Dynamical Processes in the Formation of Hot-Star Disks

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Abstract.

The characteristic signature of Be stars is the Balmer line emission understood to arise in a circumstellar disk. Unlike the *accretion* disks of protostars or mass-exchange binary systems, the evolved and generally single or wide-binary status of Be stars seems to require that its disk must form from mass *ejection* (a.k.a. *de*cretion) from the star itself. In this review, I use analogies with launching orbital satellites to discuss candidate processes (radiation, pulsation, magnetic) for driving such orbital mass ejection, with particular emphasis on the role of the rapid, possibly near-critical, rotation of Be stars in facilitating the formation of their signature disks.

1. The Puzzle of Be Disks

Be stars are main-sequence or subgiant spectral type B stars characterized by Balmer emission (e.g., Hα) that originates in a circumstellar disk. Understanding the nature of such stars, and in particular the origin of their circumstellar disks, is one of the longest-standing challenges in astronomy (Slettebak and Snow 1987; Smith, Henrichs, and Fabregat 1999; Porter and Rivinius 2003). Disks are a common consequence in astrophysical *accretion* systems, wherein they form as a means to provide outward viscous transport of the angular momentum of the infalling material (Shakura & Sunyaev 1973; Frank et al. 2002). Such accretion disks occur, for example, in protostellar nebulae, or in close binary systems with mass exchange. But Be stars are clearly too old to have retained a protostellar disk (indeed, in many Be stars the Balmer emission signatures of a disk are observed to come and go on timescales of months to decades), and moreover they are not generally found to be in close, mass-exchange binary systems. Thus lacking an outside source of material, it seems instead that Be disks must originate from ejection or "*decretion*" of mass from the underlying star. Identifying the specific dynamical mechanisms for achieving this "inside-out" formation of a circumstellar disks is perhaps the central puzzle underlying the Be phenomenon.

Dating back to early analyses by Struve (1931), rapid rotation has long been presumed to be a key piece in this puzzle. But as emphasized below, a crucial, still-open question is just how close Be star rotation might be to the "critical" speed, at which the equatorial surface would be in Keplerian orbit. Critical rotation would enable a direct centrifugal ejection of a circumstellar disk or ring, much as first envisioned by Struve, and developed further in modern "Viscous Decretion Disk" models of Lee et al. (1991) that are discussed in the contribution by A. Okazaki to these proceedings. But conventional interpretations of observed line-broadening have been that Be star rotations are typically only 70-80% of critical, and in this case solving the puzzle of Be disk formation amounts to identifying the dynamical processes that provide the additional boost into circumstellar orbit.

The present review examines several possible mechanisms for ejecting a circumstellar disk, emphasizing the dynamical challenges of doing so from a star that is substantially below critical rotation. An overall conclusion is that ejection into a stable Keplerian disk is most physically tenable when the equatorial rotation speeds are within about a sound speed of the critical value. In particular, we show that, under these circumstances, mechanisms like non-radial pulsation, which draw upon the internal energy of surface material, become quite capable of launching material into a dense, Keplerian disk.

2. Lessons from the Wind Compressed Disk Paradigm

In what seemed at first a very promising approach, the Wind Compressed Disk (WCD) model introduced by Bjorkman and Cassinelli (1993) naturally produces an equatorial disk of enhanced-density flow from just the rotational focussing of the radiatively driven stellar wind expected from such intrinsically bright Be stars. Initial dynamical simulations did in fact confirm much of the basic WCD paradigm (Owocki, Cranmer, and Blondin 1994), but subsequent work showed that non-radial (poleward) components of the driving can effectively inhibit the formation of any disk (Owocki, Cranmer, and Gayley 1996).

