Stars and their variability observed from space
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THE DEMYSTIFICATION OF CLASSICAL Be STARS THROUGH SPACE PHOTOMETRY

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Abstract. All optical high-cadence space photometers have observed Be stars and achieved some of their most prominent results with them. Single-object highlights from five different satellites are selected to delineate the progress made for Be stars. Multi-mode nonradial pulsation (NRP) is the most universal photometric signature of Be stars, and variations on timescales from days to years can be traced back to them. Nested multi-instance NRP frequency differences explain regularly repeating outbursts of Be stars, which probably are the building blocks of the formation process of the gaseous disks around Be stars. During outbursts, frequency spectra can differ drastically from those at quiescence. Observations by TESS of hundreds of Be stars may (i) pulsationally distinguish Be stars from the also rapidly rotating but diskless Bn stars and (ii) discriminate between different evolutionary paths towards Be stars. Conceivably, the angular-momentum loss incurred by pulsation-driven outbursts enables Be stars to escape rotational rupture. This process may also govern the selection of frequency differences involved in the mass loss.

Keywords: Stars: emission-line, Be, Stars: oscillations, Stars: mass loss, Stars: individual: ζ Oph, α Eri, HD 49330, KIC 11971405, 25 Ori

1 Introduction

γ Cas was the first B-type star discovered to exhibit emission lines (Secchi 1866). In the $1\frac{1}{2}$ centuries elapsed since then, new myths popped up from time to time, trying to explain complex, often coupled variabilities on timescales from hours to decades. Careful analysis of high-quality data ultimately overcame them all. Long-term space photometry made particularly valuable contributions. For broad reviews of Be stars see Porter & Rivinius (2003) and Rivinius et al. (2013).

Already in 1931, Struve (1931) realized that Be stars form a rapidly rotating sub-population of B-type stars that are surrounded by a gaseous disk. Extreme rotation is difficult to characterize quantitatively from spectra only (Townsend et al. 2004) so that the scarcity of critically rotating Be stars might be due to a bias. On the other hand, Achernar, one of the interferometrically best-studied Be stars (Domiciano de Souza et al. 2014) is probably rotating slightly sub-critically. With these caveats, it seems reasonably safe to state that rotational instability is not the mechanism by which Be stars eject matter into the disk. Even safer is the conclusion that it is viscosity that transforms $\sim$1% of the ejecta into a Keplerian disk (for the Viscous Decretion Disk [VDD] model, see Labadie-Bartz & Carciofi, these proceedings and references therein).

Very few other long-standing issues of stellar physics have benefited more from space photometry than the understanding of the mass-ejection mechanism of Be stars. After first spectroscopic detections of nonradial pulsations (NRPs), space photometry established the ubiquity of NRPs in Be stars. As elaborated below, multi-mode NRP seems to be at the core of the mass-loss process. The observed frequencies straddle the domain of plausible rotation frequencies. Therefore, it is sometimes still speculated that the variability of Be stars is due to rotational modulation of some usually undisclosed quantity (e.g., Smith et al. 2016; Balona & Ozuyar 2019). Such beliefs are only possible if the spectroscopic proof of highly structured large-scale surface-velocity fields (Rivinius et al. 2003) is ignored. Rotational modulation cannot accommodate such velocity fields whereas NRP produces them. Of course, it is impossible to exclude rotational modulation as a higher-order effect. However, given the difficulty of reliably determining the rotation rate of Be stars, it is extremely hard to identify the rotation frequency with any confidence among the often large number of peaks in power spectra.

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2 Discoveries by space photometry of specific variability properties of Be stars

All high-cadence optical space photometers observed Be stars, each made specific discoveries, and the results concatenate such that multi-mode NRP is the strongest contender for the driver of the star-to-disk mass-transfer process in Be stars. The following subsections describe the progress satellite by satellite, ordered by the start of their operations. Because of the limited space, observations of only one Be star each are highlighted.

2.1 Microvariability and Oscillations of Stars Telescope (MOST)

MOST (2003-2011, Walker et al. 2003) pioneered the photometric monitoring of stars from space. So far it was the last point-source space photometer without a dedication to exoplanets in its name. The showcase Be star was ζ Oph (O9.5 Ve, Walker et al. 2005). MOST detected at least a dozen frequencies from observations spanning 24 days. This was a significant step forward from the two groups of frequencies detected in μ Cen (B2Ve, Rivinius et al. 1998). Parallel spectroscopy from three sites with high cadence, spectral resolution, and S/N confirmed the NRP nature for 6 of the 12+ frequencies. While none of the details found in ζ Oph had not been seen before, MOST established the complexity of Be stars to be at par with other pulsating early-type stars.

