BRITEning up the Be Phenomenon

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Observations of 25 Ori much expand the picture derived of other early-type Be stars with BRITE and SMEI. Two instead of one difference frequencies rule the variability: (a) The lower one, 0.0129 c/d, is the frequency of events with full amplitudes of 100-200 mmag which may signal mass loss possibly driven by the higher one, 0.1777 c/d. (b) Much of the entire power spectrum is a tightly woven network of combination frequencies: (i) Below 0.25 c/d, numerous frequencies are difference frequencies. (ii) Many frequencies above 2.5 c/d can be represented as sum frequencies and in a few cases as harmonics. (iii) Many frequencies between 1.1 and 1.75 c/d can be portrayed as parents of combination frequencies. The number and fraction of combination frequencies increases steeply with decreasing amplitude and accuracy of the frequency matching.

1 Introduction

Be stars are extremely rapidly rotating, nonradially pulsating stars (Rivinius et al., 2013) surrounded by a Keplerian disk that is governed by viscous decretion of gas from the central star (Lee et al., 1991; Carciofi et al., 2012). The feeder process of the decretion is often eventlike and probably driven by interacting nonradial pulsation (NRP) modes (Rivinius et al., 1998a; Baade et al., 2016, 2017). Ejecta produced by such events intercept light from the central star and process and re-emit it. Except for viewing angles close to the plane of the disk, the photometric signatures of such outbursts are brightenings (Haubois et al., 2012).

The aim of the BRITE (Weiss et al., 2014) programme on Be stars is to search for links between nonradial pulsations and mass loss. So far, in η Cen (Baade et al., 2016) as well as 28 Cyg (Baade et al., 2017), a pair of g modes was found to couple to form large-amplitude variations with their difference frequencies. In η Cen, the difference frequency seems to continually modulate, or even drive, mass loss. In addition, one brightening was seen in 28 Cyg in more than 150 days of monitoring in each of two different seasons. The brightening was strongly modulated with the 0.052 c/d difference frequency the amplitude of which was temporarily increased by a factor of a few. There was no obvious major phase discontinuity during the transition from quiescence to the outburst. Complementing this description with the variability of the optical emission lines during cyclicly repeating outbursts of μ Cen (Rivinius et al., 1998b, Sect. 3 below) proves that the combination of two (or more) NRP modes is at the core of the mass-loss process from Be stars.

These outbursts may be compared to the functioning of a valve. The long-term variability of emission lines (e.g., Zharikov et al., 2013) and of the continuum flux from their disks (Keller et al., 2002; Carrier & Burki, 2003) demonstrates that the opening of the valve can be much reduced or even suspended for years because, without mass supply, the disks decay (Vieira et al., 2017). Observations of pulsations have not so far provided insights into the nature of these long timescales. Accordingly, at least four different clocking levels may need to be distinguished:

1.) g-mode frequencies
2.) Difference frequencies between g-mode frequencies. When the valve is open, they seem to provide much of the pumping.
3.) A slower clock that opens and closes the valve.
4.) A very slow clock that inhibits the opening of the valve for long times.

It is still unknown whether the hypothetical level 3 and 4 clocks are different or show any regularity. If pulsations are involved at all levels, there should be some reduction gear that can produce frequencies of $\leq 10^{-3}$ c/d from single ~ 1 c/d modes.

All space photometers that have observed Be stars (MOST, SMEI, CoRoT, *Kepler*, and BRITE) found that the frequencies of Be stars cluster in groups. Typical group boundaries are 0.0-0.35 c/d (group g_0), 1.4-1.9 c/d (g_1), and 2.5-3.7 c/d (g_2); all limits have correlated full ranges of at least ±30%. All groups can have pronounced substructures, even broad gaps, and the "voids" between them are not totally empty. Based on *Kepler* observations of the B8e star KIC 11971405, Kurtz et al. (2015) conjectured that g_1 mainly comprises g modes and that most/all of the frequencies in g_0 and g_2 may be combination frequencies. From 15 possible g-mode frequencies they succeeded in constructing five sum frequencies one of which is the sum of two difference frequencies. This scheme is in agreement with the overall architecture of the power spectra of Be stars: Groups g_0 and g_1 typically have roughly equal widths whereas g_2 is about twice as wide. In fact, the scheme was already de facto discovered with many dozens of combination frequencies in CoRoT observations of the B0.5 IVe star HD 49330 by Huat et al. (2009) but not explicitly commented upon.

