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Rotation and the Circumstellar Environment

Ian D. Howarth

Dept. Physics & Astronomy, University College London

Abstract. The observational effects of rotation on outflows in OB stars are reviewed. Direct evidence of global asymmetries in outflows resulting from moderate rotation are subtle and ambiguous. 'Discrete absorption components' have been suggested as indicators of time-dependent rotational modulation, and recurrence timescales do correlate, loosely, with the line-wdith parameter $v \sin i$, but the underlying mechanism remains elusive; neither magnetic fields nor pulsations offer a satisfactory framework for the interpretation of these episodic features. However, where truly periodic signals are observed in hot-star winds, they *are* associated with strong magnetic fields; new results on two early-type stars illustrate this. Finally, the role of *rapid* (near-critical) rotation in Be stars is examined. A simple statistical analysis is used to argue that the observed distribution of $v \sin i$ values is consistent with Be stars rotating at $\sim$95% of critical, which allows 'weak' processes (operating at or near the sound speed) to play a significant role in the production of keplerian viscous decretion disks.

1. Introduction

For the purpose of this presentation, I'll take 'circumstellar environment' to mean the near-star environment – stellar winds and accretion disks. I'll distinguish between 'rapid' and 'moderate' rotation in terms of how close a star is to its critical angular velocity, $\omega_{\rm crit}$, at which the centrifugal force matches the Newtonian gravity at the equator (so that the effective gravity is zero, and material can be easily launched into orbit); as discussed below, 'rapid' rotation means $\omega/\omega_{\rm crit} \gtrsim 0.95$ – rotation rapid enough to be interesting in terms of formation of keplerian decretion disks.

2. Global asymmetry at moderate rotation

For radiation-driven winds, a naïve prediction is that the decrease in effective gravity in the equatorial regions that results from rotation should lead to an increased mass flux ($\dot{m}(\theta) \propto 1/g_{\rm eff}(\theta)$ at latitude θ; Friend & Abbott 1986, Pauldrach et al. 1986). However, this simple notion neglects the reduction in equatorial radiative flux for stars obeying von Zeipel's (1294) 'law', which is predicted to lead to a *decreased* equatorial mass flux (Cranmer & Owocki 1995[1]).

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[1] Many of us remember John Porter as both an exceptional scientist and a convivial friend. John independently derived essentially identical results to Cranmer & Owocki as part of his PhD thesis (for which I was the external examiner), but never published because he saw their preprint before submitting his own paper.

