Be Stars Seen by Space Photometry

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Classical Be stars are introduced as object class and their particular potential for space based photometry is highlighted. A brief summary of the various types of variability observed in Be stars makes clear that an interpretation of every single frequency as a pulsation mode falls short, instead there are as well purely circumstellar variations and those that originate in the immediate stellar to circumstellar interaction region. In particular the latter offer great potential, as they are linked to one of the few remaining great riddles of Be stars, namely how they feed their disks.
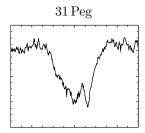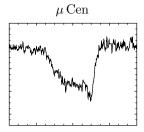
1 Introduction

The class of Be stars is simply defined as those non-supergiant B stars that at least once have shown Balmer line emission (see Rivinius et al., 2013, for a review). While this definition is very valuable for bulk classification of stars for which no high quality data is available, e.g., in the Magellanic Clouds, it is also very broad: Any circumstellar gas close to a B star and above some threshold density will produce line emission. In an attempt at a taxonomy that reflects our knowledge on how the gas was put and is kept close to the star (e.g., magnetically confined, an accretion disk, or a decretion disk), the class was subdivided. This contribution focuses on the so-called classical Be stars.

Classical Be stars are rapidly rotating B stars, surrounded by a gaseous disk that is formed by the star itself through mass ejection. As soon as there is a disk, its fate is governed by viscosity, possibly with some contribution from radiation through disk ablation. As a class, they are known to pulsate in non-radial modes, but not to harbor large scale magnetic fields. In general, Be stars and their disks could be considered as fairly well understood, was it not for the one central question that is still open: How are these disks formed and fed? Space photometry, combining long time bases, short cadence, and high precision offers a new, unique, and highly promising approach to answer this.

1.1 Be stars and space photometry

Several space photometry missions, mostly designed for asteroseismology and planet hunting, have been launched over the past decade. All of them have also observed
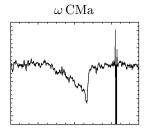
Fig. 1: Example spectral line profiles of three low inclination Be stars at the pulsational phase in which the "spike" is most pronounced.

Be stars, partly in dedicated runs, as the MOST mission, but mostly as by-catch to their regular observing strategies (CoRoT, Kepler, and also the solar mission SMEI). The BRITE-Constellation observing strategy, while not really focused on Be stars, is located somewhere between both approaches, as it gives a certain favor to Be stars, owing to their brightness and relative abundance among bright stars.

To date MOST has observed five Be stars for several weeks each (Walker et al., 2005b,a; Saio et al., 2007; Cameron et al., 2008), Kepler three for four years (Rivinius et al., 2016), CoRoT nearly 40 for between a few weeks and half a year (Frémat et al., 2006; Gutiérrez-Soto et al., 2007; Huat et al., 2009; Diago et al., 2009; Neiner et al., 2012; Gutiérrez-Soto et al., 2009; Neiner et al., 2009; Semaan et al., 2013; Semaan, 2012; Emilio et al., 2010, and Rivinius et al., in prep), and SMEI almost 130 over nine years (Goss et al., 2011; Howarth et al., 2014, and Rivinius et al., in prep). BRITE is still observing a growing list of Be stars (published so far: Baade et al., 2016b), and so is K2 (no published studies yet).

Each of these missions has its advantages and drawbacks when it comes to understanding Be stars, and in the following it will be shown how the photometric observables are formed in Be stars, what is hoped to be learned from them, in particular concerning the unsolved problem of disk feeding, and how the BRITE-Constellation finds its place in this roster of space missions (see Baade et al., 2016a, and Baade et al., this proceedings)

2 Formation of photometric observables

2.1 Stellar pulsation

Classical Be stars, with very few possible exceptions, are pulsating stars, which made them attractive targets for asteroseismology missions in the first place. All published results from space missions (see above) have found non-radial pulsation modes, with typical frequencies between 0.5 and 2 c/d. Some earlier type stars show additional high frequencies. This picture is commonly interpreted such that Be stars are mostly g-mode pulsators, with some also showing p-modes. The associated light variations are due to adiabatic changes in the local stellar surface emissivity, as the pulsational waves pass over the stellar disk. This picture had been anticipated spectroscopically, at least for the early type Be stars (Rivinius et al., 2003).