Moreover, even within the initial WCD picture based on purely radial driving, the outflow from a subcritically rotating star necessarily lacks the angular momentum for a stationary orbit. As such, material in the inner disk is pulled by gravity into reaccretion back onto the star, while material in the outer disk flows outward with the stellar wind. This overall "leaking" of the WCD limits its density to values well below (by ca. a factor 100) that needed to explain either the observed Balmer emission or continuum polarization (Bjorkman 1999). These substantial radial flow speeds also do not seem compatible with observed line-profile features, most notably the "central quasi-emissions" (Rivinius et al. 1999; Hanuschik 1995). Finally, since this radially flowing WCD material has a characteristic residence time of only a few days, the WCD model seems inherently incapable of explaining the long-term (several year) variations of Violet/Red (V/R) emission peak asymmetries seen in many Be stars; instead these seem consistent with slow one-arm disk-oscillation modes that are grounded in the gradual precession of elliptical orbits within a Keplerian disk (Savonije and Heemskerk 1993; Telting et al. 1994; Savonije 1998).

Although it thus now seems quite clear that the WCD mechanism can not explain Be star emission, its introduction and development was nonetheless a quite useful and instructive step forward, as one of the first dynamically based models with falsifiable predictions. In particular, it highlighted that among key requirements for producing a viable disk are not just to propel material from the surface and focus it toward the equator, but rather also to provide it with sufficient angular momentum to maintain a Keplerian orbit.

3. Subcritical Equatorial Rotation and the Orbital Launch Speed

Before discussing specific driving mechanisms, it is helpful to review the general requirements for propelling material into orbit from a rotating surface. As reflected in the choice of launch sites for terrestrial satellites, this is easiest when the launch occurs from near the equator and into the direction of rotation. Specifically, for a body with equatorial rotation speed V_{rot} that is less than the orbital (a.k.a. "critical rotation") speed $V_{crit} \equiv \sqrt{GM/R_{eq}} \approx 500$ km/s, a prograde equatorial launch requires an additional speed boost of $\Delta V_{orb} \equiv V_{crit} - V_{rot}$.

Compared to launching from a nonrotating surface (or into a polar orbit), the energy required is reduced by a factor $(\Delta V_{orb}/V_{crit})^2$. For earth satellites, this energy saving is modest – about 10%. But for a typical massive star (e.g. Zeta Puppis) that rotates at half the critical speed, the required energy is reduced by a much more substantial factor four. And for Be stars, the traditional estimates of rotation rates up to 80% of critical imply an impressive *factor 25* reduction in the energy to reach orbit!

Despite these significant reductions, the boost needed to reach orbit can in some respects still be quite large. For example, an alternative figure of merit is to compare the launch speed to the atmospheric *sound speed*, which for Be stars with surface temperatures of $T \approx 20,000$ K has a typical value $a \approx 20$ km/s. Then even for a star rotating at 80% of the critical speed $V_{crit} \approx 500$ km/s, one finds a ratio $\Delta V_{orb}/a \approx 5$. This moreover implies that the internal, thermal energy of gas in Be star atmospheres would still fall short – in this case by roughly a factor $(\Delta V_{orb}/a)^2 \approx 25$ – the minimal energy to accelerate material into orbit.

4. Mass Ejection by Surface Explosions or Magnetic Flares

The minimum launch speed defined above requires in general that the launched material be properly directed along the sense of rotation. But an interesting alternative, first examined through Smoothed Particle Hydrodynamics (SPH) simulations by Kroll (1995; see also Kroll and Hanuschik 1997), is to consider the effect of an undirected, *explosive* ejection of material from a localized equatorial region of a rapidly rotating surface. Despite the lack of prograde directivity, Kroll's SPH results show the natural formation of an equatorial disk, occurring through a kind of "Keplerian natural selection", in which material that happens to be propelled in the direction of rotation gains sufficient velocity to achieve circumstellar orbit, while material ejected in other directions simply falls back in a reaccretion onto the stellar surface.

In Kroll's simulations, the exploding material is arbitrarily given an initial velocity $\Delta V \approx$ 100-200 km/s that is sufficient to achieve orbit, with no consideration for what specific driving mechanism could propel the gas to this speed. Driving by gas pressure from a surface flare would require a comparable sound speed ($a \approx \Delta V$), implying gas temperatures of order 10^6 K, much higher than what characterizes the observed optical emission. Any such localized heating would most likely arise from magnetic reconnection. Such thermally driven mass ejection should be accompanied by soft X-ray flare emission, which is not generally observed.

