X-ray binaries with Be-type donors

High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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Be stars in the X-ray binary context

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Abstract. Rapidly rotating B-type stars with gaseous mass-loss disks in Keplerian rotation are common central objects in X-Ray binaries. These disks are physically well understood in the framework of the viscous decretion disk, and their typical parameters have been established for a large number of single Be stars in the recent years. According to the current observational evidence, the Be stars and disks found in BeXRBs are well within the boundaries known from single Be stars, i.e., they are normal Be stars. New results have also been obtained on the orbital disk truncation and other tidal effects of the companion objects on the disk.

Keywords. circumstellar matter, stars: emission-line, Be

1. Introduction

The primary stars in the binaries that form the class of the Be X-Ray binaries (BeXRBs) are classical Be stars. Since the first Be star was identified by Secchi (1867) by virtue of its Balmer line emission, it has become clear that many objects of different physical properties can be summarized under a not further distinguished Be star label. As a consequence, a more specific sub-classification has been introduced over the years, and Rivinius *et al.* (2013) give a general overview of the classical Be stars and their distinction from taxonomically similar objects. In the following, the article will deal only with classical Be stars, since only those are found in BeXRBs. Figure 1 illustrates the current schematic view of a classical Be star and how it relates to the spectroscopically observed appearances of Be stars.

In brief, classical Be stars are those Be stars that possess a circumstellar, typically equatorial disk. This disk is supported by Keplerian rotation, and the material of the disk originates from the Be star itself. In the past two decades, numerous interferometric and polarimetric studies have confirmed the basic geometry of Be star disks as geometrically thin disks in Keplerian motion (see, for instance Wood *et al.* 1997; Meilland *et al.* 2007), and the historical record of Be stars growing and losing disks excludes an external source of the disk material (Dalla Vedova *et al.* 2017, give a recent example).

The detailed mechanism by which the central star ejects the material and provides angular momentum for the Keplerian disk is still debated. Nevertheless, a major contributor could be identified to be common to all Be stars, namely rapid stellar rotation. At above 80% of the critical rotation, Be stars as a class are the most rapidly rotating non-degenerate objects (Rivinius *et al.* 2013).

The source of the remaining up to 20% of velocity to make the material escape remains elusive, but in a conceptual sense the reason for the existence of Be stars is much clearer. As main sequence stars evolve, their cores contract and their envelopes expand. As a consequence, the core rotates faster than the envelope and the stellar angular momentum is being re-distributed within the star. According to the current stellar evolution

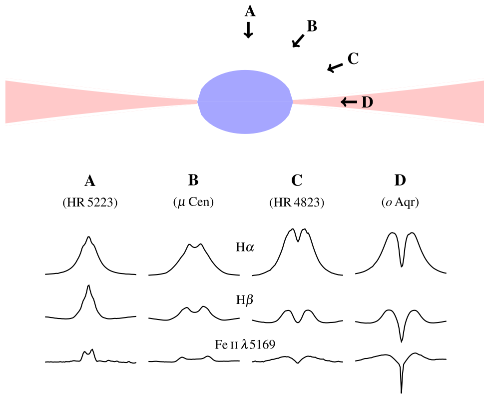

Figure 1. The upper part shows a schematic equator-on view of classical Be star, the lower part example spectral profiles from pole-on to shell Be stars for Hα, a very optically thick line, Hβ, and the mostly optically thin Fe II λ 5169 line. Reproduced with permission from Rivinius *et al.* (2013).

paradigms, the overall effect is a gentle acceleration of the stellar surface towards critical rotation, and for sufficiently high initial rotation the critical limit is reached within the MS-lifetime of a B star (Granada *et al.* 2013). The ejection of a circumstellar disk is simply the means by which a star getting close to the limit sheds angular momentum to avoid becoming a supercritical rotator. Whether and which additional mechanism supports this shedding already at 80% upwards, instead of at 100% critical rotation, is irrelevant in this context.