2.2 Solar Mass Ejection Imager (SMEI)

The mission of SMEI (2003-2011, Jackson et al. 2004) was to monitor space weather in the inner solar system. For clean maps of the light scattered by electrons ejected by the Sun, stars down to ∼10th magnitude had to be removed. The community owes the SMEI responsibles much gratitude for not scrapping these snippets on a rubbish tip but making them available in an online database*. By the example of α Eri (B6 Ve, Achernar), SMEI established for the first time the long-term coherence (over 5+ years) of a variability in a Be star (Goss et al. 2011), another important requirement if variability is to be assigned a high diagnostic value.

2.3 Convection, Rotation and planetary Transits (CoRoT)

The nominal dedication of CoRoT (2006-2012, Baglin et al. 2006) to exoplanet transits did not prevent its usage for observations of, and important discoveries in, Be stars. Most spectacular was the serendipitously captured detailed light curve of a small outburst of the B0.5 IVe star HD 49330 (Huat et al. 2009). Almost since the discovery of mass loss from Be stars, there had been indications of the now well-established fact that a large part of this process consists of a discontinuous, event-like component. The CoRoT observations of HD 49330 illustrated for the first time substantial changes in the photometric power spectrum during the course of a Be outburst. In the low-to-intermediate frequency domain, numerous features grew above the detection threshold while others lost the prominence they had during quiescence. The causality, though, remained ambiguous: Did the outburst change the pulsation pattern, or did changes in the pulsation cause the outburst? Also, were the additional frequencies stellar or circumstellar?

2.4 Kepler

The impact on Be stars of Kepler (2009-2018, Borucki et al. 2010), the most powerful space photometer to date, was limited by the selection of a patrol field with a high content of sun-like stars. However, this resulted in the data for the just three, moreover marginal, observed Be stars being analyzed by three different teams. In KIC 11971405, Kurtz et al. (2015) could reconstruct only five frequencies from, partly not particularly simple, linear relations between some of a total of 15 base frequencies, but speculated that many more such constructs should exist so that outbursts would be powered by multi-mode beating. The wavelet analysis of the light curves by Rivinius et al. (2016) identified several frequency groups and revealed variable correlated as well as anticorrelated group amplitudes. In the latest investigation of KIC 11971405, Pápics et al. (2017) realized that the top-level clustering of frequencies is probably explained by the scheme more broadly described in Sect. 2.6. Baade et al. (2018) added that the spacing in time of the outbursts noted by Kurtz et al. (2015) and Pápics et al. (2017) corresponds to the frequency difference between two of the highest-amplitude variations.

*http://smei.ucsd.edu/new_smei/data&images/stars/timeseries.html

2.5 Bright Target Explorer (BRITE)

Being nano(= dwarf)-spacecraft, the five BRITE satellites (2014-2020+, Weiss et al. 2014) easily stand on the shoulders of giants. However, with the exception of SMEI, which reached much worse single-measurement accuracy, and the few Kepler Be stars, the BRITEs spread their wings over more time than their predecessors. The resulting higher frequency resolution enabled the discovery in 25 Ori (B1 Vn, Baade et al. 2018) of outbursts apparently pumping matter into the disk with a difference frequency corresponding to multiple frequency differences of the same value ('multi-instance frequency differences'). Another, but lower, difference frequency governs the timing of the mass-loss-valve opening events. Further difference frequencies at the same or higher levels of nesting may exist. The appearance in the frequency spectra of such difference frequencies may be partly caused by the concomitant amplitude modulation with the difference frequency but is a useful empirical indicator. In power spectra, the difference frequencies appear with high power so that they are not due to a beating process. Multi-instance frequency differences would also remove the ambiguity in the CoRoT observations of the outburst of HD 49330: It is the pulsations that drive the outburst. Moreover, such tight relations are not likely to exist between stellar and disk variations or disk variations only so that they are all of stellar origin. However, one ambiguity remains: Is the increased photometric amplitude associated with the higher difference frequency the result of increased pulsation amplitudes or a nonlinear atmospheric/circumstellar response or both. Temporarily reduced amplitudes may be due to obscuration by ejecta (Maintz et al. 2003; Balona & Ozuyar 2019).

