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Challenges to the theories of B stars circumstellar environment

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We review recent developments in the field of B stars circumstellar environment modelling and discuss future improvements which are necessary to obtain more realistic models of the circumstellar environment of B stars.

Keywords: stars: winds, outflows – stars: mass-loss – stars: early-type – hydrodynamics – instabilities

1 Introduction

From the general point of view, the circumstellar environment of B stars offers a great challenge to any self-consistent theory or modelling. This is partly caused by the fact that the temperature domain of B stars lies somewhere in the middle of the hot star region, between the domain of O stars with strong radiatively driven winds and the domain of mostly relatively quiet A stars. Unlike theoretically well-studied circumstellar environment of O stars, for B stars many different physical effects occur which may significantly influence its structure and state. We can mention deviations from spherical symmetry, significant influence of magnetic fields, and occurrence of new types of wind instabilities, which may be connected, e.g., with a multicomponent nature of line-driven winds.

Unfortunately, self-consistent models of circumstellar environment of B-stars are not available yet. Most of published models use several more or less unrealistic assumptions which consequently constrain the validity of obtained models. Thus, instead of discussing individual models in detail, we aim to depict basic physical processes, which are or may be important for the circumstellar environment of B stars.

2 The rate of the mass-loss

The principal question connected with the circumstellar environment of any star is the physical nature of the process by which the star loses its mass and the rate at which the mass-loss occurs. Besides mass-transfer in close binaries, the only relatively well understood process of mass-loss available for B stars is that due to the line-driven stellar wind.

Stellar wind of hot stars is accelerated mainly due to the absorption of radiation in the resonance lines of C, N, Fe, and other heavier elements, and due to the light scattering on free electrons. From both theoretical considerations and observations we can conclude, that the amount of mass expelled from the star per element of time, the so-called *mass-loss rate* $\dot{M}$, is proportional to the stellar luminosity (Kudritzki and Puls 2000)

$$\dot{M} \sim L^{\frac{1}{\alpha'}}, \qquad \alpha' \approx 0.5. \tag{1}$$

The limit wind velocity in the infinite radius, so-called wind *terminal velocity*, is another important wind parameter. Again, according to both theory and observation, v_∞ is proportional to the escape velocity from the stellar surface (Lamers et al. 1995)

$$v_\infty = c(T_{\text{eff}}) v_{\text{esc}}, \qquad c(T_{\text{eff}}) \approx 1 - 3. \tag{2}$$

However, theoretical predictions of the mass-loss rate for B stars are only scarce since detailed NLTE models are necessary for a meaningful prediction. Reliable predictions of mass-loss rate are available only for luminous B stars (Vink et al. 2000) and for hot horizontal branch stars (Vink and Cassisi 2002). Moreover, the correspondence between observed and predicted mass-loss rates is not satisfactory, because there is a high scatter between "observed" (derived from observation) and theoretical values (see the comparison of the theoretical and observed dependence of the wind-momentum $\dot{M} v_\infty \left(R/\mathrm{R}_\odot\right)^{1/2}$ on luminosity, Vink et al. 2000, Fig. 10 therein). This may be partly due to effects which are neglected in these models, e.g. the influence of "line branching" (Sim 2004), wind clumping (Repolust et al. 2004), wind instabilities (Owocki and Puls 1999), or X-ray radiation (MacFarlane et al. 1994). For many of low-luminosity main-sequence B stars the situation is even worse, because for many of these stars we do not even know whether they have a stellar wind or not. Note that "classical" line-force parameters calculated by Abbott (1982) do not predict correct mass-loss rates even for O stars (cf. Krtička and Kubát 2004a), and consequently can be used for B stars only with caution.