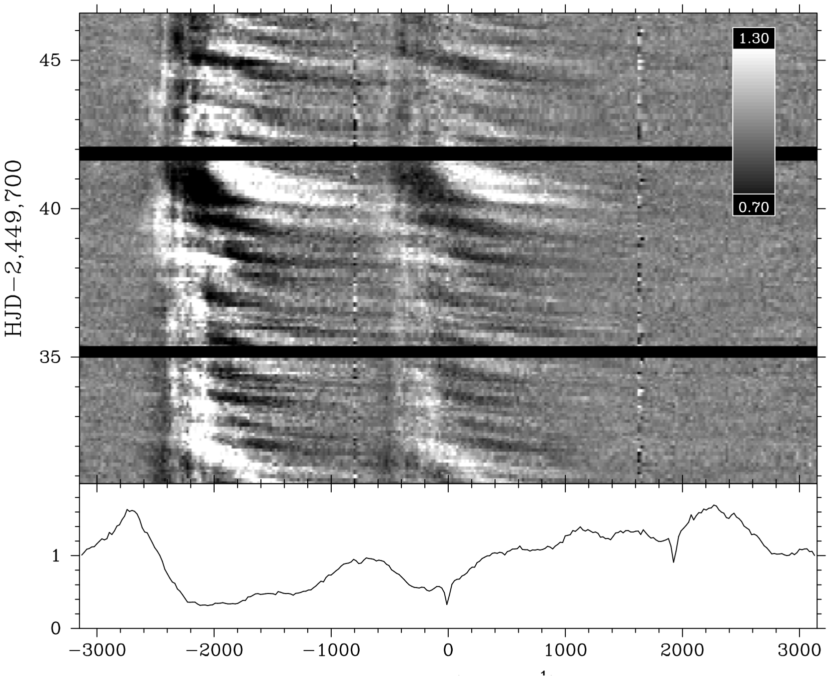

Figure 1. Time-series spectroscopy of the Si IV λ1393, 1402 resonance lines in the spectrum of ζ Pup. The greyscale dynamic spectrum displays the ratio of individual spectra against the normalized mean spectrum shown in the lower panel (black horizontal bars reflect gaps in the series). Data are from the IUE 'MEGA campaign' (Massa et al. 1995, Howarth et al. 1995).

Direct observational tests of these expectations for moderate rotators are not, generally, particularly persuasive. For example, there are some indications that the line-width parameter, $v \sin i$ (acting as a surrogate for, and approximation to, the true projected equatorial rotation velocity, $v_{\mathrm{e}} \sin i$) correlates positively with increasing column density in UV P-Cygni profiles of O-type stars (Howarth & Prinja 1989). This hints at enhanced equatorial surface mass loss, but more plausibly we may be seeing the effects of rotation on the wind *dynamics* – specifically, this result is qualitatively consistent with rotationally compressed wind zones (Ignace et al. 1996). Hα, and other wind-formed emission lines, encode information on rotationally induced distortions (Petrenz & Puls 2000; Busche & Hillier 2005), but the underlying dynamical models are currently quite simple (and incapable of reproducing observations to anything approaching the noise levels). Spectropolarimetry is a further potential diagnostic of wind asymmetries, but although such asymmetries clearly are present (e.g., Harries et al. 1998), polarization is not capable of discriminating between polar and equatorial enhancements; indeed, a spectropolarization signature can be introduced by rotation alone, in the absence of any asymmetry (Harries 2000). Thus direct spectroscopic diagnostics of steady-state wind asymmetries resulting from moderate rotation are, generally, weak and ambiguous.

3. Rotationally modulated winds

Rotational modulation? I – Discrete Absorption Components

Rotational modulation of azimuthal structures appears to hold more promise as a diagnostic tool of the influence of rotation on outflows. The problem here is largely observational: the rotational timescales of stars with strong radiation-driven winds are generally supposed to be of order several days (based on inferences from $v \sin i$), which are poorly suited to investigation from single sites in time allocations typical for common-user instruments. As a result, rather old observations made with the International Ultraviolet Explorer (IUE) satellite are still an important resource, and provide the context for much more-recent work; the sensitivity of the absorption troughs of unsaturated UV resonance-line P-Cygni profiles to small changes in column density (and/or radial-velocity structure) is another attraction.

The typical behaviour is illustrated in Fig. 1. So-called 'discrete absorption components' (DACs) migrate through the absorption profiles, from low initial velocities out to the terminal velocity, on timescales that are significantly longer than the flow timescales ($R_*/v_\infty \lesssim 1$ d). Just how much longer is related to $v \sin i$ (Prinja 1988; Henrichs et al. 1988; Kaper et al. 1999): smaller $v \sin i$ values are associated with both longer development times and longer recurrence times for the DACs. As a result, many observational efforts attempt to associate the recurrence timescale directly with rotation, mediated by some 'seeding' mechanism speculated to be tied to the stellar surface (with non-radial pulsations and magnetic fields being the most popular agents). However, I want to stress here that, as a general rule, the DACs are episodic, but *not* periodic. Under these circumstances it is difficult to tie in the triggering mechanism directly to something anchored to the photosphere (such as a magnetic field; see below).

Non-radial pulsation (NRP) models are sufficiently unconstrained that it's imprudent to be dogmatic about their role in DAC formation. Nonetheless, as far as we can tell, all OB stars with strong winds show DACs (Howarth & Prinja 1989), but only a few show detectable NRP (e.g., Fullerton et al. 1996). Moreover, in the handful of cases where NRP has been studied in relation to the wind, the timescales are not commensurate with those of the DACs (e.g., Howarth & Reid 1993, Howarth et al. 1993, Reid & Howarth 1996).