Mode identification from photometry alone suffers from the rapid rotation of Be stars, well above 50% of the critical fraction, which is beyond the current limits of
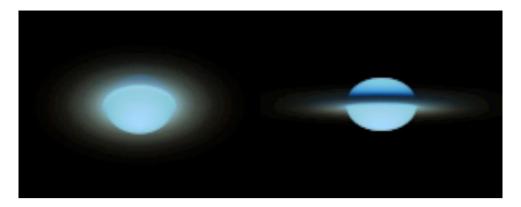
Fig. 2: Model of a Be star with a small disk, at two different inclinations, 56 and 84 degrees, as it would appear to the human eye (parameters like those of the B4 IVe star Achernar, except the inclination). The disk structure was computed according to the viscous decretion disk model, the radiative transfer with the Monte Carlo code HDUST (Faes et al., in prep.)

mode excitation theory. That said, most works based on asteroseismology agree that Be stars are seen to pulsate in prograde, low degree ($\ell \leq 4$) g-modes.

The spectroscopic picture is different. In particular Be stars seen at low inclination, i.e., near pole on, show distinct pulsational features that (see Fig. 1), as long as one assumes traditional pulsation modes, and not Rossby waves or others, can only be explained with retrograde modes. These spikes arise due to a combination of a relatively low co-rotating pulsational frequency, which causes the surface parallel velocity field to be much higher than the surface normal one, with the the low inclination. For this to happen, the mode has to be retrograde; prograde modes always have co-rotating frequencies *higher* than the rotational one. While rotational velocity is projected with a low $\sin i$, the θ velocity field is projected with a factor of, or at least close to, unity, and so the two projected fields become comparable in magnitude. Adding up the velocity fields, a large fraction of the stellar surface is projected into a narrow velocity range, causing the spike (see Rivinius et al., 2001, 2002; Maintz et al., 2003, for details). Spectroscopically, almost all Be stars seem to pulsate in a dominant g-mode, which turns out to be $\ell = m = +2$, i.e., retrograde.

2.2 Photometric contribution by the disk

The circumstellar disk reprocesses the stellar light and in the process alters the spectral energy distribution (SED). Depending on the inclination angle and the wavelength the disk may increase the total flux for pole-on systems, and decrease it for equator-on systems (see Fig. 2). In the visual domain, the inclination angle at which one regime changes into the other, and hence the total flux remains unaffected by a disk, is at about 70° (see Haubois et al., 2012, for general modeling of the disk photometry). The amount and precise properties of this re-processing of light depend, apart from inclination, on the density and density profile of the disk and the stellar SED irradiating the disk. The only variable parameters, in a given system, usually are the density-related quantities. The so-called light-house effect, in which it was speculated that the stellar pulsational lightcurve is measurably re-processed

in the disk was not observed so far. Also, while Be stars with precessing disks exist, they are very rare. Among Be stars brighter than $V = 6.5$ mag only three are known (γ Cas, 59 Cyg, and 28 Tau; all binaries), and only in one of them, 28 Tau, the precession seems permanently present (Hummel, 1998).

When a Be star is in a diskless state and starts growing a disk, the disk forms inside out, i.e., very close to the star the density rises quickly, but further out only with a delay that depends on the viscosity and the distance. After some time the disk reaches a steady state density profile, that is best approximated by a radial power law $\rho \propto r^n$ with $n = -3.5$ to -3.0. During the built-up phase the profile is steeper, and when the disk decays it decays faster at smaller radii, leading to a shallower density profile (see Fig. 1 of Haubois et al., 2012).

For a given photometric band, the disk acts like a pseudo-photosphere of radius $\bar{R}(\lambda)$, where most of the emitted flux comes from, surrounded by optically thin material. The size of the pseudo-photosphere grows with wavelength typically as $\lambda^{0.4}$ (Vieira et al., 2015). As a result, the color behaviors of growing vs. decaying disks are quite different, at least for the stars with non-equatorial inclinations at which the disk absorbs more light than it emits towards the observer (see Fig. 2 and upper row of Fig. 12 of Rivinius et al., 2013).

