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# Dynamics of Self-Accreting Disks in Be Stars

P. Kroll

*Sonneberg Observatory, Sternwartestr. 32, D-96515 Sonneberg, Germany*

R.W. Hanuschik

*Astronomical Institute, Ruhr-Universität Bochum, D-44780 Bochum, Germany*

**Abstract.** Be star disks are formed by ejection of stellar matter from the surface of a B star rotating at almost critical velocity. In SPH simulations we find that most of the ejected particles fall back on the stellar surface but those with sufficient angular momentum are able to feed a disk-like structure. Owing to viscous interaction some particles are lifted to larger radii where they carry high angular momentum. Viscous forces also cause a thinning of the initially geometrically thick disk and the final accretion of most of the disk material. Different simulations show how the formation and the extension of the *decretion* disk depend on the ejection velocity, the viscous parameter $\alpha$ and on how long the source is active. After the outburst the disk thins out more and more, over a timescale much longer than the outburst time.

The simulations are compared to $H_\alpha$ observations of the Be star $\mu$ Cen.

## 1. Introduction

Basically all other contributions to these Proceedings deal with accretion on a compact object with the material coming from far *outside* the star. Matter then usually carries a lot of specific angular momentum which it has to get rid of in order to be able to be accreted on the stellar surface.

In case of Be stars we have a totally different situation. The spectra do not give the tiniest indication of (e.g. interstellar) matter falling down from outside the star. On the other hand, we observe *very* strong emission lines (therefore B'e'-stars) indicating the presence of excited matter outside the stellar photosphere. This implies that matter must come from the star itself.

Since these emission lines are present for months, years and even decades the question arises by what physical process matter can be lifted from the stellar surface into orbits which are stable for a long time, i.e., where the specific angular momentum comes from?

In order to answer this question we shall first have a quick look at the fundamental properties and observations of Be stars, and then to some simulations.



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## 2. Be stars

Slettebak (1987) and Porter (1996) have shown that most Be stars rotate at a speed of 70 to 80 % of their critical velocity $v_{\rm crit} = \sqrt{GM_*/R_*}$. In the absence of evidence of general binarity in Be stars, it seems therefore safe to suppose that Be disks are formed of matter ejected by the central star. Since rapid rotation reduces effective gravity to near-zero values near the equator, only weak radial forces are required to lift matter into orbits. The nature of such radial forces, however, is absolutely unknown. Known from O to B-type stars, radiatively driven winds become rapidly inefficient due to the decrease in the effective temperature. Bjorkman & Cassinelli (1993) propose a focussing of such wind towards the equatorial plane. However, the predicted radial motion of the gas is not observed in optical emission lines.

Of particular interest for understanding the disk formation process are Be stars with varying strength of their emission lines. A very detailed record of $H_\alpha$ variability in the southern Be star $\mu$ Cen has been given by Hanuschik et al. (1993). Their data from 1987 show a typical saw-tooth pattern of rise and decline of $H_\alpha$ emission, with growth times of $3^{\rm d}$ to $5^{\rm d}$ and decline times of some $50^{\rm d}$.

This data suggests that $\mu$ Cen is offering the rare opportunity to observe the basic processes of *ejection*, *disk formation* and *disk decay*. The idea put forward by Hanuschik et al. (1993) is that the unknown ejection mechanism lifts matter off the stellar surface into ballistic orbits where the gas then rapidly interacts and circularizes to form a disk. The disk presumably decays thereafter by means of viscous forces which are well known to act in accretion disks (Pringle 1981).

The main problem with such a model is that gas in a Keplerian disk must carry a considerable amount of specific angular momentum. This is larger than the value at the stellar surface. Hence, disk gas must carry quite a large excess value in order to be in Keplerian equilibrium. With the central star as the source of matter, the required excess of angular momentum is the main problem for theoretical Be disk formation, rather than the small amount of radial force required for ejection.

## 3. Model

Following Slettebak (1987) we assume a model B star of $M_\star = 5\,M_\odot$ and $R_\star = 7\,R_\odot$. For the sake of simplicity, we assume critical rotation. Although a critically rotating star must be flattened, we will assume spherically symmetric gravitational potential. As Sackmann & Anand (1970) have shown, about 90% of the stellar mass of rotating B stars are concentrated within a small core which rotates well sub-critically.

Following Hanuschik et al. (1983), we investigated the following ejection mechanism: we assume a single point-like source of matter somewhere on the equatorial belt of the B star. We do not specify the nature of this source since the observations are not yet specific enough to allow any detailed conclusions. This source could be, e.g., a magnetically active region or a hot spot. We restrict our investigation to this simple case since then the maximum of density asymmetry is to be expected in the initial phase, in agreement with observed $V/R$ variability of $H_\alpha$ in $\mu$ Cen during outburst phase (Baade et al. 1988, Hanuschik et al. 1983).