5. Alfven Radius vs. Keplerian Corotation Radius

Let us next examine whether a large-scale magnetic field could spin-up the stellar wind outflow into a “Magnetically Torqued Disk” (MTD), as advocated by Cassinelli et al. (2002), and discussed further in these proceedings by J. Brown. MHD simulations (ud-Doula 2002; ud-Doula and Owocki 2002) indicate that the effectiveness of magnetic fields in channeling a stellar wind outflow can be characterized by the ratio of the magnetic to wind energy densities,

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2} = \eta_* \frac{(r/R_*)^{2-2q}}{(1-R_*/r)^\beta} \, . \tag{1}$$

Here $\eta_* \equiv B_*^2 R_*^2/(\dot{M} v_\infty)$ defines an overall “magnetic confinement parameter” in terms of the strength of the equatorial field B_* at the stellar surface radius R_*, and the wind terminal momentum $\dot{M} v_\infty$. The latter equality thus isolates the radial variation in terms of a magnetic power-law index q ($= 3$ for a dipole) and a velocity index β (≈ 1 for a standard CAK wind). If, for simplicity, we ignore the wind velocity variation (i.e. by taking $\beta = 0$), we can easily solve for an *Alfven radius* $\eta(R_A) \equiv 1$ at which the magnetic and wind energy densities are equal,

$$R_A = \eta_*^{1/4} R_* \, . \tag{2}$$

As shown by simulation results summarized below, this Alfven radius provides a reasonable estimate for the maximum radius of closed loops in a wind outflow. Moreover, since in rotating models such closed loops tend to keep the outflow in rigid-body rotation with the underlying star, it also defines the radius of maximum rotational spin-up of the wind azimuthal speed.

To characterize such rotational effects, let us next define a *Keplerian corotation radius* R_K at which rigid-body rotation would yield an equatorial centrifugal acceleration that just balances the local gravitational acceleration from the underlying star,

$$\frac{GM}{R_K^2} = \frac{v_\phi^2}{R_K} = \frac{V_{rot}^2 R_K}{R_*^2} \, , \tag{3}$$

where V_{rot} is the stellar surface rotation speed at the equator. This can be solved to yield

$$R_K = W^{-2/3} R_* , \tag{4}$$

where $W \equiv V_{rot}/V_{crit}$, with $V_{crit} \equiv \sqrt{GM/R_*}$ the critical rotation speed.

Finally, it is also worth noting here that corotation out to an only slightly higher *escape radius*,

$$R_E = 2^{1/3} R_K = 2^{1/3} W^{-2/3} R_* \, , \tag{5}$$

would imply an azimuthal speed that equals the local escape speed from the star’s gravitational field.

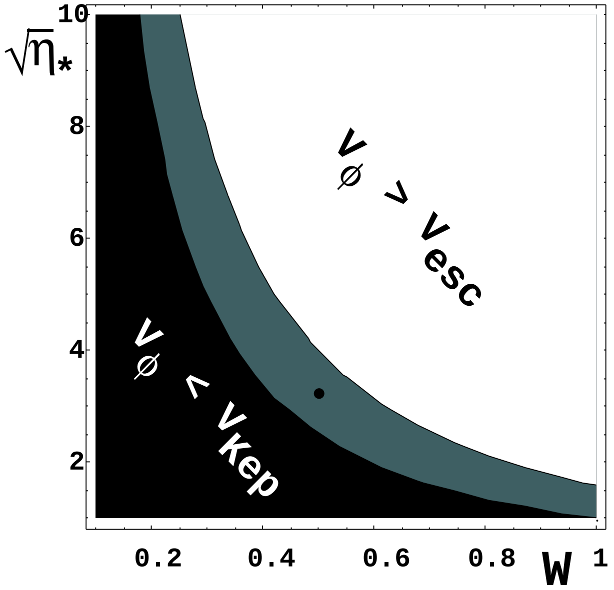

Figure 1. The key domains in a parameter plane of magnetic field strength (as represented by $\sqrt{\eta_*} \sim B_*$) vs. stellar rotation (as represented by the critical rotation fraction $W \equiv V_{rot}/V_{crit}$). The dot represent parameters for simulation models shown in figure 2.