The mass-loss rate in the B-star domain does not depend on the stellar effective temperature monotonically. Pauldrach and Puls (1990) found high sensitivity of calculated wind parameters of P Cyg on its stellar parameters, mainly effective temperature – the *bi-stability*. Vink et al. (1999) found a bi-stability jump at around $T_{\rm eff} \approx 25\,000\,{\rm K}$ for normal supergiants. They found that for stars cooler than the temperature of the bi-stability jump the mass-loss rate $\dot{M}$ increases 5×, whereas the terminal velocity v_∞ decreases 2×. They concluded that the bi-stability jump is caused by an increase of the line acceleration by Fe III lines close to the stellar surface. Note that Vink et al. (1999) calculations slightly overestimate the correct temperature location of the bi-stability jump, which occurs roughly at $T_{\rm eff} \approx 21\,000\,{\rm K}$ according to the results of Lamers et al. (1995, see also Smith et al. 2004).

3 Rapid rotation – Be and B[e] stars

Rotation can significantly influence the circumstellar environment of B stars. It is likely that the effect of rotation is one of the ingredients necessary to answer the basic question of Be and B[e] star research, which was not reliably answered for more than one hundred years: What is the reason for the occurrence of the disc around Be and B[e] stars?

Bjorkmann and Cassinelli (1993) presented a simplified model according to which discs around Be stars originate as a consequence of the equatorial compression of the radiatively driven stellar wind due to rapid rotation. However, subsequent detailed numerical simulations of Owocki et al. (1996) and Petrenz and Puls (2000) showed that gravity darkening and nonradial radiative forces inhibit the formation of an equatorial disc. Moreover, wind densities and mass-loss rates are *lower* at the equator than at the poles,

$$\dot{M}(\theta) \sim \left(1 - \Omega^2 \sin^2\theta\right), \quad \Omega = v_{\rm rot}/v_{\rm crit}. \qquad (3)$$

The original Bjorkmann and Cassinelli idea was revived by Cassinelli et al. (2002) using the magnetically torqued disc model, as shall be discussed later.

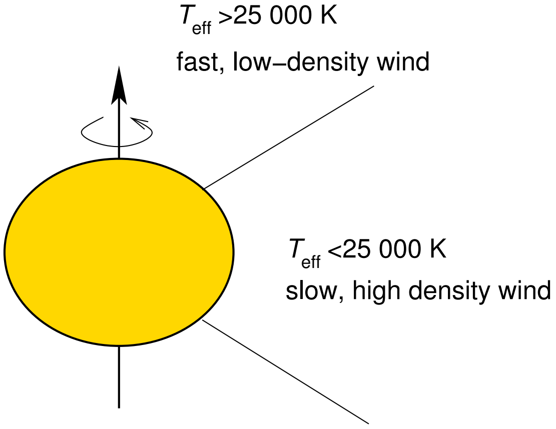

Fig. 1: Bi-stability model for the disc formation around B[e] stars

There are also other theories for the explanation of Be star disc. To complete this discussion we have to mention the *binary model* of Kříž and Harmanec (1975), according to which discs occur due to the mass transfer in an interacting binary or a *pulsational model*, according to which pulsations may eject material into the disc (see discussion in Porter and Rivinius 2003). However none of them is able to reliably describe the disc occurrence, either due to the apparent lack of close companions in the former case, or due to low amount of energy involved in the pulsations in the latter one.

On the other hand, rapid rotation together with a bi-stability can help to explain the appearance of discs in B[e] stars. As the star rotates rapidly, the polar effective temperature is higher than the equatorial one. This effect is known as the gravity darkening. Normally, as we have already discussed, according to the predictions of line-driven wind theory, the wind density and mass-loss rate would be higher at the poles than at the equator. However, in the case when polar effective temperature is higher than the temperature corresponding to the bistability jump and the equator effective temperature is lower than the temperature corresponding to the bistability jump (see Fig. 1), there may occur high-velocity low-density wind at the poles and low-velocity high-density wind at the equator (Lamers & Pauldrach 1991, Pelupessy et al. 2000). Consequently, an outflowing (angular momentum conserving) disc-like structure can form.

