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Letter to the Editor

The formation of outflowing disks around early-type stars by bi-stable radiation-driven winds

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Abstract. We propose to explain the existence of outflowing disks of rapidly rotating B-stars by means of the bi-stability mechanism of radiation driven winds, originally proposed for P Cygni by Pauldrach and Puls (1990). If the wind from a rotating B-star reaches an optical depth in the Lyman continuum at 912 Å of $\tau_L \simeq 3$ between the pole and the equator, the star will have a high velocity wind of high ionization in the polar regions and a low velocity wind of low ionization and high density (i.e. a disk) near the equator. The strong dependence of τ_L on stellar latitude makes the occurrence of such disks around rotating B-stars likely. Applications show that this mechanism can explain the B[e]-supergiants but an additional mechanism for the enhancement of the equatorial mass loss rate of Be-stars is required. The bi-stability mechanism can explain the major characteristics of the winds and disks of B[e]-supergiants and Be-stars and, in combination with some other mechanism, the variations of Be-stars into Be, B-shell and B-normal phases. It also explains why the outflowing disks occur mainly around early-B stars.

Key words: stars: Be – stars: circumstellar matter – stars: early-type – stars: emission-lines – stars: mass loss – stars: supergiant

1. Introduction

The spectra of B[e]-supergiants and of Be-stars show evidence for the co-existence of slowly expanding ($v \lesssim 10^2$ km/s) equatorial outflowing disks and fast ($v \gtrsim 10^3$ km/s) low density winds.

The evidence for the outflowing disks of Be-stars comes from the Balmer emission lines, the large IR excess and the optical polarization (see reviews in Slettebak and Snow, 1987). This outflowing disk model is confirmed by observations of Be/X binaries in which the matter from the outflowing disk of the Be-star is captured by the neutron star (Waters et al., 1988). The evidence for the fast winds of Be-stars comes from the study of the extended violet absorption wings of the UV resonance lines of CIV, NV and SiIV (e.g. Snow, 1981).

The B[e]-supergiants show a hybrid spectrum with narrow Balmer emission lines and emission lines of low ionization metals ($v \simeq 10 - 100$ km/s) as well as wide UV resonance lines and P Cygni profiles of Balmer lines with v up to 1800 km/s. The stars also show a strong IR excess. This hybrid spectrum can be explained by a model which is qualitatively similar to that of Be-stars: an outflowing disk of low outflow velocity, high density and low ionization, as well as a fast wind of low density and high ionization. (Zickgraf et al., 1986, 1989).

There is no satisfactory explanation for the formation of these outflowing disks. They are most likely related to the fast rotation of the star, but since no Be-star is found to rotate at the critical (break-up) velocity (Slettebak, 1982) the centrifugal force alone cannot be responsible for the large equatorial mass loss. Friend and Abbott (1986) proposed a rapidly rotating radiation driven wind for Be-stars, but this cannot explain the large contrast between the slow outflow of the disk and the high velocity of the wind. Poe et al. (1989) proposed a magnetic rotator to explain the disks but this requires large magnetic fields which have not been detected.

In this letter we propose that the disks are due to a bi-stable radiation driven wind. The main characteristic of these bi-stable wind models is the drastic change from a high velocity/low density wind into a wind with higher density/low velocity. These are *exactly* the main differences observed between the outflowing disks and the fast winds of B[e] and Be-stars.

2. The Bi-stability Mechanism

2.1. The mechanism

The detailed calculations of radiation driven wind models for the star P Cygni by Pauldrach and Puls (1990) show a discontinuity in the mass loss rate and the velocity of the wind when the effective gravity of the star decreases below some critical limit. This is shown in Fig. 1, where the mass flux and the terminal velocity of the wind is plotted for a set of models with $T_{\rm eff} = 19300$ K and different radii and masses. The figure shows that the mass flux increases by about a factor 3 and the terminal velocity decreases about a factor 0.3 at $\log g_{\rm eff} \simeq 1.5$. This is the bi-stability jump.