Originally, it was not clear how the quite distinct appearance of the shell stars puts them apart from the Be stars, though an inclination effect was suspected. A close relation between Be stars and shell stars was recognized early, not at least because the enigmatic object γ Cas was observed to oscillate between both states in the 1940s. But exactly this sort of transition indeed cannot be understood in the frame of an equatorial disk combined with an inclination effect, since the stellar inclination does not change. Instead, it was taken as indication that Be- and shell-phases might rather form a temporal sequence than a geometrical one (Underhill & Doazan 1982, part II). However, the proof that shell stars really are simply equatorially seen Be stars was finally delivered with the above mentioned results with modern instrumentation. Hence for γ Cas, and a few other objects showing such transitional behavior, an explanation beyond the stable equatorial disk needed to be found (see Sect. 4).

2. Disk formation and evolution

For the understanding of BeXRBs, the most important aspect of the Be star is its circumstellar environment. Once the material has been ejected with sufficient angular momentum to remain in orbit, it settles into a disk. While the ejection process might be violent and is probably localized on the stellar surface, within several orbits the viscosity acts to circularize the material into Keplerian motion and to settle it into vertical hydrostatic equilibrium. Such a Keplerian disk in vertical hydrostatic equilibrium is geometrically thin, close to the star, with the scale height being governed by the thermal speed, and hence temperature. Under the not overly unrealistic assumption of isothermality throughout the disk, that disk will flare, i.e., increase its opening angle, at larger radii (see, e.g., Sigut *et al.* 2009; Halonen & Jones 2013).

Once the freshly ejected material has settled into this Keplerian, hydrostatic disk state, its further evolution is fully governed by viscous processes. One can say that the disk, once formed, has completely lost the memory of how it was formed, which is one of the problems in tracking down the exact formation mechanism. Such a disk has been named viscous decretion disk, VDD in short.

The physics governing the disk evolution in Be stars is the same as the physics in gaseous accretion disks, it is rather the boundary conditions that are responsible for any differences. In a Be star disk, the inner boundary is a net source of both matter and angular momentum, while the outer boundary is a sink for both.

2.1. *Disk life cycle*

One important property of the Be stars is that, on time scales from weeks to many decades, these disks can newly form, grow, decay, and vanish again. Even ignoring the details of the ejection process, this makes clear that the disks must form inward-out. For simplicity assume the Be star ejection is a simple process, either active or inactive, and can be parameterized as keeping the inner boundary at a constant density. From here on, the disk is let to evolve purely viscously. Because the orbital speeds and their differentials in the inner disk regions are much faster than further out, so are the time scales there. The inner disk, within the first few stellar radii, will quickly evolve into a steady state configuration, to arrive at this state at larger distances from the star may take decades (Haubois *et al.* 2012).

The steady state is characterized by a constant density slope vs. radius of the form $\Sigma(r) \propto r^2$, where Σ is the integrated surface density in the equatorial plane. The actual volume density has an additional factor of $r^{-1.5}$ (in the isothermal case) due to the flaring height of the disk. When the density slope is measured, it is important to keep in mind that this is not global density slope of the entire disk, but always the slope of the region of the disk that is probed by the observables used. With that disclaimer, a steeper density slope than the steady state one is the signature of a disk being built-up.

An important question is the outer radius of the disk, and the answer is that an outer radius, strictly speaking, does not exist. The most meaningful approximation for a non-binary Be star is the radius at which the orbital velocity becomes comparable to the local velocity of sound. At this radius, the viscous coupling is lost and the disk makes a transition from Keplerian motion to angular momentum conserving outflow (Krtička *et al.* 2011). However, this only happens very far from the star, at hundreds to thousands of stellar radii, and no currently accessible observable is formed in that region of a Be star disk.

For Be stars in binaries, the outer radius of the disk is typically assumed to be close to the companion's orbital radius, but this is a choice driven by numerical complexity, rising steeply with outer radius when it goes beyond the orbital one, since the tidal effects would become more and more dominant for the circumbinary structure. What happens to the disk structure at such radii is discussed in the next Section.

A system that has reached the steady state throughout the disk is not static, though. There will be a constant outflow of both matter and angular momentum, and not all matter that is originally ejected from the star will move out and be lost from the system. In fact, due to the viscous process, material that loses angular momentum in an interaction will go to a lower orbit, and eventually be re-accreted. Material that gains angular momentum will be lifted away from the star, and eventually be lost from the system.

