Be Stars: Rapidly Rotating Pulsators

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Abstract I will show that Be stars are, without exception, a class of rapidly rotating stars, which are in the majority of cases pulsating stars as well, while none of them does possess a large scale (i.e. with significant dipolar contribution) magnetic field.

1 Introduction

A general discussion of classical Be stars and their properties has been presented by [16]. In this work, I would like to look into results obtained since then with respect to the rotational velocity, the pulsation, and the occurrence of magnetic fields.

To define a Be star, a broad working definition is widely employed: “A non-supergiant B star whose spectrum has, or had at some time, one or more Balmer lines in emission” [5]. However, it must be kept in mind that this definition includes a number of object types that have been awarded their own classes, like interacting binaries of Algol type, stars in which a magnetosphere clearly dominates the emission and its morphology, like σ Ori E, and young stars still accreting out of the surrounding medium or with fossil gaseous disks (for instance 51 Oph, formerly often regarded as classical Be star, has been resorted into that group when its unusual infrared excess became apparent). Therefore, although not useful as a morphological classification criterion, one should note that apart form fulfilling the above definition, only such stars are considered classical Be stars in which this emission arises in a circumstellar disk in Keplerian rotation (at least its outer parts, see [14]), formed by gas ejected by the star itself.

The question fueling the discussion is the following: What is the mechanism responsible for ejecting the material from the stellar surface, and adding sufficient
kinetic energy and angular momentum to it to assume Keplerian rotation, or, as it is usually posed in short: What is the “Be mechanism”? There was wide consensus that the rapid rotation of Be stars alone, being at about 80% of the critical value \( w = 0.8 \), defined as \( v_{\text{rot}}/v_{\text{crit}} \), with tendency to increase towards later types, is not sufficient. Therefore, the discussion about 20 years ago focused on the nature of the short term periodic variations observed both in spectra and integrated light \([1]\), seen in a vast majority of early Be stars, but (then) rarely or not at all in mid- to late-type ones. In the next section, I will review that the consensus on rapid, but not sufficient rotation, has been shaken, and to what extent it might have been restored, in the one following that there should be little doubt left that the short term periodic variations are indeed due to pulsation, and finally that the claim of wide-spread magnetism of Be stars, contributing to the Be-mechanism, does not hold.

2 Rotation

The consensus of rapid, but not sufficient rotation, increasing towards the later type Be stars, has been shaken by the interferometric measurement of the geometrical shape of Achernar \([7]\). The discussion whether or not a residual disk might have influenced the result was settled with the conclusion that Achernar rotates at \( w = 0.99 \) of its critical value \([4]\). It has also been suggested that Be star rotational rates might generally be underestimated, as any value above about \( w = 0.8 \) would not broaden the lines anymore due to gravity darkening, rendering the equatorial contribution to the line shape insignificant \([29]\).

Notwithstanding, this question is usually investigated employing statistical methods on the measured photospheric line widths and shapes, often based on the compilation by \([31]\), like \([6]\), or FASTROT modeling \([8]\), both including several hundred of stars. However, both approaches come with problems. One problem is the quality of the input data. For instance, upon close inspection several Be stars are not single Be stars, but in fact binary or triple systems where the emission comes from one component, but the photospheric profiles from another. A famous case was \( \beta \) Cep, for some time suspected to be an intrinsically slowly rotating (and magnetic) Be star, unless the binary nature was shown \([28]\). However, less obvious cases exist as well, such as \( \nu \) Gem \([22]\) or HR 6819 (Hadrava et al., in prep). Another concern is the influence of the circumstellar material on the line width and shape. In several cases this has led to published values of \( v \sin i \) differing by hundred and more \( \text{km s}^{-1} \) (like \( \zeta \) Tau, 27 CMa, \( \kappa^1 \) Aps, and \( \mu \) For). The six examples above were identified in the HEROS database of 70 Be stars \([25]\ [27]\), meaning a significant fraction of almost 10% of a given sample might bias the result towards a too early-too slow average when relying on traditional \( v \sin i \) statistics.

A more promising approach determines the full set of stellar parameters for a rapidly rotating star (including inclination and equatorial velocity separated) not from line width alone, but shape, hoping to eliminate the gravity darkening problem.
They derive $\bar{w} = 0.75$ \[8\]. Apart from that it is not entirely clear how sensitive the method is to problems like the biases above, a detailed analysis of the result reveals the certain presence of some own bias: In a histogram of inclinations, the bin from 80 to 90 degrees is almost empty, while for a random distribution (which the rest of the histogram follows well) this should be the most populated one. Also, looking at the inclinations for so-called shell stars (seen edge on through the disk, i.e. the inclination must be quite equatorial), these are fairly wide distributed between about $i=50$ and $i=80$ degrees, but again depleted for 80 to 90. On the other hand, assuming $\sin i = 1$ for shell stars $\bar{w} \approx 0.8$ is obtained for those, but independent of spectral subtype \[22\].

Finally comparing data from the Galaxy, LMC, and SMC a similar value of $\bar{w}$ as above, for Be star rotation computed back to ZAMS, was found for the Galaxy, but higher for the LMC and higher still for the SMC, again without dependency on spectral type \[13\].