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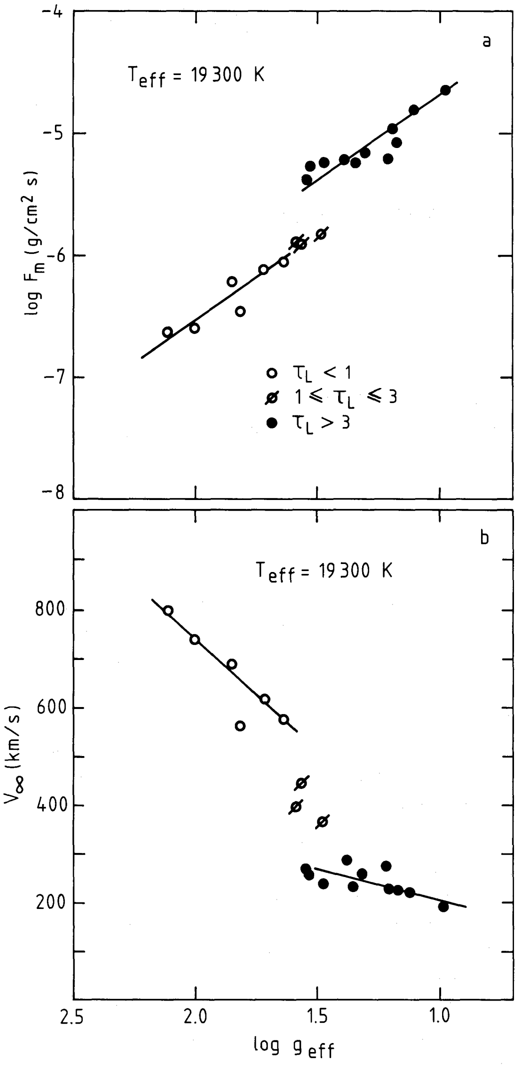

Fig. 1. The bi-stability in the radiation driven wind models from Pauldrach and Puls (1990). The upper part shows the mass flux as a function of $\log g_{\rm eff}$ for models of $T_{\rm eff} = 19300$ K. The lower part shows the terminal velocity of the wind of these models. Different symbols indicate the optical depth of the wind τ_L at 912 Å. Open circles: $\tau_L \leq 1$, divided circles $1 \leq \tau_L \leq 3$, dots $\tau_L > 3$. Notice the bi-stability jump at $\log g_{\rm eff} \simeq 1.5$ where the mass flux increases by a factor 3 and the terminal velocity decreases by a factor 3 to $v_\infty \simeq 200$ km/s.

The bi-stability jump is due to the change of the optical depth of the wind in the Lyman continuum from $\tau \lesssim 1$ (this is the branch of $\log g_{\rm eff} \gtrsim 1.5$ in Fig. 1) to $\tau \gtrsim 3$ (this is the branch of $\log g_{\rm eff} \lesssim 1.5$). Let us consider what happens to the wind if the gravity of the model decreases from $\log g_{\rm eff} \simeq 2.5$ to lower values. When $g_{\rm eff}$ decreases at constant $T_{\rm eff}$, the mass flux increases and v_∞ decreases. At $\log g_{\rm eff} \simeq 1.5$ the mass flux is so large and the velocity is so small that the optical depth of the wind in the Lyman continuum reaches a value of $\tau(\lambda 912) \simeq 3$ and $\tau(\lambda 600) \simeq 1$. At this point the Lyman photons from the star can no longer easily penetrate into the wind so the wind becomes optically thick in the Lyman continuum. This has two effects: the ions which drive the wind by line radiation pressure shift to lower ionization stages, since the flux at wavelengths below the Lyman edge is blocked by the dominating H opacity and the flux in the Balmer continuum increases slightly at the expense of the flux in the Lyman continuum. So, the contribution to the line radiation pressure changes from the high ionization lines in the Lyman continuum to the lower ionization lines in the Balmer continuum. This effect produces an increase of the mass loss rate and a decrease of the velocity which in turn increases the optical depth in the Lyman continuum. Since the density of the wind at any distance is proportional to $\rho \sim \dot{M}/v$ it will increase drastically, by about a factor 10, at the bi-stability jump.

2.2. The optical depth τ_L of stellar winds

The bi-stability depends critically on the optical depth of the wind in the Lyman continuum, as it occurs where $\tau_L \simeq 3$. We have calculated this optical depth for a large number of optically thin stellar winds with a standard velocity law of $v(r) = v_s + (v_\infty - v_s)(1 - r_s/r)$, where v_s and $r_s \simeq R_*$ are the velocity and the location of the sonic point. The ionization equilibrium is due to recombination and photoionization from the ground state. We found that the optical depth τ_L can then be written as

$$\begin{aligned} \tau_L &\simeq 1.6\ 10^{22}\ \dot{M}^2 v_\infty^{-2} (R_*/R_\odot)^{-3}\ f(T_L) \\ &= 1.5\ 10^{16}\ F_m^2 v_\infty^{-2} (R_*/R_\odot)\ f(T_L) \end{aligned} \qquad (1)$$

with $\dot{M}$ in $M_\odot/yr$, v_∞ in km/s and the mass flux F_m at the photosphere in g/s cm². The function $f(T_L)$ describes the dependence of τ_L on the brightness temperature T_L of the star in the Lyman continuum. In the range of $10000 \leq T_L \leq 30000$ this function can be approximated to an accuracy of 10 percent by

$$\log f(T_L) = -7.150 \log(T_L/10^4) + 0.905\{\log(T_L/10^4)\}^2 \qquad (2)$$

Notice the very strong sensitivity of the optical depth τ_L on T_L. For instance, τ_L will increase by a factor 7 if T_L drops from 20000 K to 15000 K. We will adopt Eq. (1) for the calculation of the bi-stability in rotating B-stars.