For a star just beginning to build a disk, most newly ejected material will begin to move outwards. In a Be star that has a fully developed steady state disk, a lot more material returns to the star, and the re-accretion ratio might be as high as 99% (Panoglou *et al.* 2016; Ghoreyshi *et al.* 2018). This means that the actual *mass ejection* rate from the star is a factor of up to 100 higher than the *mass loss* ratio through the outer boundary. Typical values, from the two works cited above, are mass ejection rates of about $10^{-7}\,M_\odot\,yr^{-1}$, but mass loss rates of only $10^{-9}\,M_\odot\,yr^{-1}$. Typical disk masses in those scenarios are between 10^{-9} and $10^{-8}\,M_\odot$. These values are observationally well supported for both the Milky Way and the Magellanic Clouds (Vieira *et al.* 2017; Rímulo *et al.* 2018).

Finally, let's consider a decaying disk. In a model computationally this can be achieved by allowing the density at the inner radius to change freely, and removing material as re-accreted when its angular momentum is lower than that needed to support that radius. Again, the innermost part of the disk will react quickest to this change of the inner boundary. Governed by viscosity, and not provided with fresh angular momentum from the star, most of this material will re-accrete, meaning the density slope of a disk in decay will be shallower than that of a disk in steady state (see Fig. 1 of Haubois *et al.* 2012).

Be stars, in particular early type Be stars, are typically not stable in either constant mass-ejection or quiescence for timescales longer than a few weeks, or at most years for later-type Be stars. Instead, they alternate between states of quiescence and ejections with various strength and length. Because the timescale is much faster close to the star, even if the inner part is highly dynamic, from a certain radius on outwards, the disk can still be considered in a quasi steady state condition, and inwards as a disk cycling through growth and decay states (see Fig. 7 of Haubois *et al.* 2012).

2.2. *Observables*

The above description creates a distinct observable signature. The most commonly used observables, like photometry or spectroscopy with optical techniques are formed within a few stellar radii of the central star. The only potential exception to this rule is the Hα line emission. In other words, all those observables are formed well within any potential binary companion's orbit (see Fig. 2 and 7 of Rivinius *et al.* 2013).

Photometry in the optical regime, for instance, is formed within a few stellar radii of the primary. It is hence highly dynamic, and to observe it in a steady state is quite unusual. This volatility decreases with wavelength, so that the near-infrared photometry is more stable, and the thermal infrared even more so.

This is in agreement with the picture described above: the time scales get longer further out, with the precise values depending on the properties of the individual feeding events. The higher the duty cycle, i.e., percentage of active time, of the disk feeding is, the closer to the star the stable region begins, and the more dense the disk will be, compared to a lower duty cycle.

For the purpose of understanding the variability originating from accretion onto a secondary, this means taking the variability observed close to the star and simply projecting this variability to larger radii will over predict the local variations at larger radii.

Unfortunately, a single Be star can undergo widely differing phases of Be activity in relatively short time. Over the 20th century, the prototypical γ Cas went from a strong emission with pole-on disk appearance through a phase oscillating between pole-on and equatorial appearance in the 1940s, then the disk dissipated almost completely, slowly recovering between 1950 and 1970, and since then having a similar appearance as it had around 1900 (Doazan *et al.* 1983). This means that to base a hypothesis on the current state of the circumstellar envelope on any single snapshot observation, instead of monitoring, is likely misleading.

3. Be stars as binary stars

What has been written so far is true for classical Be stars in general. Considering binary stars, a few statements can be made that set Be binaries apart from both single Be stars, as well as from non-Be binaries.

Other than for non-Be binaries, no short period Be binaries are known. For orbital periods below about a week this well explained by tidal forces, that will not allow any disk to settle into a VDD (Panoglou, priv. comm. The shortest orbital period for which a model is published is 10 d, by Panoglou *et al.* 2018). Observationally, the Be star binary with the shortest known period is SAX J2103.5+4545, with $P_{\rm orb} = 12.68$ d, as listed in the online catalog by Raguzova & Popov (2005)†. The period space between 12 and 28 d is not well populated, only a few BeXRBs are known. The shortest period Be star binaries with a companion other than a neutron star are 59 Cyg (Rivinius & Štefl 2000) and o Pup (Rivinius *et al.* 2012; Koubský *et al.* 2012), with orbital periods of about 28 d. They both have a subdwarf O-star companion, from which the envelope was stripped during binary evolution. So there is certainly a not yet explained discrepancy between the shortest observed orbital period and the shortest predicted ones.