2 BRITE and SMEI observations of 25 Ori

25 Ori is an early-type Be star, which in global physical properties as well as viewing perspective closely resembles η Cen and 28 Cyg. In 2014/15, its overall light curve was governed by two modes of variability: (i) the difference frequency of 0.1777 c/d between a pair of g modes and (ii) two brightenings during which the amplitude associated with 0.1777 c/d was boosted by nearly an order of magnitude to full ranges of 100-200 mmag whereas the amplitudes of its strongest parent modes only grew by a factor of 2-3. The improved frequency resolution of the combination of the BRITE data with SMEI (Jackson et al., 2004) observations between 2003 and 2010 shows that 0.1777 c/d is the difference frequency of several pairs of frequencies most of which are in the range of plausible g modes. Like in 28 Cyg, there were no major phase jumps of the difference frequency during the transitions between quiescence and brightenings. Accordingly, the two events in 25 Ori appeared to be phase coherent w.r.t. the 0.1777 c/d variability. They followed each other within about 78 d.

In the SMEI data of 25 Ori, a frequency of 0.0129 c/d or period of 77.5 d exists so that the brightenings observed in 2014/15, and their related putative mass-loss events, seem to repeat with this period. At 18 mmag, the nominal semi-amplitude exceeds all others by almost a factor of two; however, the 100-200 mmag events are part of this activity. A slow decline in mean brightness was observed after three of the four events (the fourth occurred too shortly before the end of the observing season).

0.0129 c/d is not the only low frequency of 25 Ori. It does not at all times yield a good approximation of the SMEI light curve, and the events in 2016/17 are not clearly phased with it. These brightenings look so different from the others that, without reconfirming time-series analysis, the light curve could be from some other star. Even the two events in 2014/15 differ by a factor of 2 in amplitude. Therefore, 0.0129 c/d is not the only ruler of 25 Ori's long-term variability. Similarly to 0.1777 c/d, 0.0129 c/d is the difference frequency of several pairs of strong peaks in group g_1. Because of the very large amplitudes of the events associated with the 0.0129 c/d variability, some of the weaker components of these pairs may be side lobes. The symmetrical location of such features on both sides of some strong peaks supports this possibility whereas in some cases equal strengths of central and neighboring peaks put it into question. With amplitudes of 4.5 and 4.9 mmag, respectively, the two components of the pair at 1.2963 and 1.3110 c/d are among the three strongest peaks in group g_1 of 25 Ori.

Because of the multitudes of shared difference frequencies, pairwise frequency differences were calculated for numerous frequencies in both g_0 and g_1. g_0 was defined as 0–0.25 c/d and g_1 was taken as 1.1–1.75 c/d. Only differences falling into g_0 were included. Matches were accepted as real if the deviation of a calculated difference frequency from an observed frequency in g_0 was less than 10^{-5} c/d. In g_0 (g_1), there are 16 (12) frequencies with individual amplitudes of ≥ 5 mmag (≥ 2 mmag).

Thirteen (twelve) of them form 24 (24) frequency pairs with others in the same group such that for each pair the amplitude sum as well as the amplitude associated with the difference frequency both exceed 10 (5) mmag. Among the 16 frequencies in g_0 with amplitudes ≥ 5 mmag, 3 are such difference frequencies from g_0 itself and 7 from g_1; the 3 frequencies are a full subset of the 7 and have totals of six (0.0129 c/d), nine (0.0122 c/d), and eleven (0.0074 c/d) parents in g_0 and g_1.

The number as well as the fraction of frequencies involved in combination frequencies grow very rapidly with both amplitude threshold and matching tolerance in frequency. The results above are preliminary, and the analysis will be repeated with an entirely independent algorithm and code (Baade et al., to be submitted to A&A). The preliminary results also suggest that many frequencies in g_2 (2.5-3.4 c/d) are sums of frequencies in g_1; furthermore, in g_2, there are also a few g_1 harmonics and higher-order harmonics from g_0.

3 Discussion

The BRITE and SMEI observations of 25 Ori further refine the earlier conclusions for μ Cen, η Cen, and 28 Cyg. In the latter two stars, only two frequencies each were found to combine to a high-amplitude difference frequency. In 28 Cyg, the amplitude of the difference frequency was already high during quiescence. During the brightening, it was strongly amplified within just 1-2 cycles. In agreement with the conclusions for η Cen and 28 Cyg, the elaborate pulsational model developed by Pápics et al. (2017) showed that the events seen in KIC 11971405 are not part of any beat pattern but result from genuine (unexplained) amplitude amplification. Peak-to-valley event amplitudes of 100-200 mmag in 25 Ori, which closely resemble each other, provide further motivation to invoke mass loss as the explanation.