Finally, perhaps it's worth pointing out that, although there surely *is* a relationship between $v \sin i$ and the DAC recurrence period, $t_{\rm rec}$, in the sense outlined above, it's hardly a tight, linear correlation – which is perhaps why it's invariably quantified in tabular, not graphical, form in the literature. I rectify this omission in Fig. 2, which hints at a bimodality rather than a single-valued relationship: $t_{\rm rec} \simeq 1$–$2\,$d for $v \sin i \gtrsim 100$ km s^{-1}, but with longer timescales allowed at lower $v \sin i$.

Fig. 2 includes an indication of the maximum stellar rotation period (derived by assuming $v \sin i = v_{\rm e}$; of course, $\sin(i) \leq 1$, but note that, most probably, $v \gtrsim v_{\rm e}$). Because $t_{\rm rec}$ is always less than $P_{\rm rot}$(max) it has been argued that it is an *integer* submultiple of $P_{\rm rot}$ (e.g., Kaper et al. 1999). I see no strong evidence in favour of that hypothesis; not only are the DACs not generally periodic, but the integer relationship is almost certainly ruled out in one well-studied case (ζ Pup; Howarth et al. 1995).

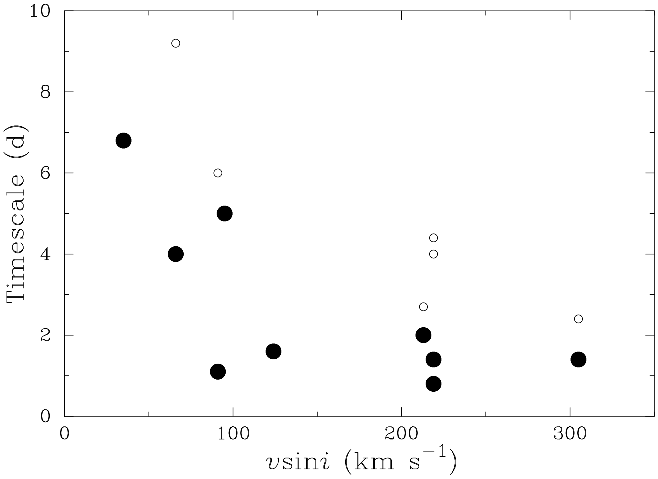

Figure 2. Large solid circles: the correlation between recurrence/development timescales for discrete absorption components (data from Prinja 1988, Kaper et al. 1999) and the line-width parameter $v \sin i$ (from Howarth et al. 1997). Small circles show the maximum rotation periods (estimated by assuming that $v \sin i$ equals v_e; several values lie off the top of plot).

Rotational modulation? II – Co-rotating interaction regions

There is one well-documented exceptional case of wind variability where there is, apparently, a truly periodic DAC-*like* wind signature: the B0.5 Ib star HD 64760 ($t_{\rm rec} = 1.2$ d; Prinja et al. 1995; Fullerton et al. 1996). The migrating absorption enhancements in this star are, however, exceptional not only in their periodicity, but also in showing 'phase bowing' in the velocity vs. time diagram – that is, they initially migrate from higher to lower velocities (unlike normal DACs), behaviour that has a kinematic interpretation in structures reminiscent of corotating interaction regions (Owocki et al. 1995). In this case, $P_{\rm rot} \simeq 4$–$5 \times t_{\rm rec}$, but, as ever, uncertainties in both v_e and R_* render an integer relationship moot. Furthermore, the NRP recently reported for this star by Kaufer et al. (this meeting, and 2006) don't appear to tie in with $t_{\rm rec}$, either directly or through beating.