However, it is possible that the correct answer to the question of the origin of Be star disc will not give the theory of the Be star circumstellar environment, but rather the theory of stellar atmospheres or even the theory of stellar evolution. The common assumption of the Be star research (supported by numerous observations) is that the rotational velocity of Be stars is high, however significantly lower than corresponding critical rotational velocity (e.g. Porter 1996, note that the rotational velocity of a rigid body star can not exceed this critical rotational velocity). However, it is possible that our current measurements of the rotational velocity for stars which rotate close to the critical rotational velocity are incorrect, i.e. that we are not able to measure very high rotational velocities correctly (Collins and Truax 1995, Townsend et al. 2004). We think that the most important question of Be star research now is: How fast do Be star really rotate? And if Be stars really rotate close to the critical rotational velocity, do we have to calculate unified models of stellar interior and circumstellar environment to understand the mechanism of spinning up the star and to obtain self-consistent disc models?

4 Disc structure

As we have mentioned in the previous section, consistent models of Be and B[e] stars' circumstellar environment are not available yet. Thus, in order to gain some useful information about the disc, people either calculate disc emergent radiation with more or less given disk density structure or study disc stability.

4.1 Radiative transfer in discs

Emission line profiles of Be star discs were calculated using different simplifying assumptions (e.g. Huang 1972, Hanuschik 1995, Hummel and Vrancken 2000). One of the most important conclusions of these studies is that it is difficult to derive the disc rotational profile from the analysis of emission line profiles only (especially, to decide if the disc follows the Keplerian rotational law or whether the disc is conserving angular momentum). To calculate detailed accurate line profiles sophisticated radiative transfer calculations are necessary (Hummel 1994, Dullemond and Turolla 2000, van Noort et al. 2002, Steinacker et al. 2003, Korčáková and Kubát 2005). A comparison of different methods of radiative transfer calculations in disks has been performed by Pascucci et al. (2004).

4.2 Disc stability

Be stars are well known for their long-term *V*/*R* variations of double-peaked line profiles (variations of heights of violet (V) and red (R) peaks of the double profile). To explain these variations, oscillations in the Be star disc are often invoked. Okazaki (1991) showed that the only possible global oscillations in nearly Keplerian discs are very low-frequency, one-armed oscillations. However, these modes are retrograde which is in contradiction with the observation, since observed oscillations are prograde. Savonije and Heemskerk (1993) showed that observed prograde oscillations can be explained by the multipole gravity terms which occur when the star is rotationally distorted. Note, however, that even this theory fails to explain observed variations of the *V*/*R* cycle (Fiřt 2004).

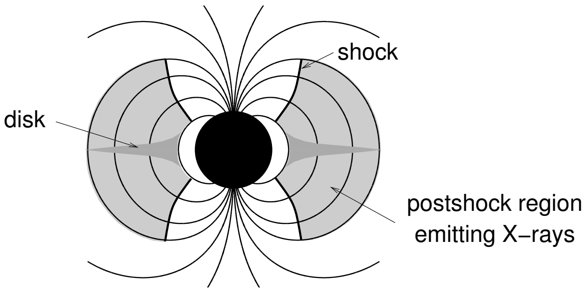

Fig. 2: Structure of the circumstellar environment around Bp stars according to Babel and Montmerle (1997)

Finally, note that there are also some other issues connected with the disc stability and variability. For example, discs may have their own winds (Proga et al. 1998).

5 Magnetic fields

One of the areas of the most intensive research in the domain of the circumstellar environment of hot stars nowadays is the issue of the influence of magnetic fields on the circumstellar environment. Although a lot has been done in this field during the last decades, no reliable models are available and many open questions remain. This is partly due to the fact that the detailed modelling in this field is a very complicated task, because the interplay between the radiatively driven wind and magnetic field is to be taken into account. This means that at least 2D hydrodynamical simulations of this environment has to be used to obtain reliable models. However, such models for B stars are not available. Thus, we shall confine ourselves only to the discussion of more simplified models.

Similarly to the rotation, also the influence of magnetic fields may cause significant deviations from spherical symmetry. This led some authors to the proposition that magnetic field is the missing ingredient necessary (together with fast rotation) for explanation of Be star discs (Cassinelli et al. 2002, Maheswaran 2003, Brown et al. 2004). However, this theory suffers with several problems, for example we do not know whether all Be stars have a stellar wind which is strong enough to create a disc. There may be also problems with stability of such a disc. These questions are still open since the detailed magnetohydrodynamic model for rotating B star has not been calculated yet.