It is important to note that such secular changes of disk growth and decay, even in the very close vicinity of the star, take at least several days, but also may be much slower and be of the order of decades. This behavior, together with a typical lack of periodicity and phase coherence, sets the photometric changes due to the disk density well apart from those originating in the stellar photosphere, in other words they are, photometrically, easy to distinguish.

While all Be stars, by definition, have a photon reprocessing disk in their active state, and almost all Be stars show pulsational variability, many of them also show additional variability that is not straightforwardly explained in the above framework. It is tempting to link this, as of yet unexplained, photometric behavior to the as of yet unexplained mass ejection process that forms the disk.

In the following section, variability properties of Be stars are shown for several typical cases.

3 Types of Be star photometric variability

Very early type Be stars: HD 51452 is a B0.5 IVe star with an emission appearance reminiscent of ζ Oph, i.e. weak emission peaks on either side of the rotationally broadened absorption profile. The CoRoT data for this B0 IVe star were analyzed by Neiner et al. (2012). Although the overall peak-to-peak variability with ∼20 mmag is quite strong, neither the power spectrum nor the wavelet analysis show clear frequency peaks above a continuum of variability (see Fig. 3, left). Neiner et al. (2012) interpreted this as a sign of stochastically excited pulsation in a multitude of modes, that arise and decay on short time-scales. This behavior is not very common among Be stars, yet it is not unique: γ Cas may show a similar behavior, as unpublished SMEI data suggests.

Early type Be stars: CoRoT 102719279 is a B1 V shell star with a strong and asymmetric Hα emission. The star shows a large number of small outbursts in the wavelet analysis, which all fainten the star to a varying degree. The stellar brightness recovers quickly within a few days or maximally two or three weeks after outburst.
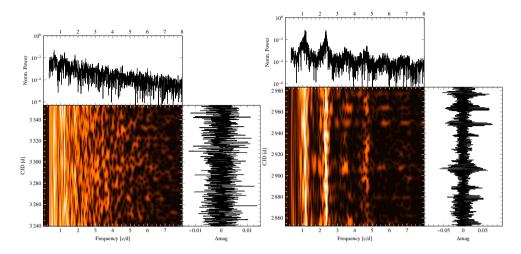
Fig. 3: Wavelet analysis (middle panels), Lomb-Scargle periodogram (top panels), and de-trended light curves (right panels) for HD 51452 (left) and CoRoT 102719279 (right). From Rivinius et al., in prep., but see also Rivinius et al. (2016) for an introduction of the analysis methods used here.

The star is close to a textbook example of a Be (shell) star showing outbursts (see Fig. 3, right). The power spectrum out of outburst is dominated by long-term persistent single, rather well defined frequencies. During an outburst this changes dramatically, and in addition strong and broad "bumps" of power around a base frequency and around a large number of harmonics of that base frequency appear. It is worth reminding that in shell stars additional disk material absorbs and scatters stellar radiation out of the line of sight, so the star is comparable to η Cen, BRITE data of which were analyzed by Baade et al. (2016b), and a bit like StHα166 (Rivinius et al., 2016), although there the individual outbursts are not as well separated as here.

Mid type Be stars: CoRoT 102721109 is a mid to early type Be star, but unfortunately a more precise spectral classification than being hotter than 15 kK is not available (Semaan et al., 2013). It shows no sign of outbursts during the observations, and there are only two frequencies, seemingly of stellar origin (see Fig. 4, left). Although the higher frequency is not far from the harmonic of the lower one, it differs from the precise harmonic value by about 4%, which is a very significant difference, given the time base and frequency resolution of the data.

