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Overview of Active OB Stars

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Abstract. In contrast to their classical ideal as constant, spherical, radiative envelopes, the hot, luminous, OB-type stars often exhibit signatures of activity, with associated variability and structure on a range of temporal and spatial scales. For example, spectral monitoring shows that even "normal" OB stars commonly exhibit variable Discrete Absorption Components (DACs) in UV lines formed in their stellar wind. And certain special classes – e.g. Be, B[e], LBV, Bp stars – are in effect defined by their particular signatures of activity. A common element is often the emission and/or absorption by *circumstellar* material. Thus a general theme here is to consider the physical mechanisms that can drive material off the nominally tightly bound hydrostatic stellar surface. Specifically I discuss the dynamical roles played by radiation, rotation, pulsation, and magnetic fields, and how these, individually or in combination, can eject the circumstellar clouds, disks, and/or mass outflows that seem to be at the root of many observed signatures of hot-star activity. In emphasizing a framework of physical commonalities, an overall goal is to foster exchanges among researchers specializing in the various classes of active OB stars.

1. Introduction

The high surface temperature of OB stars means that they lack the strong hydrogen-recombination convection zones that drive magnetic dynamo activity cycles in cooler, late-type stars like the sun. Classically, such hot stars are thus often idealized as having steady, spherically symmetric, radiative envelopes. Yet observations over the years have identified several classes of "Active OB Stars" that exhibit distinct signatures of complex spatial structure and temporal variability. An historically important, and still very prominent class is the classical Be stars, characterized by Balmer line emission that can vary on time scales ranging from hours to years. But recent years have added further examples – magnetic Bp stars, supergiant B[e] stars, Luminous Blue Variables (LBVs), Beta Cephei pulsators, and Slowly Pulsating Stars (SPBs) – that show various signatures of activity.

A central driving idea in defining the scope of this meeting has been to expand beyond the traditional focus in our community on the observational phenomenology of Be stars, to consider also these other types of active early-type stars, with a particular emphasis on the physical processes underlying such activity. Since a common property of many of these types of active hot stars is the prominence of line emission arising from circumstellar material, this overview focuses on several specific processes – e.g., pulsation, rotation, radiative driving, magnetic fields, and binarity – which, by themselves or acting in combination, could overcome the stellar gravity and propel material from the stellar surface and into a circumstellar outflow, envelope, or disk. With regards to the general, and sometimes loose characterization of a circumstellar disk, a particular emphasis here is on key distinctions among the different kinds of disk – for example outflowing vs. Keplerian vs. rigid-body –, with a focus on which of the above propulsion mechanisms are most favorable for each type.

2. Broader Relevance of Active OB Stars

Like beauty, the perception of what is interesting is often in the eye of the beholder. But in a broad astrophysical context, it is worth considering what makes study of Active OB Stars worthwhile. In my eyes, one reason is the counterexamples they provide, for example to the kind of activity seen on the sun. While there are some similarities, the lack of recombination-driven convection zones in OB stars suggests that the source of activity must have key differences from magnetic-dynamo activity cycles on the sun and other cool, late-type stars.

Another counterexample regards the nature of disks in Active OB Stars; in contrast to the *accretion* disks seen in star-formation regions or mass-exchange binaries, the disks in OB stars are thought to result from ejection, or "decretion" of matter from the star. The single or wide-binary status of Be stars gives them a relatively simple overall geometry compared to binary mass exchange systems. And the tendency for the disk emission to vary, and even disappear and reappear on human timescales of months to years, makes it possible to test dynamical processes for disk perturbation, and even destruction and reformation.

A further factor is the extreme nature of OB stars. They are the hottest, most luminous, most massive stars there are. They have the strongest mass loss, ranging up to a billion times the rate of the solar wind. They are also the most rapidly rotating stars; even normal OB stars have rotation rates of several hundred km/s, dwarfing the 1-10 km/s typical for cooler stars like the sun.

Activity can moreover affect many other stellar processes, like wind mass loss, evolution, rotation, and the ejection of nebulae in Luminous Blue Variable (LBV) phases. Perhaps even the final stages of these stars as they explode as supernova (as expected for stars with initial mass above about 8 solar masses) can be affected by activity in earlier stages. It could even help determine whether a star evolves to a rapidly rotating core collapse, giving rise to a gamma ray burst, which are among the most luminous objects in the universe.