6. MHD Models Optimized for Keplerian Spin-up

The above scalings suggest that a likely necessary condition for propelling outflowing material into a Keplerian disk is to choose a combination of parameters for magnetic confinement vs. stellar rotation such that $R_K < R_A < R_E$. In the parameter plane of $\sqrt{\eta_*} \sim B_*$ vs. W defined in figure 1, the required combination is represented by the relatively narrow gray band. The dark region below this represents parameter combinations for which the azimuthal speed at the Alfven radius is expected to be sub-Keplerian, while the white region above represents cases for which the rotation speed at the Alfven radius should exceed the local gravitational escape speed.

As a sample test case, we focus here on the specific combination $\eta_* = 10$ and $W = 1/2$, which as shown by the dot in figure 1, lies in the middle of the gray domain, and thus should represent an optimal case for magnetic spin-up into Keplerian orbit.

Figure 2 illustrates results of 2D MHD simulations for this case, using the approach and general model assumptions described in ud-Doula and Owocki (2002), but now extended to include field-aligned rotation. The left panel shows that conditions at a time 90 ksec after introduction of the field do superficially resemble a magnetically torqued disk. Closer examination shows, however, that most of this equatorial compression does not have the appropriate velocity for a stable, stationary, Keplerian orbit. Thus in just a few ksec of subsequent evolution, this putative "disk" becomes completely disrupted, characterized generally

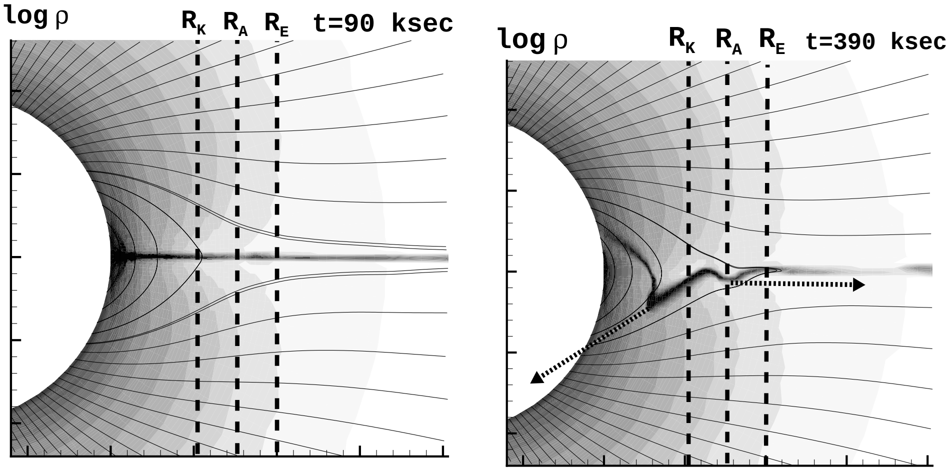

Figure 2. Density of a 2D MHD simulation for a model with $\eta_* = 10$ and $W = 1/2$, shown at time snapshots of 90 ksec (left) and 390 ksec (right) after a dipole field is introduced into an initially steady-state, unmagnetized, line-driven stellar wind. The curves denote magnetic field lines, and the vertical dashed lines indicate the equatorial location of the Keplerian, Alfven, and Escape radii defined in eqns. (3), (5), and (6) of the text. The arrows denote the upward and downward flow above and below the Keplerian radius, emphasizing that the material never forms a stable, orbiting disk.

by infall of the material in the inner region, i.e. below the Keplerian radius R_K, and by outflow in the outer region above this Keplerian radius. The right panel illustrates the irregular form of the dense compression at an arbitrarily chosen later time (390 ksec from the initial start). The arrows emphasize the flow divergence of the dense material both downward and upward from the Keplerian radius. This evolution is most vividly illustrated through animations, which can be viewed on the web at:
`www.bartol.udel.edu/∼owocki/animations/den4wp5eta10.avi`

We have carried out similar MHD simulations for a moderately extensive set of combinations for the rotation and magnetic confinement parameters. In all cases we find that any equatorial compressions are dominated by radial inflows and/or outflows, with no apparent tendency to form a steady, Keplerian disk.