Late type Be stars: CoRoT data of the late type Be star HD 50209 (B8 IVe, see Fig. 4, right) was analyzed by Diago et al. (2009). The power spectrum is quite typical for its position in the Hertzsprung Russell diagram: It shows no signs of outbursts during the observing campaign. While many frequencies are apparent, most are commensurate in that they could be explained as possible harmonics of a frequency at about 0.74 c/d. However, there is no frequency group at this base value. Instead, the two lowest frequencies bracket that hjypothetical base value on either side. Such a pattern, namely that there seems to be a large number of harmonics, but are not confirmed in a more detailed analysis is common in mid and late type Be stars.
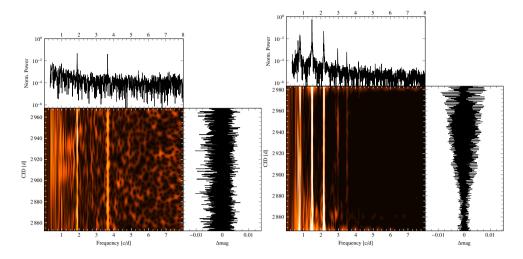
Fig. 4: As Fig. 3, but for CoRoT 102721109 (left) and HD 50209 (right).

4 Discussion

The four categories of variability described above, namely stochastic, bursting, cleanly pulsating, and almost harmonics, are labeled with the spectral subtype range in which they are common, but the borders between them are not sharp. The bursting behavior described under "early type" is the most interesting for understanding the causes and properties of the disk feeding, as outbursts, i.e., discrete feeding events, are clearly identifiable and can be investigated in detail.

The most interesting result to date is the identification of difference frequencies, see Baade et al. (2016b) and Baade et al. in this volume, but as well in many CoRoT targets (Rivinius et al., in prep.). The light modulation with the difference frequencies is unlikely of stellar origin, because the periods are too long for pulsational processes (see Sect. 2.1). More plausible is a swelling up and down of the density of the innermost parts of the disk, affecting the light reprocessing (see Sect. 2.2). The parent frequencies of the difference frequencies *are* pulsational, though. This means difference frequencies are a direct sign that interaction between two pulsation modes does modulate the density above the photosphere, and hence the disk feeding. A similar relation, between pulsation and outburst has previously been identified in μ Cen (Rivinius et al., 1998a,b). One might reconcile the two, outbursts vs. swelling up and down, in a picture in which the same mechanism acts in both types, but in μ Cen is less efficient: There it would cross a critical threshold to eject matter only at times of strongest interaction. In other stars with difference frequencies, the ejection mechanisms would always be active, but depending on beating phase at times with lower or higher efficiency, and thus modulate the density (and light reprocessing) of the innermost part of the disk in a more steady way.

In any case, past and ongoing asteroseismic space missions have enabled the Be star community to come forth with well advanced hypotheses concerning the mass ejection, that make predictions about when outbursts should occur and how they should look like, which are well testable by ground-based follow-up observations.

This might prove the final break-through to solve the long-standing question of disk feeding in Be stars.

5   The role of BRITE-Constellation

What place does BRITE-Constellation have in investigating Be stars? All the missions acquiring that type of data have unique properties. Kepler, K2, MOST, and CoRoT deliver data quality in which every individual cycle can be traced, and with which BRITE cannot compete. However, MOST and K2 campaigns are much shorter than BRITE ones, Kepler targets are virtually unknown stars otherwise, and CoRoT targets are only marginally better investigated, while BRITE observes stars for which usually a large body of supporting studies already exist, and which are even in the reach of the amateur spectroscopic community. SMEI has a hardly challengable time base of nine years and concentrates on a similar brightness range as BRITE-Constellation, but the data quality is so limited that the only reason pulsation frequencies are found at all is because cycles repeat several thousand times during the time base. No individual outbursts can be identified in SMEI data.

While BRITE-constellation does not outshine these spacecraft in any particular single mission parameter, in the combination of the observational properties it is the best possible compromise: It is more precise than SMEI, provides longer time bases than MOST and K2, and its targets are much better known Be stars than those observed by Kepler or CoRoT will ever be. The latter is a key point. Be stars are variable on a large range of time scales. At the very least the build-up or decay state of the disk must be known for a meaningful interpretation of the observed variability, and such and other supporting observations are much easier to acquire for the brighter Be stars observed by the BRITE-Constellation mission.

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