Similar phase bowing has, to my knowledge, been reported in only two other stars: HD 150168 (Prinja et al. 2002; B1 Iab–Ib) and ξ Per (de Jong et al. 2001; O7.5 III(n)((f))). The recurrence timescale of HD 150168 is not established (but is 'long'). In the case of ξ Per, a truly periodic ~2-d stellar-wind signature has been reported twice, on the basis of Hα observations (with a similar, but less precisely determined, recurrence timescale in UV P-Cygni profiles). However, while the two determinations are similar, they are *not the same:* 2.086±0.002 and 2.20±0.03 d (de Jong et al. 2001; Morel et al. 2004).

So, even in cases where a true periodicity is claimed (and associated with rotation), we should be cautious until really persuasive datasets are assembled, with adequate sampling at more than one epoch. Of course, there are good observational reasons why such datasets are rare, but in the era of 8-m cosmol-

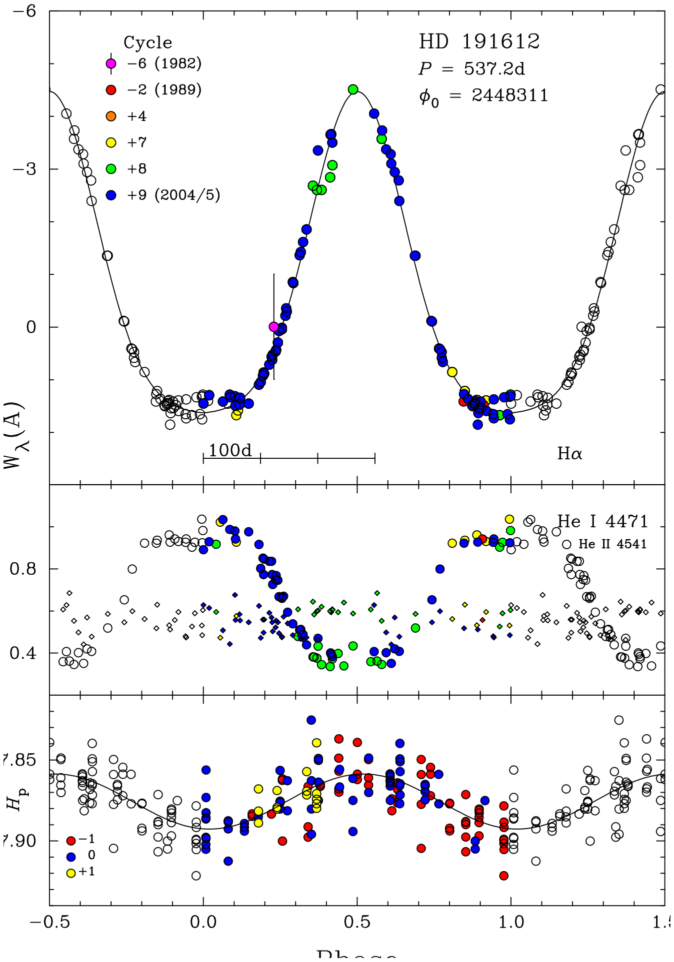

Figure 3. The variations of HD 191612 (bottom panel shows Hipparcos photometry). The strong Hα variability, in particular, repeats over 16 cycles (almost a quarter-century), and is consistent with a strictly periodic signal.

ogy the increasing availability of long-term, service programmes on 2-m-class telescopes equipped with good spectrographs holds great promise.

Rotational modulation! III – Magnetic rotators

Rotational modulation of winds is associated with a further group of stars: those for which a magnetic field directly, and rather obviously, influences the wind dynamics. In the OB-star regime, where radiatively driven winds are obvious, the archetype is θ^1 Ori C (O6–O4 p var). On the basis of a long, well-sampled spectroscopic dataset Stahl et al. (1996) identified a 15.4-d periodic signal and interpreted their results in terms of an oblique, magnetic rotator, a model triumphantly confirmed when measurement of a kG field was achieved by Donati et al. (2002) – the first magnetic-field detection in any O-type star.

