Be Stars as Seen Through Telescopes in Survey Mode (II)

Th. Rivinius,1 C. Martayan,1 and D. Baade2

1ESO – European Organisation for Astronomical Research in the Southern Hemisphere, Chile; email: triviniu@eso.org
1ESO – European Organisation for Astronomical Research in the Southern Hemisphere, Germany

Abstract. The first half of the review dedicated to survey works on Be stars (Baade, Martayan, and Rivinius, this vol.) put emphasis on what we can learn from surveys about Be stars as a part of an environment, such as Be stars in binaries, Be stars in different metallicities, or Be stars as part of a star forming and then co-evolving group. This second half will rather concentrate on the information that more focused surveys can give on a Be star, understood as an individual object, and in this way attempts to bridge the gap between highly detailed single star studies, and necessarily broad survey and catalog work.

1. Introduction

Surveys that have investigated Be stars in a more focused way usually include no more than a few dozen objects. Properties studied in such surveys include the stellar rotation of Be stars, their chemical surface abundances, the pulsational and magnetic properties, and the life cycles and evolution of the circumstellar disk.

The common theme between most of these topics is the question how, actually, does a Be star form its disk, and in particular how is the mass ejected with sufficient angular momentum to remain in orbit around the star? The answer is not yet given, but survey results have the potential to narrow down the candidate list to just a few processes, that can then possibly be tested with reasonable effort by more detailed, single star studies.

2. Rotation

The question of how rapidly do Be stars rotate was considered to be settled a while ago. Before about the year 2000, the consensus held that Be stars as a class rotate at about 80% of their critical value (i.e. at which material would escape from the equator without an additional lift-off mechanism required), but rarely above that or even at critical value. Interferometric observations of Achernar shook this consensus. Domiciano de Souza et al. (2003) reported that the star was rotationally flattened so much that it could only be explained by 100% critical rotation (or even faster). Soon afterwards, Townsend et al. (2004) explained why the 80% critical value could well be the result of an observational selection effect, namely that the most rapidly rotating parts of the star, the equator,
would become so dim due to gravity darkening that it would no longer contribute to the line width. This would mean that the observed $v \sin i$ becomes degenerate in terms of the true rotation, so that all stars rotating at and above 80% would be measured to rotate precisely at, but not with more than 80%.

Since then, several studies have aimed to determine the actual Be star rotation rate. Advances in interferometric instrumentation have allowed to re-measure Achernar with a precision that was impossible ten years ago (Domiciano de Souza et al. 2014). As a result, Achernar is now the Be star with the best known stellar parameters, and probably so by a fair margin. In terms of rotation, it was found that the the original result had to be explained by contamination due to a weak circumstellar disk. The new observations, taken in a diskless phase, revealed a rotation rate of 88% critical, which translates to 84% of the velocity needed to lift a particle into orbit just above the actual equator.

Interferometry as well served to resolve one of the largest ambiguities in measuring rotation. Meilland et al. (2012) determined the inclination angle for a number of stars, and with this could calculate the true rotational rates with better accuracy than by standard techniques. This and a number of other survey works (see Sect. 3.1 Rivinius et al. 2013, for a review) confirmed that Be stars can rotate significantly sub-critical. However, the rotational rates are not distributed narrowly around 80%, but rather spread between about 75% and 100%. In other words, once a B star rotates above that threshold, it can become a Be star. This threshold does not depend on the spectral subtype.

From a different perspective, one can ask as well whether there is a threshold above which a B star must become a Be star, i.e. no more non-emission B stars are observed. According to Huang et al. (2010) this is the case, but here it does depend on the spectral subtype: While all early type B stars above 75% critical rotation are also Be stars, the limit above which only Be stars exists increases to 90% in late type B stars. For the formation of Be stars, this means that there are either several processes that are differently weighted against each other at the different spectral subtypes, or in case that there is only one such process it must decrease in efficiency from early to late B subtypes.

3. Chemical Surface Abundances

Closely related to the question of rotation of Be stars is the one of the chemical abundances at the surfaces of Be star, potentially modulated due to rotational mixing. For slowly and intermediately fast rotating stars, rotational mixing is well understood and observationally calibrated. However, the typical rotation rates used for calibrating the models are still below the typical rotation rates of Be stars. If this scheme of rotational mixing is extrapolated into the Be star regime, one finds that a significant fingerprint of mixing should arise in a relatively short time, so much that it should be large enough to be detectable even in the very shallow lines that make rapidly rotating stars difficult to analyze, and very definitively in pole-on Be stars.

However, only few studies were available until recently. Single stars and small samples were investigated by Hardorp et al. (1986), Lennon et al. (2005), and Peters (2011), who all found negative result (i.e. no significant rotational mixing modulation or other enrichment), and by Villamariz & Herrero (2005) and Levenhagen & Künzel (2011), who find a chemical enrichment pattern, but due to the particular patterns observed favor binary interaction as explanation, rather than rotational mixing. The only
survey type study was undertaken by Dunstall et al. (2011), who did not find strong Nitrogen enrichment in 30 Be stars of the LMC and SMC.

