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Ionization Structure in the Disks and Winds of B[e] Stars

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Abstract. We investigate the ionization structure in the non-spherical winds and disks of B[e] stars. Especially the luminous B[e] supergiants seem to have outflowing disks which are neutral in hydrogen already close to the stellar surface. The existence of neutral material so close to the central star is surprising and needs to be investigated in detail. We perform our model calculations mainly in the equatorial plane, trying to find a plausible scenario that leads to recombination in the vicinity of the hot stars. Two different approaches are presented that both result in a hydrogen neutral equatorial region. We especially focus on the influence of stellar rotation which is known to play a significant role in shaping non-spherical winds. We show that a rotating star can have a neutral equatorial wind, even without the need of a density enhancement due to bi-stability or wind compression, but simply due to graviational darkening in combination with the known high mass-loss rates of the B[e] stars and especially the B[e] supergiants.

1. Introduction

The circumstellar material of B[e] stars is known to be non-spherically symmetric, and the best studied sample of B[e] stars, the B[e] supergiants, even show strong indication for the existence of an equatorial gas and dust disk. The hybrid character of their optical spectra have been interpreted by a non-spherical wind with a typical line-driven wind in polar, and a slow, high-density wind in equatorial direction (Zickgraf et al. 1985, and Zickgraf this volume). Indications for the existence of a neutral gas and dust disk come (i) from molecular emission like the CO first overtone bands (McGregor et al. 1988), (ii) the existence of dust causing a strong mid-IR excess emission (see e.g. Voors 1999, and references therein), and (iii) the detection of strong [O I] emission in the high-resolution optical spectra of several B[e] stars and supergiants (Kraus & Borges Fernandes 2005; Kraus et al. 2005, 2006), the latter even speaks in favour of a huge amount of hydrogen neutral material in the vicinity of these luminous stars. This neutral material can only exist in their dense disks, and model calculations have shown that these disks must be neutral already near the stellar surface to account for the observed line luminosities and to keep the needed disk mass loss rate at a reliable value (Kraus & Borges Fernandes 2005; Kraus et al. 2006). The goal of our study is therefore to find scenarios which allow neutral material to exist close to the surfaces of these stars.

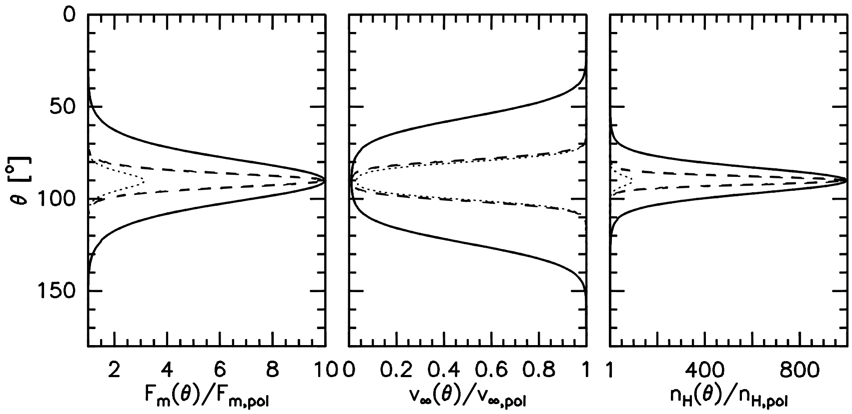

Figure 1. Distribution of the mass flux (left), escape (and hence terminal, because $v_\infty \sim v_{\rm esc}$) velocity (mid) and hydrogen density (right) over the stellar surface. The parameters are normalized to their polar values. Different line styles are for different model parameters as specified in Kraus & Lamers (2003).

2. Ionization Structure Calculations in Non-Spherical Winds

We present two different approaches which both lead to the formation of a neutral equatorial region. The first one is an empirical model which assumes a non-spherical wind with a surface mass flux that increases from pole to equator. The second one deals with the influence of rigid stellar rotation.