The number of O and early-B stars with detected magnetic fields remains small (as summarized by Neiner elsewhere in these proceedings), but, in the context of this presentation, their most important property is the clear, periodic, signature of rotation in 'windy' UV lines, including those of several B-type stars: ζ Cas, V2052 Oph, ω Ori, and β Cep (Neiner et al. 2003a, 2003b, 2003c, Donati et al. 2001). There is, of course, an obvious selection effect, in that stars with detectable field strengths (meaning ~kG fields for OB stars) will inevitably have large values for the magnetic-confinement parameter, which characterizes the ratio of the magnetic-field energy density to the stellar-wind kinetic-energy density:

$$\eta = (BR_*)^2/(\dot{M}v_\infty)$$

(ud-Doula & Owocki 2002). In cases where B, the typical magnetic-field strength, is strong enough to be measured, $\eta \gtrsim 10$; this means that 'flow follows field' (rather than 'field follows flow', when $\eta \lesssim 1$), and so a clear rotational modulation is indeed expected.

Two 'hot off the press' discoveries had their first public airing at the meeting, both the result of observations by Donati with his new, sensitive spectropolarimeter 'ESPaDOnS' at the CFHT. The first is of particular interest in terms of rotational modulation, as the target, HD 191612 (O6 f?p – O8 fp var), had been selected exactly because of its periodic spectroscopic variations (Fig. 3), there being no other previous indication of a magnetic field. It is also noteworthy is that the spectroscopic period is within a day or two of 538 d (Walborn et al. 2004) – two orders of magnitude longer than what would canonically be regarded as a 'typical' O-star rotation period. Accordingly, Walborn et al. understandably considered the period to be most probably orbital, but the sub-

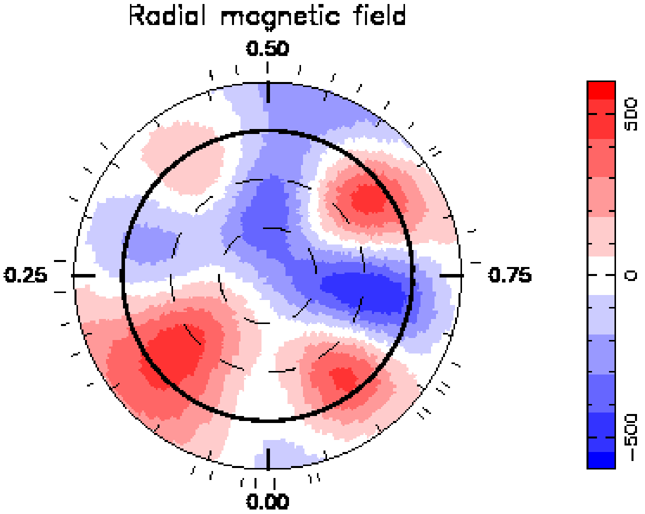

Figure 4. Maximum-entropy map of the surface radial magnetic field of τ Sco, from the pole (centre of the map) to latitude $-30°$. Circumferential tickmarks show phases of obervations in the 41-d rotation period, and the key is labelled in gauss. From Donati et al. (2006b).

sequent discovery of a kG field that did not detectably vary over a few days – of order the previously supposed rotation period – has led to speculation that the 18-month period may, after all, be the rotation period (Donati et al. 2006a). Further spectropolarimetry is needed to test this conjecture, but, as Donati et al. show, the slow rotation may be a natural consequence of magnetic braking.

A lesson here is we should not overlook the extent to which $v \sin i$ may systematically overestimate $v_{\mathrm{e}} \sin i$ for early-type stars, through neglect – and ignorance – of non-rotational line-broadening mechanisms (cf. Howarth 2004). Slow rotators may be much more common among OB stars than is generally supposed.

The second noteworthy result from the recent ESPaDOnS work is the discovery of a *complex,* ∼0.5 kG magnetic field in τ Sco (B0.2 V). Spherical-harmonic modelling of the field shows significant power in modes of degree up to at least 5, and a rotation period of 41 d. As with θ^1 Ori C, a magnetic field had long been mooted, but in this case it had been invoked to account for unusually strong, hard X-ray emission (e.g., Cohen et al. 2003), not spectroscopic variability.