3. Bi-stability as an explanation for the outflowing disks of rotating B-stars

3.1. The concept

Suppose that a luminous B-star has a radiation driven stellar wind with a mass loss rate $\dot{M}$ and a terminal velocity v_∞. The star has an effective gravity of $g_{\rm eff} = GM_{\rm eff}/R^2 = GM(1-\Gamma)/R^2$, where the factor $1-\Gamma$ is a correction factor for the radiation pressure due to electron scattering, with $\Gamma = 2.4\ 10^{-5}(L/L_\odot)/(M/M_\odot)$ for B-stars (Pauldrach and Puls, 1990). Suppose that the star rotates at a considerable fraction of its critical (break-up) velocity $v_{crit} = \{GM_{\rm eff}/R\}^{0.5}$. Define $\Omega \equiv v_{rot}/v_{crit}$ as the ratio between the equatorial rotational velocity and v_{crit} and β as the stellar latitude ($\beta = 0$ at equator). We will consider the dependence of the optical depth τ_L on β and show that τ_L increases so drastically from the pole to the equator that the bi-stability jump at $\tau_L \simeq 3$ can occur at a certain value of β_{bj} where the subscript "bj" stands for bi-stability jump. This leads to a high velocity wind of high

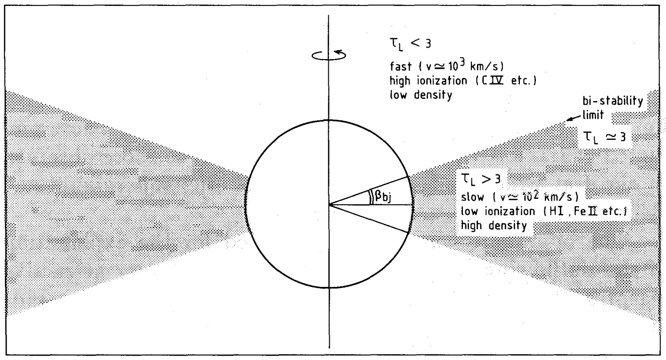

Fig. 2. A schematic figure of the disk of a rapidly rotating B-star formed by the bi-stability mechanism. The wind is optically thin ($\tau_L \lesssim 3$) in the polar region and thus has a high velocity, low density and high ionization. The wind is optically thick ($\tau_L > 3$) in the equatorial region and thus has a low velocity, high density and low ionization. The contrast between the regions results in an equatorial outflowing disk.

ionization at $\beta > \beta_{bj}$ and a slow high density wind of low ionization at lower latitudes $\beta < \beta_{bj}$: i.e. an outflowing disk! This concept is shown in Fig. 2.

Equation (1) for the optical depth τ_L shows that three β-dependent factors will affect τ_L: a) the mass loss will increase from pole to equator because the effective gravity decreases due to the centrifugal force; b) the terminal velocity of the wind will decrease towards the equator because the escape velocity decreases and c) the brightness temperature T_L will decrease towards the equator due to the Von Zeipel theorem.

The net gravity at the stellar surface as a function of latitude is given by

$$g_{net}(\beta) = g_{\rm eff}\{1 - \Omega^2 \cos\beta\} \tag{3}$$

The mass flux of the optically thin winds of $T_{\rm eff} \simeq 20000$ K varies as $g_{net}^{-1.42}$ (Fig. 1) and so

$$F_m\ (\beta) \sim \{1 - \Omega^2 \cos\beta\}^{-1.42} \tag{4}$$

The terminal velocity v_∞ scales with the escape velocity so

$$v_\infty(\beta) \sim \{1 - \Omega^2 \cos\beta\}^{0.5} \tag{5}$$

The Von Zeipel theorem predicts that the radiative flux from a rotating star is proportional to the effective gravity so $T_{\rm eff}^4(\beta) \sim g_{net}(\beta)$. The brightness temperature in the Lyman continuum varies as $T_L \sim T_{\rm eff}^{1.6}$ near $T_{\rm eff} = 25000$ K (Kurucz, 1979). This means that $T_L \sim g_{net}(\beta)^{0.4}$ and since $f(T_L) \sim T_L^{-6.6}$ we find that