Putting this all together, there seem to be few things that can be claimed without debate. One is that there is no single Be star that has been shown to rotate really slow, i.e. below about $w = 0.7$ (including uncertainties). As a population, Be stars seem to have around $\bar{w} \approx 0.8$, but given potential biases (like above and \[29\]), the example of Achernar, and the results from SMC vs. LMC vs. Galaxy, it is more safe to claim this not to be a mean but rather a lower threshold, that increases as metallicity decreases. Whether or not a real trend with spectral subtype exists is unclear.

3 Pulsation

When short term periodic variations were discovered in Be stars, both in photometry and spectroscopy and with periods typically between 0.5 and 1.5 days, the discussion concentrated on whether these should be understood as signature of pulsation or some corotating structure \[1\]. With increasing quality of spectroscopic data, multiperiodicity in distinct mode groups became apparent \[20, 30\], and it was possible to model the spectroscopic line profile variations as pulsation in great detail \[12, 21\] and for a majority of investigated objects \[17\], while the co-rotation hypothesis, apart from speculation on clouds and differential rotation and a set of toy models, has not yet produced a quantitative model to reproduce the multiperiodicity and the line profile variations. With photometric space missions the multi-periodicity, found in spectroscopic data only with major efforts, was observed to be the rule in Be stars (e.g. Semaan, this volume).

However, this picture is not complete. Again it was first in spectroscopy that secondary periods were seen, with properties clearly marking them as of circumstellar origin \[18, 26\] and typically about 10% longer than the photospheric main pulsational periods. In one intensively studied case, $\mu$ Cen, these periods were found to last only for about a dozen of cycles and re-occur with slightly different values each time \[19\]. In this case, they were ascribed to freshly ejected material, undergoing...
circularization, where the precise properties (i.e. period and phase) depend on the particular properties of the given ejection. In space photometry of Be stars, often two types of peaks are observed in the periodogram. One is narrow and easily understood as the long-term coherent periods corresponding to the stellar pulsation. A second type is typically much broader than the frequency resolution, and often has strong, yet variable contribution from harmonics (e.g. Semaan, this volume). The broad nature of these peaks is not consistent with any corotating feature, but obviously these are the photometric equivalent to the secondary periods seen in spectroscopy.

4 Magnetism

Claims of large scale magnetic fields in the few ten to few hundred Gauss regime have been made for a number of Be stars [10, 11, 15]. Upon close inspection, with one exception these are in the three to four \( \sigma \) regime of significance, which makes it mandatory to have them confirmed independently, in particular since most have been claimed with a single instrument, the reliability of which is debated in the low-significance regime [2, 3, 23, 24]. Indeed, so far two of the seven published claims, for \( \omega \) Ori and \( \mu \) Cen, were firmly rejected by the MiMeS collaboration, with none yet confirmed [9]. A re-reduction of the archival data comes to an even stronger conclusion: None of these claims hold [3].

In the MiMeS survey so far 38 Be stars have been probed for the presence of a magnetic field. Not in a single of them was one found. Comparing this to the detection statistics of non-emission B stars probed in the same program (about 8%, with similar significance limit distribution), the conclusion from this is that, in any case, Be stars, as a class, are less magnetic than non-emission B stars.

To this come theoretical problems, as in MHD simulations it was found to be impossible to form a Keplerian disk through magnetic leverage and release at a specified distance, for any degree of parameter-tuning, even though the regime where the angular momentum/kinetic energy balance seems to be correct is well within reach of MHD modeling (Owocki and ud-Doula, priv. comm.).

5 Conclusion

The problem of the Be mechanism is certainly not solved by the above results, which are summarized here:

**Rotation:** At this point, the statistical analysis of rotational velocities of Be stars is not sufficiently robust to base any firm conclusion on it. A new consensus about Be-star rotation seems to be re-emerging, which in short might be understood as “80% of critical was correct”, but a more detailed version of it rather reads like “there is a (metallicity dependent?) threshold rotation, about 80% for the MW, of the critical value, below which no Be stars are formed”.

**Pulsation:** The picture drawn by spectroscopy and space photometry is a very consistent one: There are long-term coherent photospheric pulsation periods, in many cases accompanied by circumstellar quasi-periods signaling the actual mass-transfer from the star to the environment.

**Magnetism:** Not only no magnetic field in any Be star could be confirmed, but the most thorough search so far, by the MiMeS group, came up with a very clear and significant null-result, at variance to any other class of investigated early-type objects.

As a consequence of the above, a Be mechanism relying on (magnetically) forced corotation on a large scale (i.e. other than highly localized) has no observational support, and as well on theoretical grounds seems to be excluded.

What is it, then? Rapid rotation must certainly be present. In some cases it might suffice by itself, yet in many it doesn’t. There is no need to require only one additional mechanism, though. The closer a star rotates to the critical threshold, the easier it is to launch material into a Keplerian orbit (tidal forces, weak pulsation, even turbulence). As we retreat from that limit, less and less mechanisms would get the job done (strong pulsation, pulsational beating pushing amplitudes well above the sound speed for a while), until a threshold is reached, below which no mechanism does work any more. Quite possibly, therefore, the question for the “Be mechanism” has to be recast as the question for the “Be mechanisms”.

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