3. Observational Properties of Various Types of Active OB Stars

As specific background, let us briefly summarize here the key characteristics of various types of Active OB Stars.

Classical Be Stars are characterized by Balmer line emission, with also generally strong rotational broadening in photospheric absorption lines, implying projected rotation speeds $V \sin i$ that are substantial fractions (half or more) of the estimated "critical" rotation speeds at which equatorial surface material would be in Keplerian orbit. The emission is typically separated into Violet and Red peaks, with the relative V/R strength often varying on timescales of years. In many Be stars, the Balmer emission appears and fades over timescales of years or even decades. During rebuilding phases, the added emission is sometimes discerned to appear in discrete elements, sometimes with rapid V/R variations on timescales (days) comparable to the rotation and/or near surface orbital period.

sgB[e] stars are relatively rare, supergiant B-type stars that exhibit both permitted and forbidden emission lines, with the latter thought to form in the outer regions of a dense equatorial disk. Strong IR excesses further indicate the formation of warm dust at intermediate radii of the disk, implying a very high density. Veiling by the circumstellar material complicates the interpretation of the photospheric spectrum, but in the few cases where photospheric absorption lines can be identified they also show signs of significant rotational broadening.

Magnetic Bp stars have "peculiar" spectra associated with abundance anomalies, most notably either enhanced helium in early B or depleted helium in late B spectral classes. Polarization observations also indicate the presence of a very strong (ca. 10 kG) magnetic field, generally consistent with a dipole configuration that is tilted to the star's rotation axis. These stars also exhibit Balmer emission, which in some cases show distinct, sometimes periodic variations on the inferred stellar rotational period.

Luminous Blue Variable (LBV) stars exhibit evidence of episodic outbursts accompanied by substantial mass loss, which, given their extreme luminosities, may be associated with the star exceeding a modified Eddington limit.

Beta Cephei Pulsations are early B-stars that show evidence of radial and nonradial pulsations, with relatively relatively short periods (typically a few hours) consistent with acoustic or pressure waves (p-modes).

Slowly Pulsating B-Stars show lower-period, non-radial pulsation modes that are most likely associated with buoyancy-driven gravity waves (g-modes).

Note that these categories are not always distinct and exclusive. For example, many Be stars also exhibit evidence for non-radial pulsation.

4. Circumstellar Emission and Overcoming Gravity

A common characteristic of many of these types of Active OB Stars is the spectral prominence of *emission* lines, as distinct from the absorption-line character of "normal" stellar spectra. With some exceptions (e.g. the solar chromosphere), such line emission is typically a signature of *circumstellar* material that has been lifted away from the stellar surface into some kind of circumstellar envelope, disk, or wind outflow. A key issue then regards what dynamical processes are responsible for this lifting of the material against the stellar gravity.

To illustrate this issue, it is helpful to consider the equation for hydrostatic pressure stratification in a star's envelope or atmospheric surface,

$$\frac{GM}{R^2} = -\frac{1}{\rho}\frac{dP}{dr} \equiv \frac{a^2}{H} \,. \tag{1}$$

Here G, M, and R are the gravitation constant, stellar mass, and stellar radius, and ρ and P are the mass density and gas pressure. The latter equality uses the ideal gas law $P = \rho a^2$, with a^2 the square of the isothermal sound speed (proportional to the gas temperature), to define a characteristic pressure scale height,

$$H \equiv \frac{a^2}{g} = \frac{a^2 R^2}{GM} \equiv \frac{a^2}{v_{orb}^2} R \, , \tag{2}$$

where $g \equiv GM/r^2$ is the local gravitational acceleration. The last equality defines this scale height as being the stellar radius times the squared ratio of the sound speed to near-surface orbital speed, $v_{orb} \equiv \sqrt{GM/R}$ (which itself is only a factor of $\sqrt{2}$ smaller than the surface escape speed, $v_{esc} = \sqrt{2GM/R}$). For most stars (i.e., except large hypergiants or small, collapsed stars), the orbital speed is typically $v_{orb} \approx 500$ km/s, whereas the sound speed is of order $a \sim 10$ km/s. This implies $H/R \ll 1$, which provides the essential reason why stellar atmospheres comprise only a very thin layer on the surface of a typical star. For example, for hot-stars with $a \approx 25$ km/s, we find $H/R \approx 1/400$, while for the solar photosphere with $a \approx 10$ km/s, we get an even smaller ratio $H/R \approx 1/2000$.