Another surprising result, for both Be+NS and Be+sdO, is the spectral type distribution. While the incidence of Be stars with spectral subtype is somewhat debated, it is probably flatter than previously thought, i.e., the percentage of Be stars does not drop strongly for later B subtypes (Shokry *et al.* 2018, and references therein). In stark contrast, neither Be+NS (Reig 2011; Haberl & Sturm 2016), nor Be+sdO binaries with primaries later than about B3 are known. For Be+sdO stars, a recent search by Wang *et al.* (2018) gave a highly significant result: Even though their search method was quite in favor of detecting such hot companions around later type primaries, they did not find a single candidate. It is worth noting that Wang *et al.* explain this with a flat mass ratio distribution of the progenitor systems. Another class of Be potential binaries also adheres to this subtype limit, the γ Cas analogies (Smith *et al.* 2016). It is, however, not firmly established whether all of them are binaries (some certainly are), and what it would have to do with their properties as a class.

The tidal effects of a binary companion have also been modeled. Recent results have mostly confirmed and detailed earlier models (see, e.g., Panoglou *et al.* 2016, 2018, and references therein). In a binary Be star one finds a truncation radius, typically at a strong orbital resonance radius, close to maybe half or a bit more of the semi-major axis, at which the Be star disk does not vanish, but strongly changes its density structure: The density slope with radius becomes a lot steeper. As demonstrated above, for most observables shortward of the radio regime, this is effectively a truncation. For the few stars for which radio data at sufficiently long wavelengths are available, however, this region is observable (Klement *et al.* 2017). The observations are generally in good agreement with the model as far as it concerns the change of the density structure at the the mentioned "truncation" radius. In terms of the SED, this produces a turndown, i.e., a reduction of the SED slope at a wavelength that corresponds to the truncation (see the pseudo-photosphere concept by Vieira *et al.* 2015, for the transformation of

† http://xray.sai.msu.ru/~raguzova/BeXcat/

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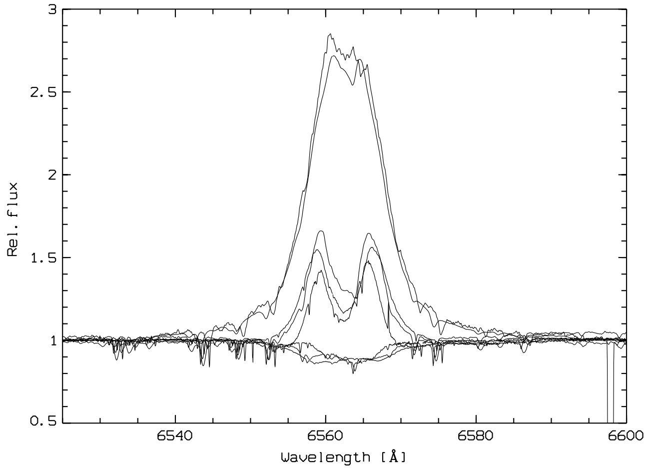

Figure 2. Selected Hα emission profiles of π Aqr from 2000 to 2018. Data from the BeSS database (http://basebe.obspm.fr/) and own observations.

radius to wavelength). At even longer wavelengths, however, there is a discrepancy. The current models do not predict another change of structure at even larger radii. However, the observations suggest that, outside the companions orbit, the disk may recover and return to the original slope, but on a lower density level. Plainly put, a very tenuous circumbinary Keplerian disk might be a possible explanation for the radio observations.

The second observable, that is potentially formed at radii far enough from the central star to show the presence of a companion, is the Hα line emission. As shown by Panoglou *et al.* (2016), a phase-locked spiral structure might arise in the disk, causing phase-locked cycling of the relative peak strength of the violet and red emission peaks, the V/R-ratio. If the disk is dense enough, one might as well observe the effects of the truncation on the emission profile directly. In Fig. 2 the Hα spectra of π Aqr show the growing emission from 2000 to 2018. π Aqr is a Be binary with an orbital period of about 84 d (Bjorkman *et al.* 2002). In the lowermost set, the star has almost no disk at all, while in the middle set the disk is present, but the morphology is fully consistent with an undisturbed, i.e., single star disk. Only when the disk has grown for a time and probably reached the steady state density at the truncation radius, this is no longer the case. Instead of the traditional double peaked profile, one now observes a flat-topped or multiply peaked profile. This morphology of the emission is very typical for Be stars in binaries, in particular when the emission is strong. In might be used as a strong candidate indicator for binarity of a Be star.