7. Rigidly Rotating Magnetospheres

As discussed in the poster paper by Townsend et al. (see also Townsend & Owocki 2004), in the limit of very strong magnetic confinement (i.e., $\eta_* > 1000$), it is possible to idealize the magnetic lines-of-force as “rigid pipes” that channel the wind outflow and forces it to maintain rigid-body rotation. Below the Keplerian radius, such material will again tend to fall back to the star, but above this radius, it will be centrifugally supported against gravity, allowing mass to accumulate at minima in the effective centrifugal-plus-gravitational potential. This leads to formation of circumstellar “clouds” near the intersection of the magnetic and rotational equators, which indeed extend to an azimuthally symmetric, equatorial disk in the limit that the magnetic and rotational axes become perfectly aligned.

It is important, however, to clearly distinguish such *rigid-body* disks from the Keplerian, orbiting disks that were the goal of the MTD model. In the latter, magnetic forces play the essential role of torquing material up to orbital speed, but are then assumed to effectively disappear in order to release material into a Keplerian disk. By contrast, in the rigid-disk model the field torques material up to *and beyond* orbital speed, but then also *persists* at a sufficient strength to *hold material down* against centrifugal forces that would otherwise propel it outward.

There are several reasons why rigid-body disks seem ill-suited to explaining Be-stars. First, the general lack of rotational modulation in Be-star emission would require a quite close alignment of the field and rotation axes, since only this would yield an azimuthally symmetric disk in the rotational equator. Moreover, the overall line profiles seem consistent with a Keplerian disk (Hanuschik 1995); in particular, the "central quasi-emissions" (Rivinius et al. 1999) seen in many nearly edge-on systems requires the azimuthal velocity to decline outward, consistent with a Keplerian disk but contrary to the outward increase of rotation speed in a rigid disk. Finally, the long-term V/R variations seen in a substantial fraction of Be stars seem best explained by a Keplerian disk undergoing a precession of elliptical orbits that characterize an one-arm disk oscillation (Savonije and Heemskerk 1993; Telting et al. 1994; Savonije 1998). In a rigid-body disk in which the individual fluid elements of the disk are tied to the rotation period of the star, it is difficult to see how any processes could reproduce the year-long timescales of V/R asymmetries that require an associated long-term distinction in the physical properties of emitting material in a specific fixed-frame direction.

To conclude, it thus seems that magnetic fields are not very well suited to reproducing emission signatures of Be-star disks. However, as shown in the poster paper by Townsend et al., the Rigidly Rotating Magnetospheres (RRMs) that obtain for the strong field limit do provide a quite promising model for the rotationally modulated emission seen in magnetic Bp stars. Moreover, the poster by Ud-Doula et al. shows that the eventual centrifugal breakout of material can lead to strong reconnection heating, and so could explain the hard X-ray flares observed from some Bp stars.

8. Radiatively Driven Orbital Mass Ejection

As another alternative for Be-star Keplerian disks, let us next examine models in which driving is provided by the radiative force from localized bright spots on the stellar surface, a scenario for "Radiatively Driven Orbital Mass Ejection" (RDOME). A key feature of these RDOME models is to include the prograde radiative force that is expected in the region ahead of the bright spot. Since radiative driving is routinely capable of driving a stellar wind to speeds well in excess of orbital launch speeds, it seems possible that the prograde force ahead of the bright spot might impart material there with sufficient angular momentum to achieve circumstellar orbit.