Anyway, magnetic field seems to be important for other subgroup of active B stars, namely for Bp stars (cf. Groote & Hunger 1997, Trigilio et al. 2004). Especially, the radio and X-ray activity of these stars is probably connected with magnetic field.

To describe circumstellar environment of Bp stars in detail, Babel & Montmerle (1997) proposed a model of interaction of a wind of Bp stars with a magnetic field. They did not solve magnetohydrodynamic equations in detail, but they assumed that the stellar wind moves along the magnetic field lines. Consequently, the wind from polar regions is focused into an equatorial plane and winds from opposite hemispheres collide and create a shock (which causes X-ray emission) and possibly a co-rotating disc (see Fig. 2).

As we have already mentioned, detailed magnetohydrodynamic models of the circumstellar environment of B stars are not available. Such models are available only for O stars. Although the detailed picture of circumstellar environment of B and O stars differs, magnetohydrodynamic models calculated for O stars can at least describe likely general behavior of circumstellar environment of B stars influenced by the magnetic field. Detailed magnetohydrodynamic models of a stellar wind of O stars were presented by ud-Doula and Owocki (2002). They concluded that the overall degree to which the wind is influenced by the magnetic field depends largely on "wind magnetic confinement parameter" η_* which characterizes the ratio between magnetic field energy density and kinetic energy density of the wind,

$$\eta_* = \frac{B^2/(8\pi)}{\rho v^2/2}, \tag{4}$$

or, approximately,

$$\eta_* \approx 0.4 \frac{\left(\frac{B}{100\,\mathrm{G}}\right)^2 \left(\frac{R_*}{10^{12}\,\mathrm{cm}}\right)^2}{\left(\frac{\dot{M}}{10^{-6}\,\mathrm{M}_\odot \mathrm{year}^{-1}}\right)\left(\frac{v}{10^{8}\,\mathrm{cm\,s}^{-1}}\right)}. \tag{5}$$

For a weak confinement ($\eta_* < 1$), the field is fully opened by the wind outflow. In this case the influence of the magnetic field is not a significant one, the structure of the circumstellar magnetic field is given mostly by the stellar wind. However, for stronger confinement ($\eta_* > 1$) the situation is basically opposite. The flow near the star is driven by the magnetic field. Most B stars have much lower wind density than O stars, hence for B stars even a moderate magnetic field intensity ($B < 100\,\mathrm{G}$) causes strong confinement of circumstellar environment by the magnetic field. We can conclude that even a moderate magnetic field is probably very important for the circumstellar environment of B stars.

6 Multicomponent wind structure

Moreover, for low-density winds even the common assumption that all constituents of the stellar wind move with the same velocity breaks down. Stellar winds of hot stars are predominantly accelerated due to momentum transfer from radiation field to heavier elements like C, N, O, or Fe. Other wind components, which predominantly contribute to the wind density (hydrogen and helium) are mostly accelerated by Coulomb collisions with heavier elements. Clearly, stellar winds of hot stars have a multicomponent nature. This means that each component of the wind (i.e. each chemical element or even each ionization state) may have different velocity. For high density winds (typically stellar winds of O stars or B supergiants) metallic and major wind components are well coupled, i.e. the velocity difference between them is much smaller than the thermal speed. However, this is not the case for low-density stellar winds of B stars (Castor, Abbott and Klein 1976, Springmann and Pauldrach 1992, Krtička and Kubát 2001) for which the velocity difference between wind components becomes comparable with the thermal speed. Many interesting physical effects appear in this case, which may influence the wind structure, ranging from frictional heating, wind decoupling, and hydrogen fallback to pure metallic wind.

An example of frictionally heated wind of a B4 star is given in the Fig. 3. Close to the stellar surface the wind is relatively dense, the velocity difference between wind components is small, and the frictional heating is negligible. However, in the outer wind regions the wind density is lower, the velocity difference between wind components increases and is comparable with the thermal speed. Consequently, frictional heating becomes important.