In other words, the observed surface abundances of Be stars are inconsistent with the values predicted by rotational mixing for typical Be star rotational velocities. One can suggest a number of hypotheses to explain such a result: First, Be stars could rotate much slower than thought, but this is not very likely in light of the previous section. Second, they could become rapid rotators only very shortly before or contemporary with becoming Be stars, and Be stars do not stay Be stars for very long; but this is hardly consistent with the incidence and statistics of Be stars. Third, somewhere above the limit at which mixing models are calibrated things go wrong, but this would require a new ingredient in the theory of stellar constitution, such as a shell/layer inside the star that blocks mixing, but arises only at high rotation rates.

However, the abundance analysis of Be stars comes with a particular set of problems, partly due to the rapid rotation that forbids treating Be star line formation with a single value of temperature and gravity, and partly due to the presence of line emission and the scattered continuum from the disk. A further confirmation of having primordial (meaning here: as the star was formed) abundances in Be stars is certainly required before overturning the established theory of rotational mixing, but neither can the studies pointing towards the need for such a revision be ignored.

4. Pulsation

Be stars, as a class, are pulsating stars. With ground-based observations the proof for pulsational variability could be delivered only for a limited set of objects, mostly early type stars with relatively high amplitudes (Rivinius et al. 2003, and references therein). Nowadays, several years into the era of space-based time-series photometry, however, the question whether Be stars are pulsators or not is settled. Of more than thirty Be stars that were observed by asteroseismology satellites so far, every single one was found to be multiperiodic (see Sect. 3.2 of Rivinius et al. 2013, for an overview). One has to stress that this does not mean that every single of those periods is due to pulsation, quite to the contrary do the data indicate that there is additional variability to the pulsational one, which we do not fully understand yet. Strictly speaking, there is as well a lack in understanding the pulsation: current theory of pulsational excitation does not cover stars rotating as rapidly as Be stars.

The relevant question for Be stars is not so much whether they pulsate or not, but if and how the pulsation is linked to their nature as Be stars, in particular since pulsation in the upper main sequence seems not to be an exception, but rather the rule. Balona et al. (2011) report an incidence of 30% pulsating B stars. However, they discard Be stars from their list, so if Be stars are added in the fraction is closer to one half, which is a lower limit. Can pulsation contribute to the angular momentum transfer into the disk? Here the picture is much less clear. There are multiperiodic stars in which co-added amplitude maxima (beating) trigger outbursts ($\mu$ Cen, possibly 28 CMa and $\eta$ Cen: see Rivinius et al. 1998; Tubbesing et al. 2000; Rivinius et al. 2003). As well some stars show either short-term amplitude change that is correlated with the mass-ejection (some asteroseismology targets, including, for instance, Achernar; Goss et al. 2011), or a pulsational phase drift during the mass-ejection episodes ($\omega$ CMa: Štefl et al. 2003). However, how all these observations could possibly be merged into a unified picture
of a pulsationally modulated and rotationally supported mass ejection is completely unclear.

Kee et al. (this vol.) have explored the potential efficiency of angular momentum transfer and found that only modes with both retrograde phase- and group-velocity would be incapable of creating and sustaining a Be star disk. Modes with both prograde velocities would be most efficient, but as well more exotic modes with retrograde phase and prograde group velocity, or vice-versa, could work to make a Be star disk. The question which of these modes exist in Be stars is open. Whilespectroscopic modeling is fairly robust and favors retrograde/retrograde modes (which would not work to form a disk), asteroseismic modeling favors prograde/prograde modes (but is outside its proven validity regime). So possibly the solution lies indeed in one of the “mixed” mode types.

5. Magnetic Fields

Just a few years ago, magnetic fields in rapidly rotating, early type stars were considered to be pretty much out of observational reach. Similar as space based asteroseismology was a game-changer for the pulsation question, with the MiMeS survey completed (Magnetism in Massive Stars, Wade et el., this vol.) the picture has drastically changed for magnetism of early type stars. For completeness we note that the second extensive survey on the matter (BOB: B-fields in OB-Stars) is not yet complete, and does not target Be stars (Morel et al. 2015).

In a simple picture, magnetic fields would elegantly provide the means for the angular momentum transport into the circumstellar environment, and indeed initially a few Be stars were reported as magnetic. However, these works (Neiner et al. 2003; Hubrig et al. 2007, 2009) reported fields close enough to the detection limit to warrant confirming observations, in particular when FORS detections came under more general criticism (Bagnulo et al. 2012). For the stars for which such confirmation was sought, the result was negative (ω Ori: Neiner et al. 2012, χ Oph: Silvester et al. 2009, and μ Cen: Wade, priv. comm.).

The MiMeS survey took it a step further by observing about 85 Be stars and analyzing the results in a firm statistical framework (Wade et el., this vol.). The result is that Be stars certainly do not possess large scale, i.e. of low multipole order, magnetic fields of any strength above a few hundred Gauss, and quite possibly not at all.