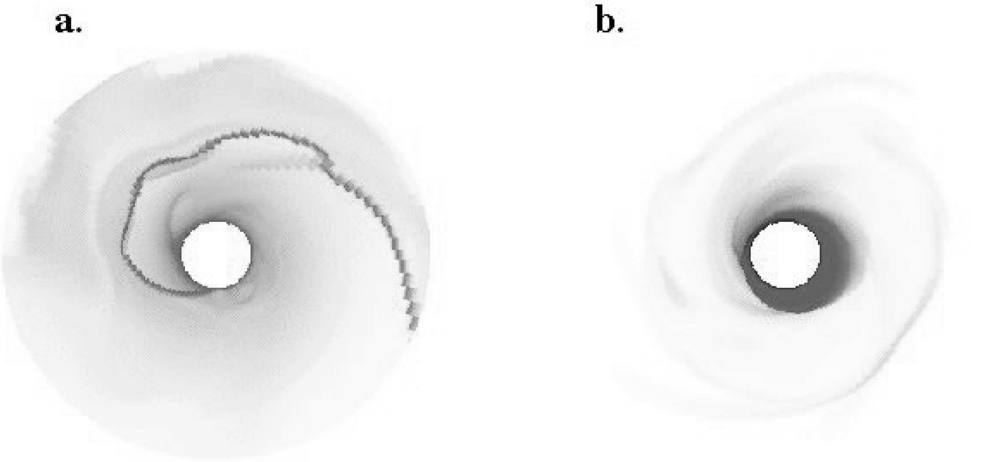

Figure 3. a. Density at fixed time snapshot of 2D, equatorial-plane models of flow radiatively driven from a bright spot on a star rotating at 70% critical, showing formation of dense CIR. b. Same as (a), but with a radiative force cutoff for $r > 1.25R_*$, resulting in fall-back of material into an orbiting disk.

For a star with equatorial rotation speed (350 km/s) that is 70% of the critical speed (500 km/s), figure 3a shows a typical time snapshot of the density from 2D radiation hydrodynamical simulations of the outflow driven by a spot with a localized brightness that peaks at a (quite large) factor of 10 times the ambient brightness. Confined to a region with Gaussian half-width of 10 degrees in longitude, this spot is suddenly turned on at some initial time within an otherwise steady-state wind model, and then shut off again after just 100 ksec, about a rotation period. Note that, instead of forming an orbiting circumstellar disk, the overall result is to propel a spiral Co-rotating Interaction Region (CIR) of enhanced density within the outflowing stellar wind. This is much the same form thought to be needed to explain Discrete Absorption Components in UV wind lines (Owocki, Cranmer, and Fullerton 1995; Cranmer and Owocki 1996). The reason to favor wind CIRs over disks is that material initially propelled ahead of the spot tends eventually (due to its extension away from the surface) to fall behind the solid body angular rotation, and so as it thus comes over the central bright spot it receives a very strong *radial* push from the bright-spot radiative force, thus propelling it away from the star in an outflowing wind CIR.

There are a variety of possibilities for instead favoring lateral over radial driving from a bright spot. One is to consider a model in which, perhaps due to distortion of the surface associated with stellar pulsation, the spot radiation might have *prograde-bias* in the direction of rotation. Another is to assume a symmetric, but highly *limb-brightened* spot emission, with the upward intensity comparatively suppressed, somewhat analogous to the emission pattern from a quiescent solar prominence, which appears bright above the solar limb, but relatively dark against the solar disk. A third possibility (first suggested by J. Bjorkman, p.c.) is to assume a *cutoff* in the radiative driving above some relatively low radius, perhaps reflecting shifts in wind ionization balance. Indeed, I find that any of these rather specialized modifications can in fact lead to formation of a circumstellar disk.

Figure 3b illustrates a snapshot of the disk density for the last scenario, assuming the same spot as figure 3a, but now with a force cutoff beyond $1.25R_*$. A fuller time sequence (see figure 5 of Owocki and Cranmer 2002) shows that above this cutoff radius the outflow stagnates, but since material has also received an azimuthal boost in angular momentum, its fallback toward the star now forms an orbiting circumstellar disk. I find similar disk formations are possible for the prograde and limb-brightened spot scenarios.