For even lower wind densities the velocity difference between wind components is larger than the thermal speed, the metallic wind component is not able to accelerate the passive component any more and, consequently, hydrogen and helium may fall back or create clouds around the star (Porter & Skouza 1999). An example of such model for a B5 star is given in Fig. 4. The wind is strongly frictionally heated in this case and may emit significant amount of X-ray radiation (Kubát et al. 2004). Note that the flow in the region where decoupling occurs is not stable (Owocki and Puls 2002, Krtička and Kubát 2002).

For stars with lowest luminosities (main-sequence B stars with $T_{\mathrm{eff}} < 14\,000\,\mathrm{K}$), either metals are not able to accelerate hydrogen any more, hydrogen stays in the stellar atmosphere and pure metallic winds may exist with $\dot{M} \approx 10^{-16}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (Babel 1995, 1996), or there are no winds at all.

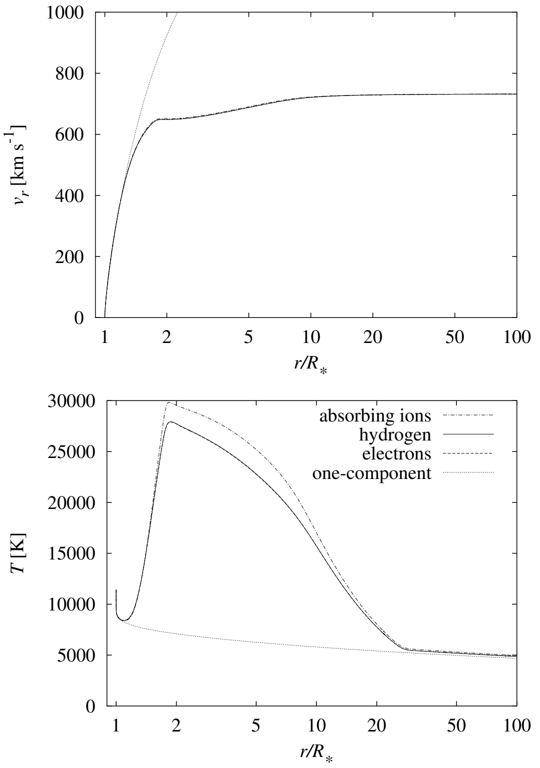

Fig. 3: An example of a frictionally heated wind of a B4 star (Krtička and Kubát 2001) with parameters $T_{\rm eff} = 17\,200\,{\rm K}$, $M = 5.12\,{\rm M}_\odot$ and $R = 3.26\,{\rm R}_\odot$. *Upper panel:* variations of wind velocity with radius. Wind velocities of each component in a three-component wind are nearly equal. *Lower panel:* wind temperature. Note the strong heating in the central parts of the model compared to the one-component one. Temperatures of electrons and hydrogen are nearly equal.

To conclude, regions in HR diagram with different types of multicomponent wind *may* look as is shown in the Fig. 5 (Krtička & Kubát 2004b). Note, however, that this diagram was obtained using simplified force-multipliers and that in reality the correct location of individual regions may be slightly different. Nevertheless, the general layout of particular regions will not change.