By contrast, in the solar corona the heating to temperatures of several million Kelvin yields a sound speed $a \approx 150 - 200$ km/s that is actually comparable to the orbital (and escape) speed, thus implying a coronal scale height that is now a significant fraction of the solar radius, $H/R \approx 1/9$. This provides the basic explanation for the relatively extended nature of the solar corona, e.g. as viewed in EUV and X-ray pictures of the extended solar surface, or in white-light photos taken during with a coronagraph or during an eclipse. In the latter, the outer corona shows radial streamers characteristic of the radial expansion of the corona into the solar wind, which in fact is *driven* by the high coronal gas pressure relative to the near vacuum of the interstellar medium.

Spacecraft images of the sun and corona in EUV, X-rays, and white-light coronagraphs also show extensive spatial structure, with extended "Active Regions" overlayered with magnetic loops and arcades. Temporal monitoring further shows a persistent, often violent variability, characterized by episodic flares and Coronal Mass Ejections (CMEs). This extensive solar activity is quite obviously rooted in the complex magnetic field structure that is generated by the sun's rotation-convection dynamo. Its dissipation by magnetic reconnection leads to flares and coronal heating, and ultimately to the complex solar wind expansion, with its continuous outflow punctuated by recurrent episode of CMEs.

The vividness of such direct observations of solar activity makes it tempting to imagine that the spatially unresolved activity in OB stars might share many similar properties. However, there are some key differences that imply the analogy could in fact be rather limited, and thus should be applied with caution. Most notable is the fact, already emphasized above, that hot, luminous stars have mostly radiative envelopes, and thus lack the strong near-surface convection zones needed to drive magnetic-dynamo activity cycles. As such, hot-star magnetic fields that have been detected are often inferred to have a relatively large, dipole scale, with a steady, perhaps even constant magnitude and orientation, showing little evidence of active generation or a decadal cycle analogous to the 11-year sunspot cycle.

From a related perspective, the ratio $H/R = (a/v_{orb})^2$ can be thought of as characterizing roughly the ratio of the internal gas energy of the atmosphere to the gravitational binding energy at the stellar surface. The typically small value for this ratio in hot stars thus generally suggests that some additional, quite energetic mechanism for outward propulsion is needed to lift material away from the stellar surface. The following section thus examines in turn the various processes – pulsation, rotation, binarity, radiative driving, and magnetic fields – that could play a role in OB star activity, and/or in lifting material into circumstellar emission, either as an orbiting disk or an outflowing wind.

5. Processes for OB Activity and Overcoming Gravity

5.1. Pulsation

OB stars often lie within various pulsational "instability strips" in the H-R diagram, identifying stellar parameters for which various opacity (kappa) mechanisms, associated with H, He and Fe ionization/recombination, can drive radial or nonradial pulsation (NRP).

One of the key distinctions to be made is whether the main restoring force is associated with gas pressure, as in ordinary sound waves or"p-modes", or is due to gravitational buoyancy, as in gravity waves or "g-modes". P-modes can be either radial or non-radial, and generally have relativity high frequency or short periods, shorter than the atmospheric acoustic cutoff period, which is typically of order a few hours. G-modes are only non-radial, and are lower frequency or longer period, above the acoustic cutoff period, typically on the order of a day, or a significant fraction thereof. Both mode types occur in early type stars, for example p-modes in Beta Cepheid variables, and g-modes in Slowly Pulsating B-stars (SPBs). Another distinction is that p-modes are longitudinal and compressive, whereas g-modes involve lateral circulations and overturning.

Such pulsations can have an effect in perturbing the outflow of the star's radiatively driven stellar wind. A promising example regards the very large *radial* pulsations of the B1V-B2III star BW Vulpeculae, for which variations in wind lines have been quite successfully modeled as arising from changes in the radiative driving associated with the pulsational brightness variations of the underlying star (Owocki & Cranmer 2002).

In the case of non-radial modes, a key issue is whether the azimuthal propagation is *prograde* or *retrograde* relative to the sense of the stellar rotation. Prograde g-modes in particular have their peak density occurring when the material is moving in the direction of rotation, suggesting perhaps a natural way to boost material into circumstellar orbit. Sometimes there can be multiple modes of closely separated frequencies (reflecting a small difference in a large radial order), which can thus "beat" against each other. For example, Rivinius et al. (2001) have identified such beating in the Be-star μ Cen; Baade et al. (2002) indicate moreover that intervals of maximum beat amplitude seem to coincide with epochs of sudden enhancements in circumstellar emission, which suggest perhaps a pulsation link to mass ejection into circumstellar orbit.