Zeeman observations reveal a field geometry that is, roughly, a warped torus of closed field lines approximating a great circle of longitude; there is no evidence of intrinsic variability on a baseline of ∼1.5 years. Examination of archival IUE data shows the same period, with the expected phasing, in quarter-century-old spectra of stellar-wind lines. Most probably, these are characteristics of a fossil field, rather than an ongoing dynamo, but the important point in the present context is that, yet again, a detectable magnetic field turns out to be associated with a *strictly periodic* spectroscopic signature (cf. the 'episodic' nature of DACs), albeit previously unsuspected in this case.

4. Be stars: how close to critical?

The second major topic I want to examine is the role of rotation in the Be phenomenon. It is generally accepted that Be stars are characterized by keplerian viscous decretion disks, but it remains unclear exactly how material is moved from the photosphere into the disk. If a 'strong' mechanism were involved (e.g., large-amplitude pulsations) then, surely, there would be strong observational signatures. In the absence of such signatures we are driven to appeal to 'weak' processes, characterized by velocities of order the sound speed. For such processes to be capable of placing material into orbit, the effective gravity they have to overcome must be very small; and for centrifugal acceleration to almost overcome Newtonian gravity requires equatorial rotation velocities very close to v_{crit}.

This inference is qualitatively consistent with the close association of rapid stellar rotation and the Be phenomenon, as was first recognized in a seminal paper by Struve (1931). He remarked that "rapid rotation appears to be prerequisite to the appearance of bright lines. . .stars which have such enormous rotational velocities are in danger of becoming unstable. It is therefore reasonable to expect that B stars in extremely rapid rotation will eject gaseous matter at the equator." However, on examining this hypothesis quantitatively, Slettebak (1949) concluded that "the observed rotation in the Be stars is somewhat lower than would be expected under the assumption that these stars may be represented by Roche models at the point of rotational instability.”

For the following half-century, this assertion, bolstered by subsequent work (e.g., Slettebak 1982), has formed the basis of the ‘received wisdom’ that Be stars are significantly subcritical rotators. This is understandable given that Slettebak was an exceptionally skilled, careful, and conservative observer whose work rightly commanded wide respect. Nonetheless, he had to work with the tools of the day, and in the modern context these are not above critical scrutiny. For example, there is evident numerical noise in the models that formed the basis of the ‘Slettebak system’ (Collins 1974), and the line widths in those models increase with increasing $\omega/\omega_{\rm crit}$ at fixed $v_{\rm e}\sin i$ – behaviour that is very difficult to understand (and which is not reproduced in more-recent models; see below).

Furthermore, the standard system of velocities for Be stars very largely rests on results from Slettebak (1982), for which “rotational velocities were estimated for the program stars by visual comparison of line widths on the [photographic] spectrograms with those of standard rotational velocity standards”. This was the standard technique at that time, and Slettebak was probably its best practitioner. Nonetheless, it’s not the objective process that we (or, for that matter, Slettebak, if he were alive) would now normally pursue; it also represents a retrograde step with respect to Slettebak’s own earlier work, in that it implicitly (and wrongly) assumes a single-valued correspondence between line width and $v_{\rm e}\sin i$.

Townsend et al. (2004) recently conducted a re-examination of these issues, stressing in particular the role of von Zeipel (1924) gravity darkening in reducing the contribution of the equatorial regions of rapid rotators to the observed spectrum. As a result of this effect, increasing the rotational velocity doesn’t lead

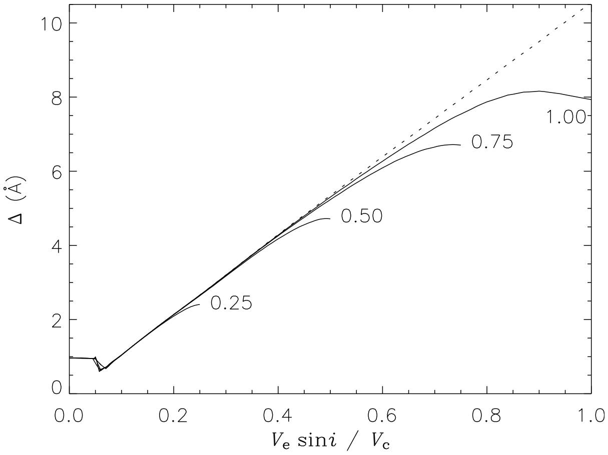

Figure 5. The relationship between line width and rotation velocity, calculated for He I λ4471 in models mimicking a B2 main-sequence star (from Townsend et al. 2004; see also Stoeckley 1968). Curves are labelled with $\sin i$ values, and the dashed line shows how line width varies in the absence of gravity darkening.