$$f(T_L) \sim \{1 - \Omega^2 \cos\beta\}^{-2.6} \tag{6}$$

Combining Eqs. (1), (4), (5) and (6) we predict that the optical depth of the wind in the Lyman continuum will vary with stellar latitude as

$$\tau_L(\beta) \sim \{1 - \Omega^2 \cos\beta\}^{-6.5} \tag{7}$$

This strong dependence of τ_L on β implies that the wind of a rapidly rotating B-star will have a much larger optical depth at the equator than at the pole. For instance for a star rotating at $\Omega = 0.7$, τ_L has increased by a factor 36 at $\beta = 30°$ and by a factor 80 at $\beta = 0°$ relative to the optical depth at the pole. If the optical depth of the wind at the poles of such a star is as small as $\tau_L(90°) = 0.05$, the bi-stability jump will occur at $\beta = 15°$ where $\tau_L \simeq 3$. This star will thus have an outflowing disk with a full opening angle of 30°. If $\tau_L = 0.1$ at the pole the bi-stability jump will occur at $\beta = 33°$ and the star will have an outflowing disk with a full opening angle of 66°.

3.2. Application to B[e]-supergiants

The B[e]-supergiants have effective temperatures in the range of $17000 \lesssim T_{\rm eff} \lesssim 26000$ K (with one exception at $T_{\rm eff} = 12000$ K) and luminosities of $2.10^5 \lesssim L \lesssim 1.10^6 L_\odot$ and masses in the range of $25 \lesssim M \lesssim 50 M_\odot$ (Zickgraf et al., 1986, 1988). For the purpose of this paper we adopt a hypothetical B[e]-star with typical values: $T_{\rm eff} = 20000$, $L = 5.10^5 L_\odot$, $R = 59 R_\odot$, $M = 35 M_\odot$ and an effective gravity at the pole of $\log g_{\rm eff} = 2.3$. The terminal velocity of the wind near the pole is assumed to be 2.5 times the escape velocity so $v_\infty = 1010$ km/s. The observed mass loss rates from the polar regions of B[e]-supergiants are about $10^{-6} \lesssim \dot{M} \lesssim 10^{-5}$ (Zickgraf et al., 1986, 1988) and we assume a mean value of $\dot{M}_{pole} = 2.10^{-6} M_\odot/yr$ which corresponds to a mass flux of $F_m = 6.10^{-7} g/cm^2 s$. The brightness temperature in the Lyman continuum is about 0.65 $T_{\rm eff}$ so $T_L = 13000$ K. This results in an optical depth of the wind at the pole of $\tau_L = 0.049$ (Eq. 1).

The values of $\tau_L(\beta)$ are given in Table 1 for various values of Ω. For $\tau_L \gtrsim 3$ the assumptions about the photo-ionization in a wind which is optically thin in the Lyman continuum is no longer valid. So in that case only a lower limit of τ_L can be given. Table 1 shows that a B[e]-supergiant rotating at 70 percent of its critical velocity will have a bi-stability jump, $\tau_L \simeq 3$, at $\beta \simeq 15°$ and a star with $\Omega = 0.8$ will have this jump near $\beta = 45°$, if the mass loss rate at the pole is $2.10^{-6} M_\odot$. If the polar mass loss rate is $6.10^{-6} M_\odot/yr$ the jump will occur at $\beta \simeq 10°$ if $\Omega = 0.5$ and at $\beta \simeq 60°$ if $\Omega = 0.70$. The calculations of the bi-stable wind on P Cygni by Pauldrach and Puls (1990) suggest that the terminal velocity in the optically thick region will drop to about 200 km/s and the mass flux will have increased by a factor 30 relative to the poles. So the expected density contrast between the wind at the pole and the equator will be about a factor 10^2. This agrees with the estimate derived from the observations of B[e]-supergiants by Zickgraf (1989).