We assume that matter with a ballistic velocity, $v_b$, is ejected isotropically into the half space above the point source. This is achieved by ejecting gas particles with randomly distributed starting angles as measured against the local surface. The (arbitrary) additional ballistic velocity $v_b$ should not exceed $(\sqrt{2}-1)v_{crit}$ since otherwise many particles reach escape velocity and are lost before a viscous disk is formed. For our model star, $v_{crit} = 365$ km s$^{-1}$. We investigated the case $v_b \sim (\sqrt{2}-1)v_{crit} \sim 0.41\, v_{crit} \sim 150$ km s$^{-1}$.

Since viscous forces play an important role we have to estimate the influence of the viscosity. Usually in such problems the parameter $\alpha$ is introduced by $\nu = \alpha c_s H$ (see, e.g. Frank et al., 1996), where $\nu$ is the dynamical viscosity as part of the stress tensor in the Navier-Stokes-Equation, $c_s$ the speed of sound, and $H$ the scale height of the disk. For typical values ($\alpha = 1$ and $c_s = 10^6$ cm/s for hydrogen gas of $10^4$K) we obtain $\nu = 5 \cdot 10^{16}$ cm$^2$ s$^{-1}$. We chose this value for the simulation presented here.

As suggested by the observations of Hanuschik et al. (1983), we fix the duration of the stellar outburst in our simulation to 5 stellar rotational periods, $T_*$, corresponding to five days.

## 4. Results

Since space is very limited here we dispense with the presentation of figures and refer instead to a forthcoming paper by Kroll & Hanuschik (1996).

The simulations show clearly three evolutionary phases:

1. In the *outburst phase* ($t/T_* = 0 \ldots 5$), the disk is fed with matter. The distribution of matter is very inhomogeneous, and the line profiles have irregular shapes and fluctuating $V/R$ ratios.

2. As soon as the outburst is stopped, the *circularization phase* ($t/T_\star = 5 \ldots 15$) starts. The number of particles is nearly constant, and angular momentum is only redistributed due to viscous interaction. Backfalling particles returning from far distances on highly elliptical orbits get stuck in the ring, which is formed during this phase. A distinct gap between the stellar surface and the ring is formed at $t/T_\star \approx 10$. This is due to a selection effect: particles with insufficient specific angular momentum have already fallen back on the star before the ring had formed. All remaining particles ultimately get stuck in the ring. At the end of that phase, the ring becomes quite narrow.

   The line profile becomes more and more symmetric at this stage, in fairly good agreement with observation. A narrow inner double peak, arising from the far-distance particles on elliptical orbits, rapidly fades away, while an outer double-peak structure emerges, caused by the inner ring forming.

3. The third stage is the *viscous phase* starting around $t/T_\star \approx 15$. The ring now broadens due to viscous forces (Pringle 1981). Particles at the inner rim of the disk drift back onto the stellar surface, while particles

at the outer edge move outwards due to angular redistribution: the disk starts decaying. Line profiles are symmetric ($V/R = 1$) with double-peak structure.

The total number of particles in the simulation, $N = \int N(v_{\rm rad})dv$, is proportional to the equivalent width of an (optically thin) emission line. The function $N(t)$ shows the typical saw-tooth pattern of $H_\alpha$ activity and can be directly compared with the $H_\alpha$ light-curve as shown in Hanuschik et al. (1983).

A further relevant observational parameter is the radius of the disk, which can be derived from the separation of the double peak of the line profile. Assuming a circularized Keplerian disk, this method is frequently used by observers to derive disk radii. It grows from about 1.6 $R_*$ at circularization phase to about 3 $R_*$ at the end of the simulation (80 $T_*$).

## 5. Conclusions

We successfully simulated the disk formation and decay during a Be star outburst. On account of the assumed isotropy of the ejection in the stellar rest frame, the average angular momentum of all ejected particles initially is $\overline{l_z} = l_*$, with a random distribution between $(2 - \sqrt{2})\ l_*$ and $\sqrt{2}l_*$. However, since those particles with $l_z < l_*$ cannot move far out and rapidly fall back on the star, their number of interactions with other particles is by far lower than for particles with $l_z > l_*$. The latter ones initially form a ring with $\overline{l_z}l_*$, in our model with $\overline{l_z}/l_* \approx 1.2$. By viscous forces, this ring spreads out with $l_z$ becoming even larger. Thus the natural selection process, that only high-$l_z$ particles exchange specific angular momentum, can form a circumstellar disk around a rapidly rotating B star.

Subcritical rotation of the star makes disk formation more difficult but not impossible. Disk radii in our model approach $2 \ldots 3R_*$. Typical fall-off time of the lightcurve is set by the viscous timescale, $t_{\rm vis} = r^2/\nu \approx 100$ days for $r = r_\rho$. These values are in fairly good agreement with the observations of $\mu$ Cen.

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