to a one-to-one (or even monotonic) increase in line widths; and the line width is *always* narrower than expected in the absence of gravity darkening (Fig. 5).

Although the principal action is gravity darkening of the continuum, different lines have different dependencies of strength (i.e., equivalent width) on temperature, and so the $v_{\rm e}\sin i$–line-width relationship varies from line to line; and, furthermore, has a $T_{\rm eff}$ dependence for any given line. It is also a function of inclination (clearly, excepting any sensitivity to gravity, line widths are independent of rotation for pole-on stars), so that, contrary to common observational practice, there cannot be any single-valued correspondence between line with and $v_{\rm e}\sin i$ for rapid rotators.

The converse of this is that, in principle, line profiles of rapid rotators encode sufficient information to determine $v_{\rm e}\sin i$, $\omega/\omega_{\rm crit}$, and i (which, with $\log g$, yield absolute, spectroscopic values for R_* and M_*; Howarth & Smith 2001). However, in practice these quantities are very difficult to determine to interesting levels of accuracy, and statistical approaches offer a pragmatic alternative. John Porter demonstrated that 'shell' stars are normal Be stars seen close to equator-on in this manner (Porter 1996), and a number of other authors have used the observed distribution of $v\sin i$ to infer the intrinsic distribution of $v_{\rm e}$ in Be stars, by inversion (e.g., Balona 1975) or forward modelling (e.g., Cranmer 2005).

Early statistical studies uniformly suffer from neglect of the systematic underestimation of $v_{\rm e}\sin i$ afforded by $v\sin i$, but the most recent work, by Townsend et al. (2004) and Cranmer (2005), attempts to correct for this bias. Unfortunately, the two analyses come to different conclusions! We can trace this disagreement to two factors.

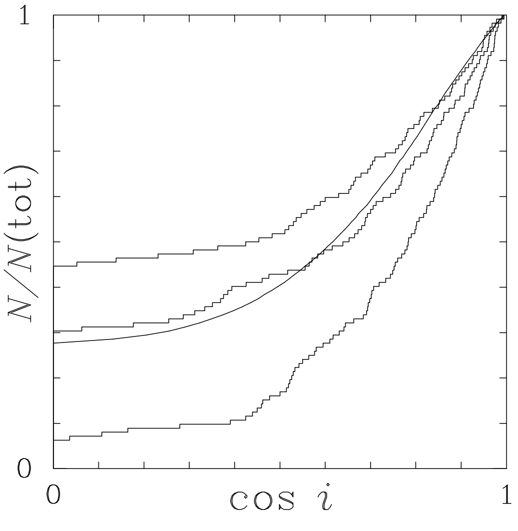

Figure 6. Cumulative distribution functions of $\cos i$ in Be stars. The upper and lower solid 'histogram' lines show the CDFs for the Chauville et al. sample inferred assuming, respectively, giant-star and main-sequence (MS) $v_{\rm crit}$ calibrations. The smooth continuous curve shows the CDF for a simulated population of near-critical rotators, while the middle histogram is the best-fit 'observed' CDF assuming a simple mix of giant-like and MS-like $v_{\rm crit}$ values.

First, the adopted observational datasets are different, not merely in a trivial sense, but also in their statistical properties. Townsend et al. adopted a *relatively* small sample (Chauville et al. 2001), but one based on high-quality data and a well-defined, objective measurement process; Cranmer employed the much larger database compiled by Yudin (2001). Yudin's compilation is very extensive, and a valuable resource for many purposes, but the the primary data are very heterogeneous, and the adopted $v \sin i$ calibration is *systematically* different from the Chauville database, in the sense of cataloguing smaller values for $v \sin i$. (It appears also to be systematically different from the Slettebak scale on which it is supposedly founded.)