Table 1. The optical depth τ_L of the wind of a typical B[e]-supergiant

β	$\Omega = 0.5$	0.6	0.7	0.8	0.9
90	0.05	0.05	0.05	0.05	0.05
60	0.12	0.18	0.30	0.60	1.43
45	0.17	0.33	0.78	2.46	> 3
30	0.24	0.56	1.78	> 3	> 3
15	0.30	0.79	> 3	> 3	> 3
0	0.32	0.89	> 3	> 3	> 3

3.3. Application to Be-stars

The Be-stars have spectral types between B0 and B9 but they are clearly concentrated at early-B spectral types. For the purpose of this study we will adopt the parameters of a typical Be-star of approximate spectral type B1IVe: $T_{\rm eff} = 25000$ K, $L = 3.10^4 L_\odot$, $R = 9.2 R_\odot$, $M = 12 M_\odot$ and $\log g_{\rm eff} = 3.56$. The brightness temperature of the star in the Lyman continuum is $T_L = 17000$ K. The escape velocity at the poles is 680 km/s and the terminal velocity of the wind at the poles is assumed to be $2.5 v_{esc} = 1700$ km/s. The mass loss rate from the poles of the Be-stars is very uncertain. Snow (1981) and others derived rates of 10^{-11} to $10^{-8} M_\odot/yr$ from the UV resonance lines. We assume a value of $1.\ 10^{-9} M_\odot/yr$ which corresponds to a polar mass flux of $1.2\ 10^{-8} g/cm^2 s$.

With these parameters the optical depth of the polar wind in the Lyman continuum is only $\tau_L = 2.\ 10^{-7}$. With such a small value of τ_L the wind will not become optically thick at any stellar latitude, unless the rotation velocity is so large that $\Omega \gtrsim 0.95$. The rotation velocity of Be-stars is smaller than $0.8 v_{crit}$ (Slettebak, 1982). However, other mechanisms such as non-radial pulsations or co-rotating magnetic fields may enhance the mass flux from the equatorial region. Both mechanisms have been proposed for the explanation of the high mass loss rates from the disks of Be-stars (Poe et al., 1989; Baade, 1985; and review by Marlborough, 1987).

The main point we want to make here is that *if* there is a mechanism to enhance the mass flux of rotating B-stars at the equator more efficiently than by reduction of the gravity only, then the bi-stability mechanism will automatically produce a stellar outflowing disk with characteristics remarkably similar to those observed in Be-stars.

The bi-stability mechanism might also provide a natural explanation for the variability of Be-stars. Some Be-stars can change from a Be-phase (with disk) into a normal-B phase (without a disk) and into a B-shell star phase. Such a variability can be explained by the bi-stability mechanism if the mass loss rate of the star is variable.

Assume that a rotating B-star has a bi-stability jump, $\tau_L \simeq 3$, at some stellar latitude, say $\beta_{bj} \simeq 20°$, which produces an equatorial outflowing disk and that the star is observed at an inclination angle of 45°. Then the star will show the characteristics of a Be-star: fast low density wind and slow high density disk. If for some reason, which we do not understand, the mass loss rate drops so that $\tau_L \lesssim 3$ even at the equator, then the bi-stability jump will not occur and the star will have a fast low density wind at all latitudes. The characteristics of the star will be those of a normal B-star. If, on the other hand, the mass loss rate increases so that the bi-stability jump occurs at stellar latitude $\beta_{bj} > 45°$ the disk will extend to $\beta > 45°$. The line of sight from the observer will then pass through the disk and the spectra will show slightly shifted narrow low-ionization absorption lines formed in the outer slowly rotating part of the disk, i.e. B-shell spectrum.

So the bi-stability mechanism can explain the three phases of the variable Be-stars if the mass loss rate is variable. The bi-stability mechanism only acts in regulating the presence and the thickness of the disk.

4. Summary and discussion

We propose that the outflowing disks of rapidly rotating B-stars are due to the bi-stability mechanism of radiation driven stellar winds: winds which are optically thin in the Lyman continuum have high velocities ($v \simeq 10^3$ km/s), low density and a high degree of ionization, whereas winds which are optically thick in the Lyman continuum have low velocities ($v \sim 10^2$ km/s), high density and a low degree of ionization. These predicted characteristics are remarkably similar to those observed in the fast winds and the slow disks of B[e]-supergiants and Be-stars.

The bi-stability mechanism proposed for the explanation of the outflowing disks of B-stars has several very attractive features. It explains the observed hybrid nature of the winds of the B[e]-supergiants and the Be-stars in the form of high velocity/high ionization winds and low velocity/low ionization disks. It also explains why these outflowing disks are most common near early-B-stars, because the bi-stability mechanism is most efficient in the range of $15000 \lesssim T_{\rm eff} \lesssim 30000$ K. For stars with $T_{\rm eff} > 30000$ K the wind will remain optically thin in the Lyman continuum at all stellar latitudes unless the polar mass loss rate is very high. Stars with $T_{\rm eff} \lesssim 15000$ usually have too low mass loss rates to reach an optically thick wind near the equator, unless they are very rapid rotators.

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