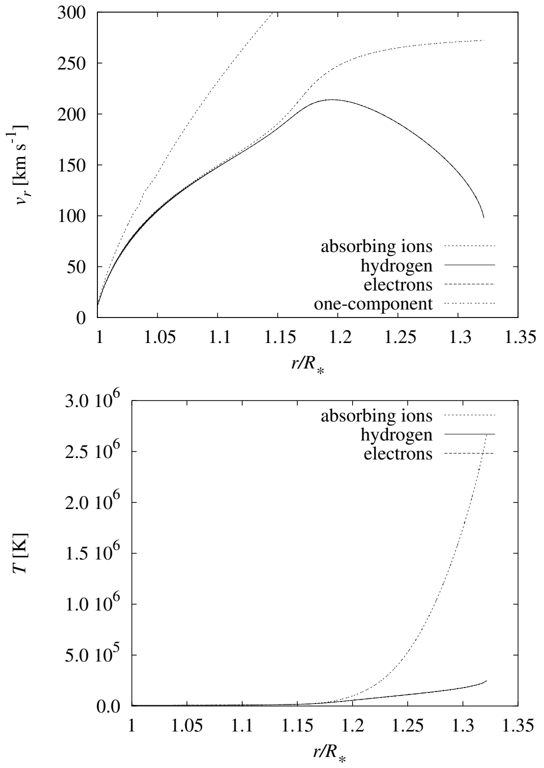

Fig. 4: An example of wind decoupling (close to the star) in the wind of a B5 star (Krtička and Kubát 2001) with parameters $T_{\rm eff} = 15\,500\,{\rm K}$, $M = 4.36\,{\rm M}_\odot$ and $R = 3.01\,{\rm R}_\odot$. *Upper panel:* variations of wind velocity with radius. Hydrogen and metals decouple in the middle of the model, metals may leave the star, however hydrogen decelerates and may fall back onto the stellar surface or possibly create some kind of clouds above the stellar surface. Velocities of hydrogen and electrons are nearly equal. *Lower panel:* wind temperature. Note strong heating up to coronal temperatures. Temperatures of hydrogen and electrons are nearly equal.

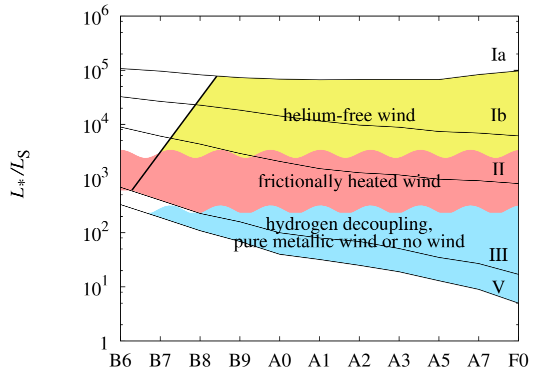

Fig. 5: Regions in HR diagram with different types of multicomponent wind (Krtička & Kubát 2004b)

7 Other problems of low-density winds

However, there are also other problems which may occur in low-density stellar winds. For thin winds with optically thin continuum the applicability of the Sobolev approximation may fail at the sonic point which can result in a wind instability (Owocki and Puls 1999).

Moreover, shadowing by photospheric lines (Babel 1996) may result in a lower mass-loss rate. There are also difficulties with modelling of the transition region between photosphere and wind, because the Sobolev approximation is not valid there. A complicated interplay between wind, radiative diffusion, and gravitational settling, which may be especially important for hot chemically peculiar stars, may occur there.

The wind temperature of a low-density stellar wind may be influenced by the so-called Gayley-Owocki heating (Gayley and Owocki 1994). The origin of this effect lies in the processes of absorption and emission of photon in a given line. The photon carries its own momentum, thus after the absorption of the photon atom moves with slightly different velocity. Consequently, due to the Doppler effect, the photon is afterwards emitted with a slightly different frequency (see Fig. 6). This means that the photon energy changes and the energy difference may be used for plasma heating or cooling. However, in reality the distribution of atomic velocities is random, consequently contributions of heating and cooling terms in many cases cancel. This process can be viewed from another perspective. Imagine, that we have a light source which emits radiation with wavelengths corresponding only to the left (blue) part of the line-profile (see Fig. 7). After the processes of absorption and emission of the radiation the light from this source is redistributed to all wavelengths of given line. Clearly, a part of the radiative energy is thermalized, radiation has less energy now, and the plasma can be heated by this process. On the other hand, imagine that we have a light source which emits radiation with wavelengths corresponding only to the right (red) part of the line-profile. Again, the radiation from this source is redistributed to all wavelengths of the line. Clearly, after this process radiation has more energy and this energy is taken from the kinetic energy of particles. Consequently, the plasma is cooler now. Krtička & Kubát (2001) showed that Gayley-Owocki heating term can be obtained from Boltzmann kinetic equation and calculated wind models with an influence of this type of heating.