2.1. Empirical Non-Spherical Wind Model

In a first attempt we developped a code to calculate the ionization structure in a pure H plus He wind (Kraus & Lamers 2003). We used empirically defined latitude dependent mass flux and escape (or terminal) velocity distributions (left and mid panel of Fig. 1), which define a surface density distribution that accounts for the observed velocity and density ratios between equator and poles, and creates a disk-like structure with an opening angle of $20^\circ - 30^\circ$ (mid and right panel of Fig. 1).

We solved the ionization balance equations for H and He in the on-the-spot approximation which means that all photons generated via recombination and suitable for re-ionization are absorbed in situ. The electron temperature and radial wind velocity were set constant and we used the point source approximation for the stellar radiation field. These restrictions resulted in the calculation of an *upper limit* of the recombination distances which are plotted for three different model parameters in Fig. 2 (for more model details see Kraus & Lamers 2003).

All these models for which the total mass loss rates were in the range $2.4 \times 10^{-6} \ldots 2.4 \times 10^{-5}\,{\rm M}_\odot{\rm yr}^{-1}$, which is a reasonable range for B[e] supergiants, resulted in a hydrogen neutral disk close to the hot stellar surface.

2.2. Stellar Rotation and the Formation of a Non-spherical Wind

During the last years, the non-negligible influence of stellar rotation on stellar evolution has been investigated in detail (see e.g. Maeder 1999; Maeder & Meynet

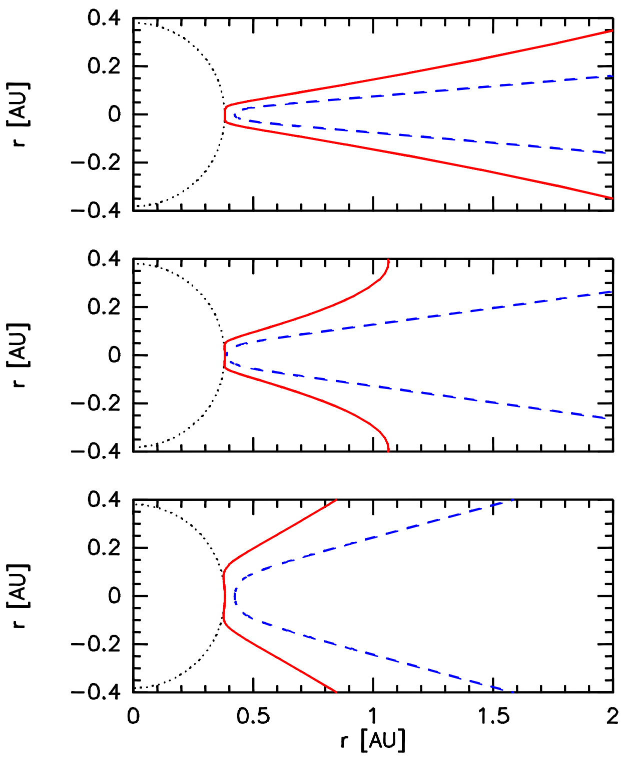

Figure 2. Three examples for the ionization structure of H (dashed) and He (solid) in non-spherical winds (taken from Kraus & Lamers 2003). The material to the right of the full or dashed line is neutral. Both elements clearly recombine close to the stellar surface in the equatorial plane, leading to a hydrogen neutral disk.

2000; Meynet & Maeder 2000, and this volume), and it has been suggested that the appearance of non-spherical winds around luminous stars might be caused by rotation (Maeder 2002; Maeder & Desjaques 2001). We therefore started to investigate the influence of rigid stellar rotation on the formation of a hydrogen neutral disk. Rotation causes a flattening of the stellar surface and therefore a reduction of the local net gravity in the equatorial region. The decrease in gravity from pole to equator equally results in a decrease of the stellar flux which is proportional to the local net gravity. Hence, the effective temperature also decreases from pole to equator (left panel of Fig. 3), known as the gravity darkening (or polar brightening, von Zeipel 1924).

The latitude dependence of the gravity and effective temperature has also impacts on the stellar wind parameters: The escape velocity following from the balance between gravitational and centripetal forces becomes latitude dependent, decreasing from pole to equator. The same holds for the terminal wind velocity which is (for line-driven winds) proportional to the escape velocity. And even the mass flux from the star tends to decrease from pole to equator when implementing gravity darkening into the CAK theory, as shown by Owocki et al. (1998).