4. Disturbed Be star disks

The previous sections dealt with largely steady state disks, if at all only slightly disturbed by the tidal forces due to a companion. There are, though, much stronger instabilities that can act in a Be star disk. These can fully dominate the disk emission morphology and temporal behavior, and completely veil the presence of binary effects.

The first is that a strong, global density wave pattern can grow in a disk, and then precess around the central star on the time scale of a few years (see Štefl *et al.* 2009,

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for a comprehensive observational description). Because of the behavior of the emission lines, this is called violet-to-red, or V/R, cyclic variation. The density wave itself and its precession behavior is theoretically well understood (Carciofi *et al.* 2009, and references therein), but what triggers the disturbance, and what lets the density wave decay after a number of precession cycles, is not really known.

Finally, there is the drastic changes that have been mentioned in the Introduction. These are called "Spectacular Variations" (SV) and are best described as one and the same Be star changing from a pole-on or low inclination appearance to a high-inclination or shell star appearance within a few years and back again. Among the brighter classical Be stars, only three objects are known to have shown that behavior, γ Cas, 59 Cyg, and Pleione. However, there might be more of them among the BeXRBs, like Reig *et al.* (2000) have shown for LS I +61° 235. With the geometry discussion of the Be star circumstellar environment being settled, it became clear that a disk with stable orientation would not explain this behavior. Instead, an inclined and precessing disk was considered by Hummel (1998). Unfortunately, the SV episodes of γ Cas and 59 Cyg took place before modern instrumentation and detectors were available. In Pleione, however, the SV is ongoing. Hirata (2007) presented a series of spectroscopic and polarimetric observations, in which they showed that the rotation of the polarization angle is in very good agreement with the misaligned, precessing disk hypothesis proposed by Hummel.

Counting in LS I +61° 235 as fourth case of SV, it is striking that all the four stars are known binaries, with orbital periods from one month to a bit less than one year. Unfortunately, no model could yet reproduce this behavior.

5. Conclusions

In the context of BeXRBs, only the conditions as found in early type Be stars are of relevance. This is because no BeXRBs are found with primaries later than about B3. Compared to late type Be stars, early ones have shorter variability time scales and higher disk densities. The variability of Be star disks, though, is typically assessed by observables that form very close to the central star, like photometry or spectroscopy (other than Hα). At the position of a binary companion, this variability has typically been averaged out by viscous processes acting in the disk. The companion perceives a much more stable, steady state disk, from which it accretes, than one would expect from the observables mentioned above alone. Disk observables sensitive to the orbital region in the vicinity of the secondary might rather be the Hα emission line, at least for dense, well developed disks, and photometry and bolometry from the thermal infrared long-wards to cm-radio observation, depending on orbital dimension.

Yet, even if the disk has settled into a steady state configuration at the companion position, the historical context must be known for any reliable analysis, since Be stars may change also their long-term activity level. For this, fortunately no high cadence data are needed, but in turn a long time base. In the past decades many monitoring projects were started that are capable of providing these data, such as the OGLE projects for the Magellanic Clouds (Udalski *et al.* 2015), or the ASAS (Pojmanski 1997), KELT (Pepper *et al.* 2007), and similar surveys for the Milky Way.

There is a characteristic radius for the disk in a binary, commonly called the truncation radius. It is typically at some resonance radius at about half or a bit more of the semi-major axis of the binary. To imagine the truncation radius as an outer edge of the disk would be misleading, however. What really happens is that the density slope inside the truncation radius is slightly shallower than in the single star steady state case, but considerable steeper outside. For a dense disk, this becomes apparent when the Hα emission morphology becomes flat-topped or multiply peaked, instead of having a clear double peak behavior.

Finally, in case one wants to study the binary evolution in such a system, it is important to remember that the disks are not very massive. The disk is primarily the means by which the Be star gets rid of angular momentum *without* having to lift more than the bare minimum of mass needed.

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