But two key issues here regard the *sense* and *amplitude* of the pulsation velocity variation. Observations of NRPs generally infer a *retrograde* phase propagation, which would seem to work against a role in mass ejection. But recent work suggests that at high-rotation, there can be "mixed-modes" (mixed between gravity and rotational or "Rossby" modes) that can have *prograde group* propagation even when the phase is retrograde (see poster by R. Townsend and references therein); this keeps alive a potential role for pulsation in mass ejection.

However, because the velocity amplitude of both sound and gravity modes is likely to be limited to of order the sound speed, such ejection seems energetically possible only when the rotation is within about a sound speed of the critical speed. For the above typical values of $a \approx 25$ km/s and $v_{orb} \approx 500$ km/s, this thus requires the stars to be very close to critical rotation, with a velocity ratio $v_{rot}/v_{crit} \gtrsim 0.95$. Initial hydrodynamical simulations (see, e.g. Owocki 2005) indicate that pulsational feeding of a disk can be quite promising under such conditions of near-critical rotation.

Pulsations could even play a role in spinning up the equatorial regions by transporting angular momentum toward the equator (Ando 1986). Even if the overall stellar rotation is relatively modest, such a *differential* rotation in latitude could allow the equatorial regions to approach critical rotation, setting the conditions for mass ejection, including perhaps by individual pulsation resonances or by some other kind of disturbance (e.g. from magnetic reconnection).

Finally, in very luminous (B[e], LBVs) stars in which radiation pressure dominates, a new kind of "strange" or s-mode pulsation can come into play, and perhaps even drive mass ejection. The review by W. Glatzel (these proceedings) gives further details.

5.2. Rotation

So we see rotation can be a key factor in Active OB stars. Indeed, early-type stars tend generally to be quite fast rotators, in contrast, for example, to late-type stars like the sun. And even apart from the issue of just how close they may be to critical rotation, it is clear that Be, and perhaps also B[e] stars (and even perhaps some LBV stars like η Carinae), are particularly rapid rotators.

One question is thus: what can spin up these stars? For single stars, G. Meynet (these proceedings) discusses how the reduction of the envelope moment of inertia due to evolutionary contraction toward the interior can lead to a spin-up toward the end of the main sequence. But G. McSwain (these proceedings) presents evidence that many Be stars are in fact in binary systems, thus suggesting that an earlier epoch of mass exchange, when the binary components were closer together, could be a key factor in the Be star spin-up. Podsiadlowski (2006) has even recently suggested that B[e] stars, and perhaps also bipolar LBVs like η Carinae, may be the result of spin-up by massive star binary merger. An important question is how we test these various spin-up scenarios.

With regard to rapid rotation itself, a central issue is the role of equatorial *gravity darkening*, as first posited for radiative envelopes by von Zeipel (1924). This can both influence the radiatively driven mass loss (Owocki et al. 1996; Maeder & Meynet 2000; Maeder & Desjacques 2001), and lead to an underestimate of the stellar rotation speed from photospheric line broadening (Stoeckley 1968). It is rather remarkable, and unfortunate, that the important work by Stoeckley (1968) had been essentially ignored in the Be-star literature, for it implies that, when gravity darkening is fully taken into account, the rotational broadening of lines essentially saturates at rotation rates beyond about 75% of critical, due to the diminishing relative flux contribution of the equatorial regions that would otherwise contribute most to the broadening. There is also an associated shifting in the H-R diagram, toward higher apparent luminosities for pole-on stars, cooler apparent temperatures for equator-on stars, and roughy parallel to the diagonal evolutionary sequence for intermediate inclinations. Both results have recently been reconfirmed (and indeed reemphasized) by studies using modern atmospheres codes (Townsend et al. 2004).