However, photometry alone cannot diagnose genuine mass loss with any certainty. The nondetection during brightenings of phase shifts of the difference frequency makes it impossible to separate immediate pulsational effects on the photosphere and secondary effects due to matter elevated to exophotospheric levels. Neither can it be stated, without detailed modeling, whether possible azimuthal temperature variations in the photosphere with the difference frequency lead to a similar modulation of the flux emitted by ejecta. Perhaps, the slow fadings after brightenings are the most robust indicator of matter temporarily added to the inner disk and subsequently removed by viscosity and/or radiation pressure. All in all, it is very plausible to think of brightenings as extra light re-emitted by ejecta (Haubois et al., 2012) from mass-loss events. Only parallel high-cadence photometry and spectroscopy will lead to an unambiguous conclusion. However, the earlier spectroscopy of μ Cen gave already very clear hints in favor of this idea.

With the hindsight of the photometric difference frequencies, one would perhaps describe the mass-loss activities of μ Cen in terms of two difference frequencies, 0.0180 c/d and 0.0337 c/d. In addition, variable line emission, indicating mass ejections, permitted the inference of a threshold above which the superposition of NRP velocity fields caused mass ejections (Rivinius et al., 1998a, 2001). This threshold of 15-20 km/s for the amplitude sum of the NRP modes involved was only exceeded for combinations of the strongest with either the second- or the third-strongest mode. Superpositions of the second- and third-strongest modes alone were ineffective.

Two more spectroscopic modes were found in μ Cen (Rivinius et al., 2001). One of them had an amplitude that would have been sufficient to let its combination with the strongest of the first four modes exceed the mass-loss threshold. However, these modes seemed to be different ($\ell = m = +3$ vs. $\ell = m = +2$) so that the co-added vectorial velocity sum reached its scalar value hardly anywhere. It is only thanks to these selection rules that the effects of combined NRP modes on mass loss could be derived so clearly. Otherwise, the star could have appeared to be in permanent outburst as it does present itself in broad-band photometry (Baade et al., 2016) which is lacking an equivalent of velocities as a means to distinguish ejecta from other matter in the disk. The numbers of frequencies visibly involved in the mass-ejection process from μ Cen and 25 Ori are smaller than those in η Cen and 28 Cyg. However, the greater simplicity of the latter two stars may well be only apparent if the sensitivity of the observations used for their analysis was not sufficient.

In 25 Ori, the frequency seems to have been found of the clock that opens and closes the mass-loss valve (# 3 in the list in Sect. 1), namely 0.0129 c/d. Its value does not appear to be numerically related to 0.1777 c/d. The significant frequencies nearest to their linear combination frequencies, 0.1648 c/d and 0.1806 c/d, are 0.1643 c/d (semi-amplitude 3.3 mmag) and 0.1833 c/d (5.4 mmag). Therefore, 0.1648 c/d is a marginal second-level difference frequency whereas the mismatch seems too large for the possible sum frequency.

It may be of concern that the relevance of low difference-frequencies in Be stars is discussed for BRITE/SMEI observations only. However, low-frequency variations are often removed up-front because they are a priori suspect of being artefacts, or in power spectra they may appear as unwanted side lobes of higher frequencies. In other cases, combination frequencies are just discarded because they are of no obvious asteroseismic interest. One exception is the recent analysis of the *Kepler* observations of KIC 11971405 by Pápics et al. (2017) who mention a frequency of 0.27644(2) c/d which had one of the 4 largest amplitudes found in the full dataset. The amplitude declined from 1800 ppm to 900 ppm after two events of enhanced variability that Pápics et al. call outbursts. The middle value between maximum and minimum read off Fig. 22 of Pápics et al. is 0.2761 c/d with a full range of ±0.0004 c/d. These authors' Table 12 contains two series of frequencies. Guided by the BRITE/SMEI experience with other Be stars, the frequencies with the largest amplitude were searched for the occurrence of 0.2761 c/d as a difference frequency. The frequency with the second-largest amplitude in the first group, 2.17192(2) c/d, and the highest-amplitude frequency in the second group, 1.89575(2) c/d, differ by 0.27617 c/d. That is, most probably, this frequency is a difference frequency.

0.276260 c/d was found by Kurtz et al. (2015) and can be described as the sum of two difference frequencies. As in 28 Cyg and 25 Ori, this variability seems to be phase coherent (see Fig. 26 in Pápics et al.) through the two events when its amplitude temporarily increased. The latter are reported as separated by 76.81 d but events are not repetitive on this timescale. There were also various smaller events which all occurred at different intervals.