The key questions surrounding such RDOME models regard the rather extreme brightness variations that are assumed, as well as the rather arbitrary fine-tuning of the spot emission or line-force cutoff. Brightness fluctuations are sometimes observed in Be stars, but further work is needed to determine whether these have a time-scale and magnitude that might be consistent with this RDOME scenario.

Indeed, recent analyses suggest that, quite apart from propelling material to feed a circumstellar disk, radiative forces may actually play a key role is *dissipating* an existing disk, for example through “line-driven ablation”, which could drive a wind outflow from the disk surface (Gayley et al. 1999, 2001; Rivinius et al. 2001). From this perspective, radiative forces might instead be considered an “enemy of the disk”, perhaps of more relevance for their intermittent *dis*appearance whenever other mechanisms for ejecting fresh material into orbit are inoperative or reduced.

9. Pulsationally Driven Orbital Mass Ejection

Observations by Rivinius et al. (1998, 1999) suggest that in at least one Be star (μ Cen) there may be a coincidence between multiperiodic beating of nonradial pulsation (NRP) modes and outbursts in circumstellar lines that signify star-to-disk mass transfer. This motivates consideration of whether such pulsations could themselves be the mechanism for launching material in Keplerian orbit, a scenario for “Pulsationally Driven Orbital Mass Ejection” (PDOME).

In this regard, a key consideration is the nature of the pulsation and its characteristic velocity variation. For high-frequency, acoustic (p-mode) pulsations, the compressional velocity is primarily radial, with an amplitude that is generally well below the sound speed; such modes seem ill-suited to ejecting material with the speed and direction to achieve orbit. But in μ Cen the observed periods are well above the acoustic cutoff period, indicating that the relevant pulsations are instead gravity waves (g-modes), with the restoring force due to buoyancy transmitted through the gas pressure. Instead of a radial compression, the gas motion is more a lateral circulation, with a velocity amplitude that can feasibly approach or even slightly exceed the sound speed, Moreover, for prograde modes, the peak height of the pulsation occurs when the lateral velocity is directed in the direction of the stellar rotation, a situation that seems much better suited to ejecting material into orbit.

Still, this mechanism requires that the difference $\Delta V = V_{crit} - V_{rot}$ between orbital and rotation speed must be comparable to the pulsation velocity amplitude ΔV_{NRP}, which itself can perhaps only approach or slightly exceed the

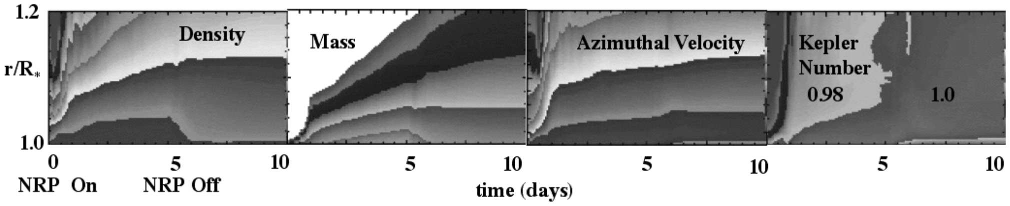

Figure 4. Results of a 2D hydrodynamical simulation of non-radial pulsations introduced for a 5-day interval in the equatorial plane of a nearly critically rotating star, with pulsation velocity amplitude equal to the star's orbital jump velocity, $\Delta V_{NRP} = \Delta V_{orb} = 25$ km/s. The panels show contours for the height and time variation of the azimuthally averaged values of (a) density ρ, (b) radially integrated disk mass m, (c) azimuthal velocity v_ϕ, and (d) Kepler number ($\equiv v_\phi / V_{Kep}$, with V_{Kep} the local Keplerian orbital velocity).

sound speed $a \approx 25$ km/s. For typical orbital speeds $V_{crit} \approx 500$ km/s, this requires

$$W \equiv \frac{V_{rot}}{V_{crit}} \approx 1 - \frac{a}{V_{crit}} \approx 0.95\,. \tag{6}$$

Such rotation fractions are substantially higher than the canonical values of $v_{rot}/v_{crit} \approx 0.75 - 0.8$ that have been commonly cited in the past. On the other hand, as discussed in several of the focus sessions at this workshop, recent reanalysis (Townsend et al. 2004) of the effect of gravity darkening (von Zeipel 1924) on the rotational broadening of absorption lines suggests that Be star rotation rates could indeed quite generally be within a few percent of critical.