The overall implication is that Be stars, which some statistical studies have inferred to have mean rotation rates of ca. 75% of critical (Chauville et al. 2001, e.g.), could actually be rotating much closer (perhaps even within a few percent) to critical. Recent work by Cranmer (2005) challenges this notion, arguing that Be rates may actually average only 50% of critical, for which the gravity darkening effect would not be so important. But it is important to realize that any such analysis also depends crucially on the inference of the critical speed, which because of the ambiguities in inferring the fundamental stellar parameters from the observed spectrum of rapidly rotating stars, may actually be quite uncertain (see, e.g., Howarth, these proceedings).

In this issue of how close rotation might be to critical, an important new clue comes from interferometry, namely recent measurement using the VLTI of the oblate shape of the B3Vpe star α Eridani, a.k.a. Achernar (Domiciano de Souza et al. 2003). The results indicate a ratio of ca. 1.6 between the longer and shorter axes, which in fact is greater that the maximum ratio of 1.5 expected from classical (rigid-body, Roche-potential) models of a critically rotating stellar envelope. Achernar shows quite moderate rotational broadening ($V \sin i \approx 250$ km/s), and only occasional, marginal emission, implying a transient, relatively weak disk (which was ostensibly absent during the time of the VLTI observations). Yet the large oblateness would seem to require a quite fast, near-critical rotation for this star.

If Be stars are indeed nearly critical rotators, there could even be direct decretion into an orbiting disk, as first envisioned in early models by Struve (1931), and inherent in modern simulations of "Viscous Decretion Disks" (Lee, Saio & Osaki 1991).

5.3. Binarity

In addition to the possible role (discussed in §5.2) of binary mergers or binary mass exchange in spinning up the stellar rotation, there exists an intriguing possibility that tidal interactions from an OB star's binary companion might induce mass ejections into a circumstellar disk, either directly or indirectly, e.g. by exciting stellar pulsations. The steep decline of tidal interactions with distance would normally require a relatively close, short period system. But for a wider, longer period system that is sufficiently elliptical, tidal interactions near periastron passage could exert an important influence, particularly if the excited star already has rotation close to critical, since then even small perturbations might be sufficient to kick material into circumstellar orbit (see, e.g. Harmanec et al. 2002). A possible candidate for such tidal induction of mass ejection is the B0IVe star δ Scorpi, which is in a wide binary (period of 10.6 years) with an eccentric orbit ($\epsilon \gtrsim 0.9$), with evidence of emission line outbursts associated with periastron passage, which last occurred in 2000.

5.4. Radiative driving

The high luminosity of OB stars means that radiative driving by line scattering can be a quite efficient means to lift material from the star into an outflowing stellar wind (Castor et al. 1975). The intrinsic instability of this line driving is thought to be the source of extensive small scale structure and variability, leading to shocks that produce soft X-ray emission (Feldmeier et al. 1997). In low-density winds, the relatively weak collisional coupling can allow separation of minor ions, which receive the direct impulse of radiation, from the bulk of passive mass in hydrogen and helium (Springmann & Pauldrach 1992; Krtička & Kubát 2001) leading to a so-called metal wind, with associated effects on surface abundances, e.g. in the Bp stars. In rotating stars, surface variations in longitude can induce "Co-rotating Interaction Regions" (CIRs) in the wind, providing a possible explanation for the "Discrete Absorption Components" commonly seen UV wind lines (Cranmer & Owocki 1996; Fullerton et al. 1997).

In rapidly rotating stars, the wind can also develop variations in latitude, raising the potential for connections to the equatorial disk inferred from Balmer line emission. In what seemed at first a very promising approach, the Wind Compressed Disk (WCD) model introduced by Bjorkman & Cassinelli (1993) naturally produces an equatorial disk of enhanced-density flow from just the rotational focussing of the radiatively driven stellar wind expected from intrinsically bright Be stars. Initial dynamical simulations did in fact confirm much of the basic WCD paradigm (Owocki et al. 1994), but subsequent work showed that non-radial (poleward) components of the driving can effectively inhibit the formation of any disk (Owocki et al. 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 (Hanuschik 1995; Rivinius et al. 1999). 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 & Heemskerk 1993; Telting et al. 1994; Savonije 1998).