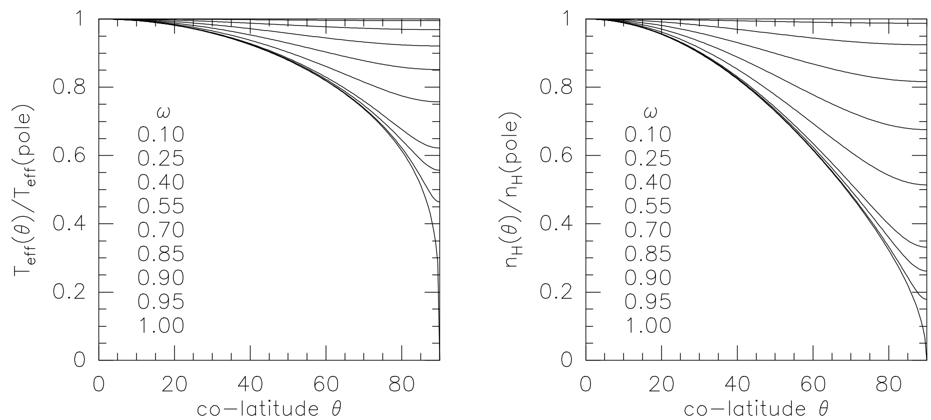

Figure 3. Normalized surface distributions of the effective temperature (left) and the wind density (right) as a function of the co-latitute, θ. The curves from top to bottom are for an increasing rotational velocity indicated by the parameter ω, which is the ratio of the equatorial rotation velocity over the critical velocity.

More important for the ionization structure calculations is the density in the wind. According to the mass continuity equation the hydrogen density scales as $n_{\rm H} \sim F_{\rm m}/(v\,r^2)$. A proper elaboration of this ratio, taking into account the rotational distortion of the stellar surface, resulted in surface density distributions of rotating stars as shown in Fig. 3 (right panel). From this plot it is clear, that the density at any given distance also *decreases* from pole to equator. A rotating star, when neglecting additional effects like bi-stability or wind compression, will therefore have a less dense wind in the equatorial region.

Both important parameters in the ionization balance equations, i.e. the effective surface temperature *and* the surface density, decrease from pole to equator. While the decrease in surface temperature tends to decrease the number of available photons suitable to ionize H and He, the decrease in surface density reduces the optical depth along the line of sight from a point in the wind to the star. Both effects are therefore counteracting with respect to the location where recombination takes place: While a reduction of ionizing photons will shift the recombination distance towards the star, the reduction in optical depth along the direction to the star will shift it further outwards. The outcome of the ionization balance equations is therefore unpredictible and very sensitive to the chosen input parameters. This makes it worth to investigate the ionization structure in the wind of a rotating star in more detail.

In our model calculations, the wind is assumed to be composed of H and He, and we solve the ionization balance equations in the equatorial plane, only. The radiation field from the star is calculated properly in 2D, which means that for the available radiation at every point in the equatorial wind we integrate the stellar radiation over the non-spherical surface and take into account the latitude variations of the individual parameters like effective temperature, net gravity, escape velocity and mass flux. We make, however, several assumptions and simplifications for the calculations which all have in common that they