However, it should be noted that the presence of a magnetic field and rapid rotation are not mutually exclusive, but in such stars the circumstellar environment takes the form of a magnetosphere that is governed by the magnetic field, rather than a Keplerian disk as in Be stars.

This means that the average Be star is actually less magnetic than the average non-emission B star (of which about 5 to 10% possess a kG large scale magnetic field, see Wade et al., this vol.), and although the MiMeS result does not entirely rule out small-scale fields, such as magnetic loops, such fields have not been observed in any early type star yet. The detectability of such fields depends on several assumptions, so it will always be possible to argue for a specific geometry to remain undetected. Notwithstanding, with current capabilities, including MiMeS, the detection could already have been possible under certain circumstances, as demonstrated by Kochukhov & Sudnik (2013). Rather, such small scale fields and are either merely hypothesized to save the magnetic ejection model that gave rise to the search for magnetic fields in the first place,
or are hinted at only by indirect evidence, e.g. from the X-Ray regime (see Sect. 3.3 of Rivinius et al. 2013).

6. Disk Properties

Concerning Be star disks, most survey type work has been done with photometry obtained during campaigns such as OGLE or MACHO. The currently published results concentrate mostly on the phenomenological properties of the light curves on medium and long time scales, i.e. those governed by the built-up and decay of the disk. However, during this meeting a number of interesting works have been presented that take it a step further, namely into determining physical properties of the disks from the shape and amplitude of the observed variations.

From the theoretical side, the dynamical viscous disk model has achieved a stunning success in the past decade. It should be kept in mind that any substantiated criticism to this model is possible not despite, but only because its success in the quantitative modeling of the behavior of Be star disks. The model has, for instance, been applied to the the well observed disk formation and decay phases of ω CMa (Carciofi et al. 2012). The result was somewhat surprising, although the decay of the light curve could be modeled quite well, it required a fairly high value of the turbulent viscosity parameter, namely \( \alpha = 1 \). Further works since then have confirmed that result for ω CMa (see Ghoreyshi et al., this vol.).

Since the method applied for ω CMa relies on photometric data alone, it can be applied to light curves observed in surveys. Preliminary results, based on the work by Rímulo et al. (this vol. and priv. comm.) indicate that a high value of \( \alpha \) is the norm for Be star disks. Since \( \alpha \) parameterizes the turbulent speed in relation to the speed of sound, a value of unity is normally considered a natural upper limit, and even that is not usually observed: Observational determinations of the viscosity parameter in gaseous disks, e.g. of cataclysmic variables, usually derive values one order of magnitude or more lower.

One question is whether the assumption of using the \( \alpha \) prescription is justified. If a non-viscous process, like radiative ablation, would contribute to the disk decay this may mimic a high value of \( \alpha \). However, results by Ghoreyshi et al. and Rímulo et al. (both op. cit.) indicate that also the build-up of the disk has to be modeled with a high value of \( \alpha \). If \( \alpha \) is indeed due to turbulent viscosity, there might be a mechanism that drives the value to its natural limit. The contribution by Fung (this vol.) has shown the interesting prospect of increased turbulence at the inner edge of the disk, induced by the radiation pressure of the central star.

On the other hand, some Be stars, including ω CMa show an underlying, very long-term secular trend in the light curve. Every outburst in the last 40 years returned to a somewhat lower base value, and in quiescent times a downward slope could be observed directly. This type behavior is as well seen in OGLE data for some stars. Such a slow trend is hard to explain with a high \( \alpha \), unless one assumes a tuned mass-loss behavior with the same properties, i.e. a long term decrease with overriding outbursts. In turn, attempts to model that behavior with a value of \( \alpha \) that is not constant, either in time or over the disk (suggested e.g. by Kurfürst et al., this vol.) have not been successful, either (Carciofi, priv. comm.). The source and properties of the viscosity in the otherwise very successful viscous disk model remain puzzling.
7. Some Conclusions

Summarizing what has been learned from surveys, but as well what new questions were opened:

- As a group, Be stars rotate rapidly (>75%), including some even at the critical limit.
- Although the rapid rotation is the most important single factor in forming a Be star, it is not sufficient to explain Be stars without further mechanism(s) acting.
- The chemical surface abundance pattern observed in Be stars seems inconsistent with the current theory of rotational mixing in rapidly rotating stars.
- Be stars do not possess low-order, large scale magnetic fields.
- Be stars are pulsating stars, with most (possibly all) Be stars pulsating in SPB-like modes. Some Be stars are β Cephei pulsators, too (π Aqr, for instance: Peters & Gies 2005).
- The precise nature and excitation of the pulsation modes are unclear.
- In some stars, the pulsation is clearly linked to the disk formation.
- The nature of this link, or links, is unclear.
- The disk, once formed, is governed by viscous processes.
- The viscosity parameter is surprisingly high, close to a natural limit of unity. Whether it is constant across the disk and among Be stars as a group is unclear.

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