Contrary to other pulsating stars, difference frequencies of Be stars appear to be of twofold practical relevance: (i) They are involved in the driving of mass loss. (ii) Isolated frequencies without relation to combination frequencies may be circumstellar frequencies as there is no plausible way for extrastellar variabilities to be part of the stellar grid of combination frequencies. It is important to distuinguish these two categories because they are diagnostics of completely different physical processes. In some Be stars, temporary so-called Štefl frequencies (Štefl et al., 1998; Neiner et al., 2002; Huat et al., 2009; Baade et al., 2016) seem to trace the amount of matter in non-circularized and/or azimuthally inhomogeneous near-stellar orbits (Carrier & Burki, 2003). No such frequency with amplitude $\geq$2 mmag was identified in 25 Ori.

The apparent nature as combination (or harmonic) frequencies of many high-amplitude frequencies in groups g_0 and g_2 may suffer from chance coincidences of unresolved frequencies. However, the bulk of the identifications should be real since high-amplitude parent and difference frequencies were selected for the analysis. Frequency groups also occur in SPB and γ Dor stars. They have been attributed to rotation (Balona et al., 2011) although most SPBs do not rotate particularly rapidly (e.g., Pápics et al., 2017) whereas very rapid rotation is a strong requirement for the development of decretion disks in Be stars (Rivinius et al., 2013). Another possible speculation is, therefore, that high-amplitude combination frequencies play a role in the selection of those modes in Be stars that are highly unstable among a vast number of other modes with amplitudes not exceeding the detection thresholds.

4 Conclusions

Various studies have suggested that outbursts of Be stars may be driven by many modes that are once in a while randomly constructively cophased (e.g., Kurtz et al., 2015). The converse causality has also been proposed, namely that an outburst may lead to the temporary enhancement or excitation of numerous pulsation modes (Huat et al., 2009). The picture derived fom BRITE/SMEI observations of η Cen, 28 Cyg, and 25 Ori and the spectroscopy of μ Cen is much simpler and does not depend on a strong random component. It is based on just a handful of modes which hierarchically control the mass-loss process on four different frequency scales ν that roughly differ by an order of magnitude:

1.) $\nu \sim 10^0$ c/d: many g modes. Example from 25 Ori: 1.5014 c/d.
2.) $\nu \sim 10^{-1}$ c/d: pairwise difference frequencies of g modes. During outbursts, the amplitudes of a very small number of them may increase by up to an order of magnitude and contribute to the driving of the mass loss. Example from 25 Ori: 0.1777 c/d.
3.) $\nu \sim 10^{-2}$ c/d: A very small fraction of these low difference frequencies trigger the outbursts (open the hypothetical valve) by temporarily and quickly increasing the amplitude of the variations with the higher level-1 difference frequency. Example from 25 Ori: 0.0129 c/d.
4.) $\nu \sim 10^{-3}$ c/d: On this timescale, the triggering of outbursts (opening of the valve) is cyclicly suspended and activated. It could be another difference frequency, here between extremely closely spaced frequencies of individual NRP modes, or the presumably nonlinear combination of several level-2 variabilities.

Each of clocks 2-4 may have variable power, depending on whether or not further NRP modes enhance or obstruct the main process. These additional modes may be drawn randomly from the general NRP floor or, more likely, from the modes sharing the same difference frequency (frequencies). If the frequency network does not at all times behave like a perfect spreadsheet, small frequency variations may result in disproportionately large amplitude variations. The presence of an amplitude threshold for events as in μ Cen could add a strong nonlinear element.

The putative 4th level is lacking direct empirical support and only based on an extrapolation of the first three levels. An alternative could be recovery phases in the driving of leaking NRP modes as proposed by Shibahashi (2014). Clock levels 1-3 are in agreement with the idea since the apparent pulsational driving of mass loss implies considerable energy losses. However, the postulated temporary cessation of NRP variations seems unsupported by their observed long-term presence (e.g., Štefl et al., 2003; Baade et al., 2016).

When the star-to-disk mass transfer is shut off (the valve opens too rarely and/or too little), the disk quickly transforms itself from a decretion to an accretion disk (Carciofi et al., 2012). Radiative ablation is expected (Kee et al., 2016) to further accelerate the destruction of the disk. The accompanying decrease, and ultimately disappearance, of line emission would be the consequence. In this way, disk life cycles of 10 or more years could be built from elementary clocks running more than a thousand times faster. Even very simple and clean light curves (Keller et al., 2002, their Fig. 5) demonstrate that several such clocks may act in parallel, leading to the coexistence of several long timescales ruling the emission-line strength. If there are also multiple level 2 and 3 clocks, the behavior of a Be star may soon look erratic.

