rates seem to be more than ten times lower than the predicted ones (Fig. 6). Similar effect was detected for SMC stars by Bouret et al. (2003). Thin-wind effect (Owocki & Puls 1999) may help to understand the origin of this difference.
7. Conclusions

We have discussed basic physical principles that drive the stellar winds of OB stars both on micro and on macro levels. We have also seen that despite the tremendous effort of many astronomers, more than 30 years after the publication of the seminal CAK paper we are still not sure what the mass loss rates of hot stars are. To conclude with something more optimistic we switch to slightly different stars – WR stars. Gräfener & Hamann (2005) were able to theoretically explain the acceleration of the stellar wind of WR stars. According to these models, wind sonic point is located deep in the stellar interior and the stellar wind in the inner regions is accelerated due to the iron opacity bump and convection in WR stars occurs also as a consequence of the iron opacity bump. Iron opacity bump stands also behind pulsations in β Cep stars (Moskalik & Dziembowski 1992; Cox et al. 1992). Consequently, processes of the same physical nature cause completely different behaviour in different circumstances! Since wind critical point in the case of WR stars is located relatively deep in the stellar interior, any differentiation between stellar core, atmosphere, and wind may become artificial and we might need to (at least for some specific problems) calculate "unified" models of stellar interior and exterior.

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Owocki: I must disagree with the notion that Fe opacity bump can be an important mechanism for wind driving. I think to focus on using this bump to set the wind through the sonic point is mis-guided. The sound speed is of order $25 \text{ km s}^{-1}$, about 30 times smaller than the escape speed $v_{\text{esc}} (\approx 700 \text{ km s}^{-1})$; implying an energy that is 1/1000 of that needed to escape the star Thus even if Fe opacity sets the wind through the sonic point, we must appeal to some other mechanism to do the 99.9% of the remaining work needed to escape. I think understanding wind mass loss should focus instead on the mechanism that does this overwhelming bulk of the work.

Krtička: I agree that iron bump opacity alone is not able to drive the stellar wind of WR star and does only a certain part of work necessary to launch the wind. Also other opacity sources should be included. To drive the wind it is necessary to accelerate the wind material from the subsonic velocities to the velocity higher than the escape speed.

Townsend: Another way of thinking about the iron opacity bump is to recall that it drives SPB & $\beta$ Cep pulsations. The reason these stars show pulsations is that the iron opacity bump disappears when the temperature varies significantly from 200000 K. This makes it very difficult to understand how a wind – which requires a spatially-extended region of high opacity – could be driven by the iron opacity bump.

Krtička: Gräfener & Hamann (2005) were able to consistently accelerate the wind from the subsonic velocities to the velocities higher than the escape speed. I do not think that your argument is important, because the physical mechanism that drives the pulsations is different. Pulsations are driven basically by the heat flux, however the stellar wind is driven by the gradient of the radiation pressure.

Stéée: The terminal velocity and the mass flux is strongly depending on the inclination angle (on the stellar colatitude) i.e. larger at the poles and lower at the equator. Thus it is normal that there is a large scattering in the mass loss rate versus effective temperature graph. Moreover the mass loss also depends on the lines you are using to determine it (IR, visible, UV). Finally, it seems difficult for me to compare observational and theoretical $v_{\infty}$ and $\dot{M}$ for nonspherical wind (for instance following the bi-stability scheme you have shown).

Krtička: Rotation is important for wind structure, however it has only second order effect for stars with rotational velocities well bellow the critical one (Petrenz & Puls, 2000). It is not likely that it causes order of magnitude differences of $\dot{M}$ for cool B stars or too high predicted $\dot{M}$ for low-luminosity stars.