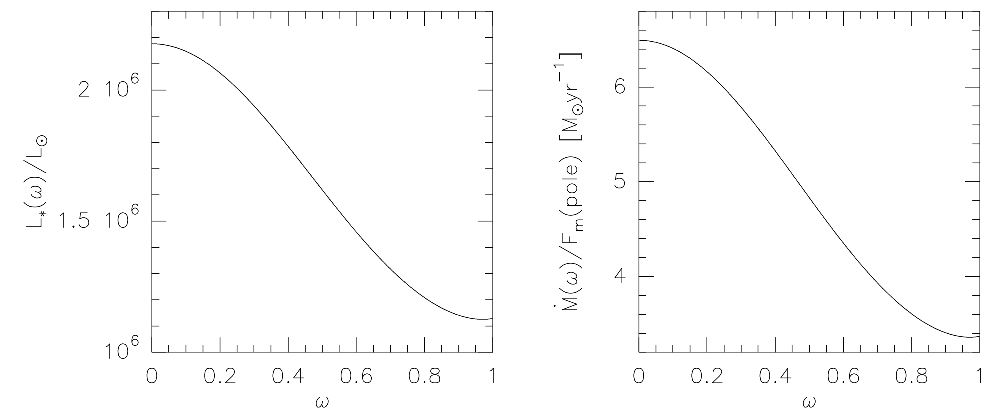

Figure 4. Left: Stellar luminosity as a function of ω ($\omega = v_{\rm rot}/v_{\rm crit}$) for our model stars with $T_{\rm eff,pole} = 24\,500\,$K and $R_* = 82\,R_\odot$. Right: The ratio between the mass loss rate, integrated over the stellar surface, and the polar mass flux as a function of ω. The decrease in both, luminosity and total mass loss rate, is about a factor of 2 between the non-rotating and the critically rotating star.

shift the location of recombination to larger distances. This means that we are calculating an *upper limit* for the recombination distances[1].

We performed a series of test calculations where we fixed the polar values of the stars, i.e. the polar effective temperature and gravity which determine the radiation temperature of the ionizing stellar radiation, and the polar terminal velocity. Fixing the polar effective temperature means that we are *not* calculating a star that is spinning up which would result in an increase of polar temperature with increasing rotation velocity, but we are calculating stars with the same polar effective temperature having different rotation velocities. This means that we are dealing with stars of *different luminosities*.

The difference in luminosity of these stars can be seen in Fig. 4 (left panel) where we plotted the distribution of the stellar luminosities of our model stars as a function of stellar rotation. This difference is largest between the non-rotating and the critically rotating star, and is about a factor 2.

Also shown in Fig. 4 (right panel) is the variation of the total mass loss of the rotating stars. For the chosen polar mass fluxes of 1.5×10^{-6} and $1.5 \times 10^{-5}\,{\rm g\,s^{-1}cm^{-2}}$, the mass loss rates decrease from 10^{-5} and $10^{-4}{\rm M_\odot yr^{-1}}$ (non-rotating) to 5×10^{-6} and $5 \times 10^{-5}{\rm M_\odot yr^{-1}}$ (critically rotating), respectively.

First results of the ionization structure calculations in the equatorial winds of luminous rotating stars are shown in Fig. 5. These calculations have been performed for polar mass fluxes that differ by a factor 10 to show clearly the influence of the input parameters. For the high mass flux (bottom panels) both elements recombine right above the stellar surface for $\omega \geq 0.8$, resulting in a (hydrogen) neutral equatorial outflowing wind. The lower mass flux model (top panels) also shows the trend of a decrease in recombination distance with increasing rotation. In the case of hydrogen, this distance has however a minimum

[1]For details on the assumptions and their influence see Kraus (2006).