A second factor is that a comparison of $v \sin i$ with $v_{\rm crit}$ incorporates *two* sets of assumptions and models; not only does the mapping of $v \sin i$ to $v_{\rm e}$ require attention, but also the determination of $v_{\rm crit}$ for any given star. In the literature, this determination is invariably based on simple 'look-up' tables, relying on correspondences between spectral type and physical properties established for single stars. Those calibrations are in principle questionable for rapid rotators, not only because the apparent spectral type is a function of inclination for such stars (e.g., Slettebak et al. 1980), but also from a stellar-evolution perspective (rotation results in changes in R_* and $T_{\rm eff}$ for given M_*).

One way to address these issues is to test explicitly the specific hypothesis that Be stars have randomly orientated rotation axes, and $v_{\rm e}/v_{\rm crit}$ is 'large' (for specificity I use $v_{\rm e}/v_{\rm crit} = 0.95$; the exact value is unimportant precisely because of the insensitivity of $v \sin i$ to this $v_{\rm e}/v_{\rm crit}$ for 'large' values, illustrated in Fig. 5). One can generate artificial distributions of $v \sin i$ under this hypothesis and compare them to the observed distribution, under different assumptions about $v_{\rm crit}$.

Figure 6 shows the results of such a comparison, and demonstrates that the Chauville et al. sample is fully consistent with a parent population of near-critical rotators *if* the critical velocities of Be stars are intermediate between those of giants and main-sequence stars at the same apparent spectral types. How persuasive the reader will find this argument will depend on how well s/he believes we know $v_{\rm crit}$, but in making that judgement it may be as well to keep in mind that many Be stars may be the product of binary, not single-star, evolution (McSwain & Gies 2005), as well as the difficulties in luminosity-class assignment for Be stars. My own view is that, at the least, the hypothesis that Be stars are near-critical rotators survives this statistical test.

5. Summary

The main points I wanted to make here are:

1. Most mass-loss diagnostics are measures of the spatially integrated properties of stellar winds, albeit resolvable in projected velocity. Unique inversion of such observations to determine rotationally-induced distortions isn't possible (in practice nor, usually, even in principle). The tools we have at hand – detailed emssion-line modelling, measures of P-Cygni column densities, and spectropolarimetry – are all rather blunt.

2. UV 'discrete absorption components' reveal time-dependent azimuthal structure in outflows, on timescales that correlate with rotation (or at least, with $v \sin i$), but only very loosely. There is no evidence for direct rotational modulation (and some evidence against).

3. Where a strictly periodic signal in wind variability has been reliably established, it is associated with a magnetic field (and *vice versa*). Other periodic signals (non-radial pulsations) leave a clear 'fingerprint' in the supersonic flow only when the surface amplitudes are large; those fingerprints are quite different in nature to DACs.

4. Line-width measures, $v \sin i$, are an unreliable guide to the projected equatorial rotation velocity, $v_{\rm e} \sin i$. For normal (moderately rotating) OB stars, $v \sin i \geq v_{\rm e} \sin i$, but for Be stars (rapid rotators) $v \sin i \leq v_{\rm e} \sin i$.

5. Because of this, the possibility that Be stars are, as a class, near-critical rotators merits close re-examination. This should be done both by detailed modelling of spectra of individual stars, and by careful statistical analyses. A simple statistical analysis presented here shows that the best available data are consistent with Be stars being near-critical rotators.

Acknowledgments. I'm grateful to Jean-François Donati for sharing results in advance of publication, and to the army of colleagues who contributed observations that have gone into Fig. 3. Hackneyed though it may be, I nonetheless also want thank the scientific and local organizers, and especially Akemi Okazaki, for putting together an exceptionally enjoyable and rewarding meeting; and the editors, for accepting a later-than-last-minute manuscript.

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