2.6 Transiting Exoplanet Survey Satellite (TESS)

At the time of this conference, TESS (2018-2020+, Ricker et al. 2016) had accumulated half of its prospected data harvest, which will include precision light curves of many hundred Be stars covering between 1 and 12 months. Even at the upper end of this range, observations with other satellites do not predict three periodically repeating outbursts as a standard feature, placing the slow periodicity, which could be the 'secret' of many Be-stars, out of reach. Accordingly, TESS will probably make its biggest impact by exploiting the vast superiority of its statistics. Two applications not so far observationally accessible jump to mind:

- Do Bn stars, which are rapidly rotating B stars without disk, pulsate differently than Be stars as unpublished spectroscopy reportedly suggested (Penrod 1986)? If yes, this would support the conclusion that pulsations are at the root of the Be phenomenon.
- Do *bona fide* single and binary Be stars pulsate differently? If yes, there might be (at least) two evolutionary paths towards Be stars: If single Be stars are not the result of mergers, their formation process (Martayan et al. 2007) and the evolutionary contraction of the core (Granada et al. 2013) could combine and lead to the observed rapid surface rotation. Competing models (cf. Langer et al. 2019, and references therein) attribute the rapid rotation to mass and angular-momentum transfer in a binary. Bimodal pulsation properties could hint at both evolutionary paths having been followed.

As a byproduct, the clustering of frequencies could be studied in more detail. Preliminary evidence suggests (Pápics et al. 2017; Baade et al. 2018) that many Be-star frequency spectra exhibit three major clusters. The main one is around 1 c/d, a second one consists mostly of difference frequencies built from the main one, and the third one comprises mainly sum frequencies and second harmonics from the main cluster. In this scheme, the main (middle) cluster would host the stellar eigenfrequencies. The location, width, total population, internal spacing etc. of these clusters should be investigated for links to spectral type, rotation rate, etc.

In addition, some Be stars also exhibit higher frequencies that occupy the range of p-modes in β Cephei stars. The dependence of such frequencies on spectral type, $v \sin i$, and other parameters as well as any correlation with the slower variations in the three clusters mentioned could provide important global asteroseismological indicators of the structure and, by implication, formation process of Be stars.

3 Conclusions

Two developments have removed the veil of alleged mysteriousness from Be stars: the VDD model and the satellite-boosted quality of light curves. Together they have laid the foundation to an incipient ability to crudely 'read' the observed variability of many classical Be stars. Nonlinear coupling of multi-instance frequency differences is the key process. In the simplest case, one such difference frequency opens and closes the mass-loss valve of a Be star and another, lower difference frequency triggers these events on timescales that can be arbitrarily long. Conventional beating and stochastic processes do not seem to play major general roles.

Compared to amplitudes of individual modes, group amplitudes of coupled modes can be huge, thereby probably enabling sufficient star-to-disk mass-transfer rates even in significantly sub-critical rotators. However, it is not clear whether the amplification concerns pulsation amplitudes, some atmospheric response, or circumstellar reprocessing of stellar light. In any event, most historical (ground-based + Gaia) Be-star photometry only pertains to the circumstellar response and carries no information about the underlying mass-loss process.

Future work will answer the following questions:

- Is the difference between the open and the closed state of the mass-loss valve simply the difference between the respective total (nonlinear) sums of the pulsation-amplitudes?
- Can pulsation spectra distinguish Be stars according to their provenience from single-star evolution or mass transfer in a binary? What is the binary status of Bn stars?

Because only differential analyses are required, the answers will be unambiguous.

A daunting task will it be to explain how seemingly arbitrary multi-instance frequency differences are selected in a continuum of eigenfrequencies. Perhaps, their involvement in mass loss gives a first hint: The upward rising angular momentum (due to core contraction and mixing) might be the frequency matchmaker so that pulsation-driven angular-momentum loss in outbursts can prevent rotational rupture (see Krtička et al. 2011). If the lower activity of late-type Be stars signals lower mass loss, the also observed higher fractional critical rotation of late-type Be stars (Cranmer 2005) could be the consequence. However, the slower evolution of lower-mass stars can have the same effect. A tantalizing speculation could be whether the episodic mass loss from Be stars is a quasi-real time observable of stellar evolution.

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