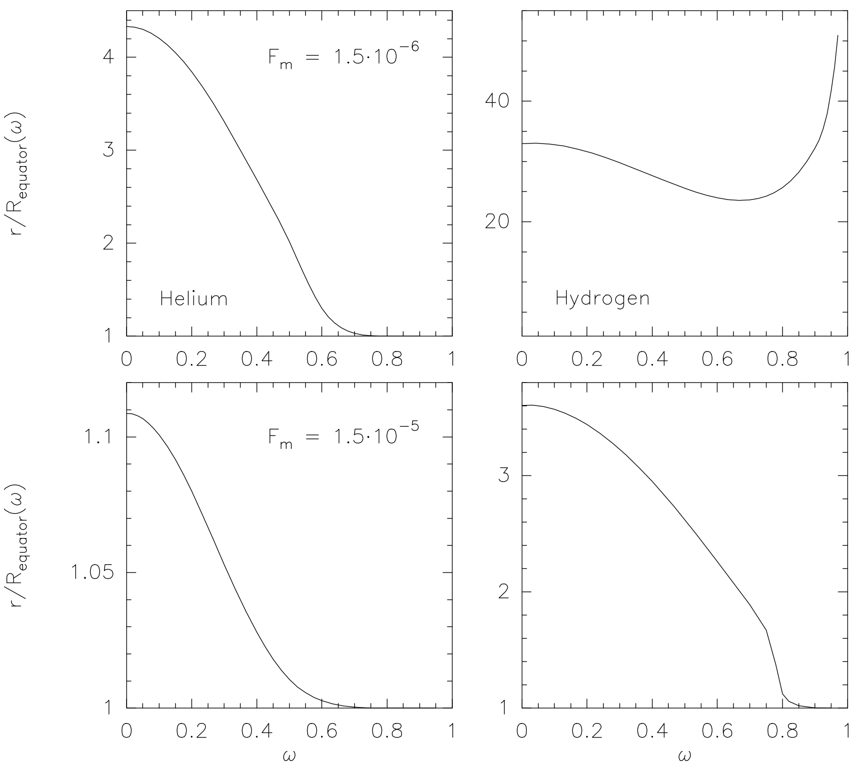

Figure 5. Helium (left) and hydrogen (right) recombination distances in the equatorial plane as a function of ω. The polar mass flux used for each model is indicated. While for the high mass flux model hydrogen recombines right above the stellar surface for $\omega \geq 0.8$, the recombination distance for the model with lower mass flux has a minimum at about $\omega \simeq 0.7$ and increases again for higher rotation rates.

around $\omega \simeq 0.7$, and increases again for higher rotation rates. This behaviour is unexpected but can be understood by looking at the variation of the individual equatorial surface parameters, especially of the temperature and wind density, with increasing rotation velocity as shown in Fig. 6. This figure shows that with increasing rotation velocity, the density drops much quicker from pole to equator than the temperature. For recombination to take place right above the stellar surface, the number of ionizing photons has to be reduced. This can be done either by decreasing the radiation temperature, or by increasing the equatorial surface density and hence the optical depth. Since the decrease in radiation temperature is determined by the rotation velocity (with a fixed input polar value) we can only increase the input polar mass flux to achieve a higher surface density for a given rotation velocity. The density in the model shown in the top panel of Fig. 5 is not high enough any more for stars with $\omega \geq 0.7$ to absorb the ionizing photons provided by the still rather high radiation temperature. Therefore, ionization takes over again and shifts the recombination distance for higher rotation velocities further out. Whether recombination takes place close to the star therefore sensitively depends on the chosen input parameters of the rotating star.

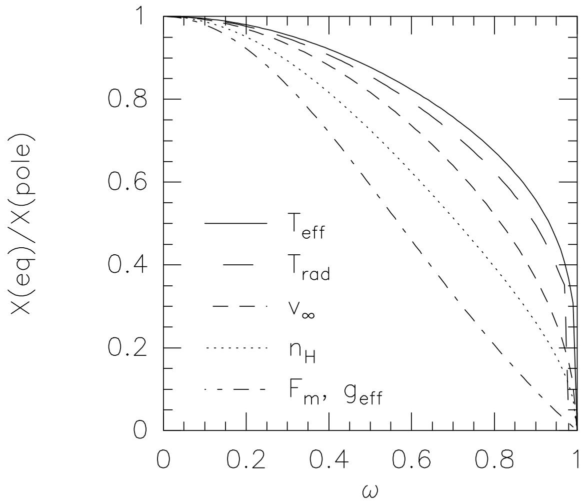

Figure 6. Surface parameters in the equatorial plane as functions of the rotation velocity. n_{H} is the density at any distance.

3. Conclusions

We presented two different wind scenarios that resulted in the formation of a hydrogen neutral region in the equatorial plane: a non-spherical wind model with a surface mass flux that increases from pole to equator, and a model investigating the influence of rigid rotation on the wind structure. We show that the model of a rotating luminous star can have a hydrogen neutral equatorial region simply due to the effects of gravitational darkening. In that case, it makes however no sense to speak of a "disk" because the density in the equatorial plane (when neglecting additional effects like bi-stability and/or wind compression) is much lower than in the polar wind.

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Michaela Kraus enjoying the fantastic view and a cup of coffee.