8 Conclusions

The aim of this review is to discuss the circumstellar environment of B-type stars from the theoretical point of view. For an approach based more on observational data we can can refer an interested reader to reviews by Kudritzki & Puls (2000) for the discussion of stellar winds, Harmanec (2001) and Koubský (2005) for the discussion of Be stars, and Groote (2003) for the review of chemically peculiar stars.

There are many issues which were not discussed in this review. Moreover, our discussion was focused mostly to radiatively driven stellar winds, although also other types of circumstellar environment may exist in the B star domain. For example, the existence of coronae around B stars is time-by-time discussed in literature (e.g. Kubát at al. 2004, and references therein). However, consistent models are not available. Moreover, there may occur time and spatially confined ejecta of matter into the circumstellar environment. Finally, the complicated problem of envelopes of binary stars created in the course of mass-transfer in B binaries has been completely neglected here. However, we can apologize these omissions by the lack of detailed self-consistent models in the former cases and by our will to depict only individual physical processes which have to be considered in self-consistent models of circumstellar environment of B stars in the latter case.

We have shown that there are many physical effects which may significantly influence the theoretical modelling of B star circumstellar environment. Hence, schematic “toy” models have only limited applicability and detailed consistent models are necessary. We would like to encourage theorists to provide such models to help to solve the long-standing problems connected with the circumstellar environment of B stars.

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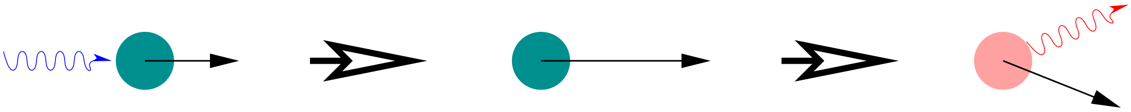

Fig. 6: Change of atomic velocity during the processes of photon absorption and emission. After the absorption of a photon the atom accelerates. Subsequently, the photon is emmited, however, due to the Doppler effect, with a slightly different frequency. The energy difference of absorbed and emitted photons may be used to heat the gas.

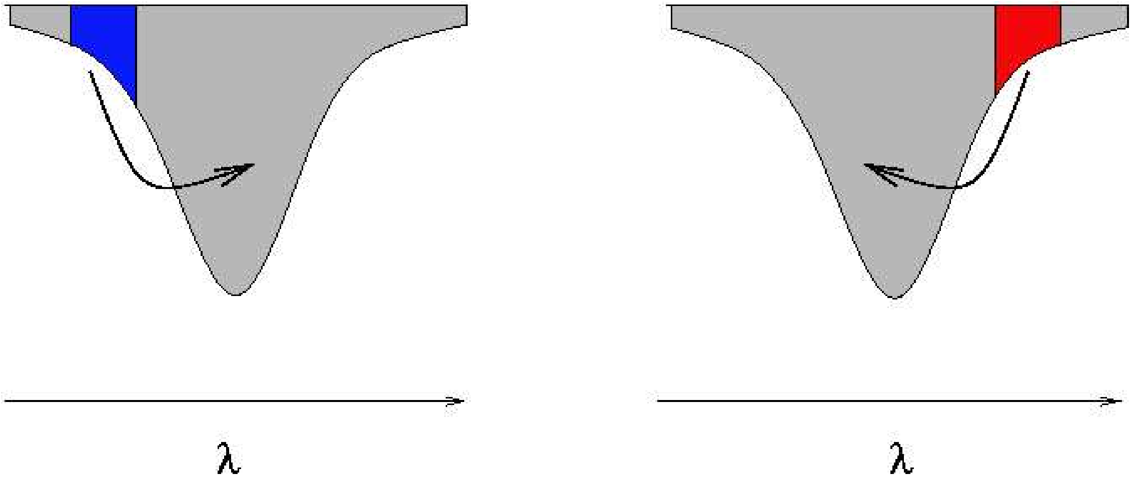

Fig. 7: Schematic description of redistribution of the light from the artificial source which emits radiation in a very narrow wavelength interval during the processes of light absorption and emission. *Left panel* heating of plasma, *right panel* cooling of plasma.

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