Wind simulations that fully include equatorial gravity darkening, and the associated polar brightening, give in fact an *enhanced polar* mass flux (Owocki et al. 1996; Maeder & Meynet 2000; Maeder & Desjacques 2001). While this is the opposite of what is needed to explain the equatorial enhanced densities in Be and B[e] stars, it has ironically turned out to have potential relevance for explaining the bipolar mass loss of LBV stars like η Carinae. Indeed, HST slit spectra across the dust reflection of η Car's Homunculus show the absorption troughs from the present-day dense wind to be both broader and deeper along the bipolar axis

(Smith et al. 2003), in accord with the expected faster and denser polar wind from a nearly critically rotating central star. The Homunculus itself is estimated to consist of more than $10M_\odot$ flowing at speeds ranging from 500-1000 km/s, again with highest speed and mass flux along the polar axis. All this was ejected during the ca. 1840-60 giant eruption, when the star brightened to an estimated luminosity of $25\times10^6 L_\odot$, well above the Eddington limit. It is far too much mass loss to be explained by the standard driving by lines, which would saturate in such a dense outflow, but recent analyses of continuum driving during the super-Eddington outburst suggest it too can have the appropriate scaling to give the bipolar mass flux and speed if the star is near critical rotation (Owocki, Gayley, and Shaviv 2004).

Dense equatorial line-driven outflows have nonetheless still been proposed as models for B[e] stars. Models by Pelupessy et al. (2000) invoke the bistability jump for radiation temperatures near 23,000 K, which gives enhanced line opacity to the relatively cooler equatorial regions of a gravity darkened, rotating source star, with a strong enough effect to overcome the reduced radiative flux to give moderately enhanced (less than factor 10) equatorial density. Recent extensions by Curé et al. (2005) invoke the further density enhancement from a slower, subcritical wind outflow that occurs when rapid rotation leads to mass overloading of standard CAK critical solutions. Though net equatorial density enhancements can range up to a factor 100 in such 1D models, a full analysis of 2D flow and transfer effects would be needed to show if wind models could be viable for explaining the very dense, dust-forming B[e] disks. In general, the limitations of single-scattering seem to make radiative driving ill-suited to driving such a dense, geometrically thin disk outflow.

Indeed, it seems instead that radiative *ablation* could be a key factor in the gradual fading or disappearance of Be disk emission during epochs when mass ejection disk-feeding events are weak or absent. This could also explain the relatively dense UV wind line absorption in Be and B[e] stars viewed from inclinations along the equator. In this way, radiative driving may actually be a greater factor in the *destruction* than in the *creation* of circumstellar disks.

5.5. Magnetic fields

Magnetic fields play a key role in the activity of the sun and other cool stars, through for example the heating associated with reconnection of small-scale field structure. Such small-scale structures are difficult to detect on hot-stars, and may be less relevant due the lack of an active convective dynamo. The fields that have been detected on hot stars are generally large-scale dipoles, with little or no evidence of temporal variation. A principal effect of such large-scale fields occurs through their interaction with the radiatively driven stellar wind, by perturbing, channeling, torquing, and/or confining the wind outflow.

Even relatively weak, still-undetected fields could still likely play a role in inducing the lateral variations that lead to DACs in UV wind lines. Stronger fields can result in direct channeling, leading to "Magnetically Confined Wind Shocks" that provide a natural explanation for the relatively hard X-ray emission from magnetic hot stars like θ^1 Ori C (Babel & Montmerle 1997; Gagné et al. 2005), which has been detected to have a dipole field of ca. 1100 G (Donati et al. 2002) tilted by ca. 45^o to the star's rotation axis.

In rotating stars, the channeling is accompanied by a torquing up of the outflow, with then a potential for producing a "Magnetically Torqued Disk" (MTD, Cassinelli et al. 2002). In the strongly magnetic Bp stars, the field can both spin-up and *confine* the channeled wind material, keeping it rigidly rotating well beyond the Keplerian co-rotation radius, but also holding it down against the net outward centrifugal force relative to gravity. As discussed further in the contribution by R. Townsend (these proceedings), this leads to a "Rigidly Rotating Magnetosphere" model that has proven highly successful in explaining the rotationally modulated Balmer emission (as well as other observational diagnostics, like the photometric eclipses from the circumstellar clouds) in the B2p star σ Ori E (Townsend & Owocki 2005; Townsend et al. 2005).