Many frequencies in g_0 and g_2 were excluded as possible stellar eigenfrequencies. The implied strong reduction of the overall variability spectrum mostly to g modes in g_1 indicates another large simplification of the description that needs to / can be given of the once enigmatic variability of some Be stars, one and a half centuries after their discovery by Secchi (1866).

Many questions remain though. Currently, most pressing among them are:

- How broadly representative is the above simplified picture of Be stars?
- Is it applicable to late-type Be stars which in ground-based observations appear much less active? The case of the B8e star KIC 11971405, which is the only late-type Be star studied at this level of detail, suggests that at least some late-type Be stars do agree with it.
- Does the distribution of NRP frequencies select the difference frequencies involved in the mass-loss process, or do atmospheric timescales favoring large-amplitude variations filter the NRP spectrum?
- How do amplitudes of difference frequencies grow during brightenings by up to an order of magnitude and 3-5 times more strongly than those of the parent frequencies?
- What is the stellar/circumstellar contribution to this amplitude amplification?
- What is the nature of the postulated valve? Is it a threshold in the combined amplitude of the NRP modes involved?

Acknowledgements. DB's attendance of the conference was made possible by support from the Polish National Science Centre grant No. 2016/21/B/ST9/01126 and from the Natural Sciences and Engineering Research Council (NSERC) of Canada via GAW's Discovery Grant; this is very gratefully acknowledged. This study is based on data collected by the BRITE Constellation satellite mission, designed, built, launched, operated and supported by the Austrian Research Promotion Agency (FFG), the University of Vienna, the Technical University of Graz, the Canadian Space Agency (CSA), the University of Toronto Institute for Aerospace Studies (UTIAS), the Foundation for Polish Science & Technology (FNiTP MNiSW), and National Science Centre (NCN).

References

Baade, D., et al., *A&A* **588**, A56 (2016), (Paper I), `arXiv:1602.01744`

Baade, D., et al., *ArXiv e-prints* (2017), `arXiv:1708.08413`

Balona, L. A., et al., *MNRAS* **413**, 2403 (2011), `arXiv:1103.0644`

Carciofi, A. C., et al., *ApJ* **744**, L15 (2012), `arXiv:1112.0053`

Carrier, F., Burki, G., *A&A* **401**, 271 (2003)

Haubois, X., et al., *ApJ* **756**, 156 (2012), `arXiv:1207.2612`

Huat, A.-L., et al., *A&A* **506**, 95 (2009)

Jackson, B. V., et al., *Sol. Phys.* **225**, 177 (2004)

Kee, N. D., Owocki, S., Sundqvist, J. O., *MNRAS* **458**, 2323 (2016), `arXiv:1602.07874`

Keller, S. C., et al., *AJ* **124**, 2039 (2002), `arXiv:astro-ph/0206444`

Kurtz, D. W., et al., *MNRAS* **450**, 3015 (2015), `arXiv:1504.04245`

Lee, U., Osaki, Y., Saio, H., *MNRAS* **250**, 432 (1991)

Neiner, C., et al., *A&A* **388**, 899 (2002)

Pápics, P. I., et al., *A&A* **598**, A74 (2017), `arXiv:1611.06955`

Rivinius, T., Carciofi, A. C., Martayan, C., *A&A Rev.* **21**, 69 (2013), `arXiv:1310.3962`

Rivinius, T., et al., in P. A. Bradley, J. A. Guzik (eds.) A Half Century of Stellar Pulsation Interpretation, *Astronomical Society of the Pacific Conference Series*, volume 135, 343 (1998a)

Rivinius, T., et al., *A&A* **333**, 125 (1998b)

Rivinius, T., et al., *A&A* **369**, 1058 (2001)

Secchi, A., *Astronomische Nachrichten* **68**, 63 (1866)

Shibahashi, H., in J. A. Guzik, W. J. Chaplin, G. Handler, A. Pigulski (eds.) Precision Asteroseismology, *IAU Symposium*, volume 301, 173–176 (2014)

Štefl, S., et al., in P. A. Bradley, J. A. Guzik (eds.) A Half Century of Stellar Pulsation Interpretation, *Astronomical Society of the Pacific Conference Series*, volume 135, 348 (1998)

Štefl, S., et al., *A&A* **411**, 167 (2003)

Vieira, R. G., et al., *MNRAS* **464**, 3071 (2017)

Weiss, W. W., et al., *PASP* **126**, 573 (2014), `arXiv:1406.3778`

Zharikov, S. V., et al., *A&A* **560**, A30 (2013), `arXiv:1310.6499`