We have recently carried out hydrodynamical simulations of the effect of equatorial pulsations in stars with such near-critical rotation rates. Azimuthal velocity variations are introduced as an Eulerian perturbation at the star's equatorial surface, with corresponding logarithmic variation in density (typically factor 10) to account for the associated vertical oscillation within an exponentially stratified atmosphere. A positive (negative) phase relation between azimuthal velocity and density then corresponds to an NRP with phase propagation that is prograde (retrograde) to the sense of rotation. To mimic an interval of enhanced amplitude from beating between two modes, the pulsations are switched on for a fixed time interval.

Figure 4 illustrates simulation results for a model in which a prograde NRP (with $m = -2$) is introduced for an interval of 5 days, with velocity amplitude equal to the star's orbital velocity jump, $\Delta V_{NRP} \approx \Delta V_{orb} \approx 25$ km/s. Once the pulsation is started, there is a systematic buildup of circumstellar density and mass (panels 4a and 4d), with azimuthal velocity very close to that required for Keplerian orbit (panels 4c and 4d). After the pulsation is stopped, the density buildup levels off, but there remains a substantial orbiting disk.

In accord with the orbital launch requirements outlined above, we generally find that significant disk production requires such a *prograde* pulsation with an azimuthal velocity amplitude ΔV_{NRP} that is comparable to the orbital launch speed ΔV_{orb}. The need for prograde modes stands in apparent contradiction with the interpretation by Rivinius et al. (1999) that NRPs observed in μ Cen correspond to *retrograde* modes. This, and the need to assume near-critical rotation, thus represent key issues for the viability of this PDOME scenario for disk formation.

10. Concluding Outlook

If Be-star rotation rates are indeed found to be very near critical, the implications for developing dynamical models of Be disk formation would be quite profound. As emphasized above, a key parameter is the ratio of the minimal launch speed to the atmospheric sound speed. If $\Delta V_{orb}/a \gg 1$, then a rather strong orbital ejection mechanism is required, with obvious candidates like radiative driving or magnetic spin-up (Cassinelli et al. 2002) so far needing rather special conditions and fine-tuning (ud-Doula 2002; Owocki and ud-Doula 2003).

But if $\Delta V_{orb}/a \sim 1$, then a much broader range of atmospheric-based ejection mechanisms are possible, including non-radial pulsations. In this case, the complex behavior of individual Be stars – the sporadic brightenings, even disappearance and reappearance of disk emission – may be associated with the various processes that could spark individual mass eruptions. But the overall Be phenomenon itself would essentially be the consequence of near-critical rotation, owing perhaps to envelope spin-up associated with the evolutionary contraction of a massive-star's core toward the terminal age main sequence, as reviewed in this workshop by G. Meynet.

From this perspective, the disk emission that characterizes Be stars could be considered the result of interior-driven processes that require equatorial shedding of excess angular momentum, somewhat like a rotational analog of the Roche-lobe overflow in mass-exchange binary systems. In both cases, a disk forms as a repository for the ejected material, with its net mass – and thus its observed emission strength – depending on the competition between the stellar ejection rate and the rate for disk dissipation, e.g. from radial diffusion and perhaps surface ablation. Although the overall mass ejection is controlled by interior processes, the details can be variable and spatially complex, controlled by surface disturbances. Indeed the dynamics and energetics of the specific perturbation processes can even influence how much below the critical level the mean surface remains.

To conclude, I believe a top priority for Be-star research should be the development of dynamical models of disk production within a context of more firmly established observational constraints on how close the stellar rotation may be to critical.

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