MHD simulations (ud-Doula & Owocki 2002; ud-Doula 2003) 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. This defines an overall "magnetic confinement parameter" $\eta_* \equiv B_*^2 R_*^2/(\dot{M} v_\infty)$ in terms of the strength of the equatorial field B_* at the stellar surface radius R_*, and the wind terminal momentum $\dot{M} v_\infty$. For $\eta_* \lesssim 1$, the relatively weak field can still perturb the wind, perhaps leading to DACs. For $\eta_* \gtrsim 1$, the field can channel the flow into X-ray emitting shock collisions, as in the MWCS for θ^1 Ori C. For $\eta_* \gg 1$, the confinement is strong, and can keep material rigidly rotating, and held down, to substantial radii from the star, as in the RRM model for σ Ori E.

If, for simplicity, we ignore the wind velocity variation, we can also easily define an *Alfven radius* at which the magnetic and wind energy densities are equal, $R_A = \eta_*^{1/4} R_*$. 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.

As discussed further by ud-Doula (these proceedings), MHD simulations for the field-aligned rotation case, with parameters optimized to produce torquing out to the Keplerian co-rotation radius, do *not* produce the MTD envisioned in the phenomenological analysis by Cassinelli et al. (2002). Instead, there is persistent infall below the Keplerian radius, and centrifugal ejection from the outer region, resulting from the persistent influence of the field above this radius. An essential result is that large-scale magnetic torquing does not appear to represent a suitably fine-tuned mechanism for producing a stable, Keplerian disk.

6. Concluding Remarks on Circumstellar Disks

An overall conclusion is thus that steady, large-scale magnetic fields are not likely to be an essential mechanism for producing the disks from Be stars, which V/R variations and other lines of evidence point to having a Keplerian nature. In contrast, the very strong large-scale fields of magnetic Bp stars do seem appropriate for producing *rigid-body* disks that could explain the rotationally modulated Balmer emission in these stars.

Moreover, variable reconnection of small-scale fields could still play a role in mass ejection to feed an orbiting, Keplerian disk. More generally, such disks seem to require some kind of feeding by mass ejections, perhaps from a nearly critically rotating equator. If Be (and B[e]) stars are indeed nearly critical rotators, there could even be direct decretion into an orbiting disk, as first envisioned in early models by Struve (1931), and inherent in modern simulations of Viscous Decretion Disks (Lee et al. 1991).

Thus while the term "disk" is sometimes loosely used to refer to varied cases of circumstellar emission, one should keep in mind these key distinctions between Keplerian and rigid-body disks, and the distinction of these with outflowing WCD or bi-stability wind disks sometimes invoked for Be and/or B[e] stars.

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References

Ando, H. 1986, Ap&SS, 118, 177
Baade, D., Rivinius, T., & Stefl, S. 2002, Be Star Newsletter, 35, 26
Babel, J., & Montmerle, T. 1997, ApJ, 485, L29
Bjorkman, J. E., & Cassinelli, J. P. 1993, ApJ, 409, 429
Bjorkman, J. E. 1999, LNP Vol. 523: IAU Colloq. 169: Variable and Non-spherical Stellar Winds in Luminous Hot Stars, 523, 121
Cassinelli, J., Brown, J., Maheswaran, M., et al. 2002, ApJ, 578, 951
Castor, J. I., Abbott, D. C., & Klein, R. I. 1975, ApJ, 195, 157
Chauville, J., Zorec, J., Ballereau, D., et al. 2001, A&A, 378, 861
Cranmer, S. R., & Owocki, S. P. 1996, ApJ, 462, 469
Cranmer, S. R. 2005, ApJ, 634, 585
Curé, M., Rial, D. F., & Cidale, L. 2005, A&A, 437, 929
Domiciano de Souza, A., Kervella, P., Jankov, S., et al. 2003, A&A, 407, L47
Donati, J., Babel, J., Harries, T., et al. 2002, MNRAS, 333, 55
Feldmeier,A.; Puls,J.; Pauldrach,A.W.A. 1997, A&A322, 878
Fullerton, A., Massa, D., Prinja, R., et al. 1997, A&A, 327, 699
Gagné, M., Oksala, M., Cohen, D., et al. 2005, ApJ, 628, 986
Hanuschik, R. W. 1995, A&A, 295, 423
Harmanec, P., Bisikalo, D., Boyarchuk, A., & Kuznetsov, O. 2002, A&A, 396, 937
Krtička, J., & Kubát, J. 2001, A&A, 369, 222
Lee, U., Saio, H., and Osaki, Y. 1991, MNRAS, 250, 432
Maeder, A., & Desjacques, V. 2001, A&A, 372, L9
Maeder, A., & Meynet, G. 2000, A&A, 361, 159
Owocki, S. P., & Cranmer, S. R. 2002, ASP Conf. Ser. 259: IAU Colloq. 185: Radial and Nonradial Pulsationsn as Probes of Stellar Physics, 259, 512
Owocki, S. P., Cranmer, S. R., & Blondin, J. M. 1994, Ap&SS, 221, 455
Owocki, S. P., Cranmer, S. R., & Gayley, K. G. 1996, ApJ, 472, L115
Owocki, S. P., Gayley, K. G., & Shaviv, N. J. 2004, ApJ, 616, 525
Owocki, S. 2005, ASP Conf. Ser. 337: The Nature and Evolution of Disks Around Hot Stars, 337, 101
Pelupessy, I., Lamers, H. J. G. L. M., & Vink, J. S. 2000, A&A, 359, 695
Podsiadlowski, P. 2006, ASP Conf. Ser.: Stars with the B[e] Phenomenon, in press.
Rivinius, T., Baade, D., Stefl, S., et al. 2001, A&A, 369, 1058
Rivinius, T., Stefl, S., & Baade, D. 1999, A&A, 348, 831
Savonije, G. J., & Heemskerk, M. H. M. 1993, A&A, 276, 409
Savonije, G. J. 1998, Cyclical Variability in Stellar Winds, 337
Smith, N., Davidson, K., Gull, T. R., Ishibashi, K., & Hillier, D. J. 2003, ApJ, 586, 432
Springmann, U. W. E., & Pauldrach, A. W. A. 1992, A&A, 262, 515

Stoeckely, T. R. 1968, MNRAS, 140, 141
Struve, O. 1931 ApJ, 73, 94
Telting, J., Heemskerk, M., Henrichs, H., et al. 1994, A&A, 288, 558
Townsend, R. H. D., Owocki, S. P., & Howarth, I. D. 2004, MNRAS, 350, 189
Townsend, R. H. D., Owocki, S. P., & Groote, D. 2005, ApJ, 630, L81
Townsend, R. H. D., & Owocki, S. P. 2005, MNRAS, 357, 251
ud-Doula, A. 2003, Ph.D. Thesis, Univ. of Delaware.
ud-Doula, A., & Owocki, S. P. 2002, ApJ, 576, 413
von Zeipel, H. 1924, MNRAS, 84, 665

Discussion

H. Henrichs: Could you say something about the role of differential rotation?

S. Owocki: There was theoretical work on this back 10-15 years ago [*Ando 1986*]. I think there have also been several efforts by observers to detect signatures of differential rotation, though that gets mixed up with gravity darkening and other complicated effects.

I. Howarth: There have been published claims for observational evidence of differential rotation, but I don't believe them. Differential rotation can't be ruled out, but generally results are consistent with solid-body rotation.

R. Townsend: There's a distinction between differential rotation as function of *latitude* that we can see on the surface, and Ian [*Howarth*] points out there is no clear *observational* evidence for that. But there can also be differential rotation as a function of *depth*, and for recent asteroseimological studies of two β Cephei stars, the more thorough analyses to date have revealed the presence of radial differential rotation.

D. McDavid: You mentioned BW Vulpecae as an example of a pulsation-wind connection. In your hydro code, do you remember how fast you had it spinning?

S. Owocki: It doesn't have to spin. BW Vul is a radial pulsator, and it's the photospheric *brightness* variations that induce the wind variations. It was a 1D model, and not focussed on azimuthal variations.

A. Okazaki: In the case of δ Sco, you say that being very close (99%) to critical rotation could allow the companion to induce outburst. But the outburst lasted for more than one year, so I think the mechanism is different. I thus wonder if the connection [*of outburst with periastron*] is just a coincidence.

S. Owocki: Well, as I understand, it has about a ten-year orbit that is very highly eccentric, and outbursts occur around periastron. Because the star is orbiting very quickly at periastron, it is indeed strange that outbursts last for a year. But it also seems too much of a coincidence not to have something to do with binarity, if such outbursts are indeed concentrated around periastron.

K. Bjorkman: We've been monitoring δ Sco since the outburst, both spectroscopically and polarmetrically. Spectroscopically the outburst is *still* continuing, 5 years later. And there is little evidence during previous periastron passages for outbursts at this level; they have all been much smaller emission features, whereas now there is a very strong H-α emission, which continues to grow today.