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Spectroscopic Diagnostics for Circumstellar Disks of B[e] Supergiants

M. Kraus[1,2]

[1]*Astronomický ústav AV ČR, v.v.i., Ondřejov, Czech Republic;*
`michaela.kraus@asu.cas.cz`
[2]*Tartu Observatory, Tõravere, Estonia*

Abstract. B[e] supergiants (B[e]SGs) are emission-line objects, presumably in a short-lived phase in the post-main sequence evolution of massive stars. Their intense infrared excess emission indicates large amounts of warm circumstellar dust. It has long been assumed that the stars possess an aspherical wind consisting of a classical line-driven wind in the polar direction and a dense, slow equatorial wind dubbed outflowing disk. The general properties obtained for these disks are in line with this scenario, although current theories have considerable difficulties reproducing the observed quantities. Therefore, more sophisticated observational constraints are needed. These follow from combined optical and infrared spectroscopic studies, which delivered the surprising result that the circumstellar material of B[e]SGs is concentrated in multiple rings revolving the stars on stable Keplerian orbits. Such a scenario requires new ideas for the formation mechanism where pulsations might play an important role.

1. Introduction

B[e] supergiants (B[e]SGs) form a subgroup of stars displaying the B[e] phenomenon. This phenomenon was originally discovered by Geisel (1970), who detected infrared (IR) excess emission due to hot or warm dust in a sample of B-type emission-line stars known to display low-excitation forbidden and permitted emission lines (predominantly from Fe II). This IR excess emission was confirmed by follow-up surveys (Allen & Swings 1972; Allen 1973, 1974; Allen & Glass 1974, 1975). Inspection of these objects revealed that the sample consists of stars in different evolutionary phases, including pre-main sequence stars, compact planetary nebulae, supergiants, and symbiotic binaries.

Based on the classification criteria defined by Lamers et al. (1998), a star with the B[e] phenomenon is assigned a B[e]SG status when it fulfills additional criteria. These are a supergiant luminosity ($\log L/L_{\odot} \geq 4.0$), small photometric variability, chemically processed material indicating an evolved nature, indications of mass loss in the optical spectra, and a hybrid spectrum consisting of narrow low-excitation emission lines of low-ionized metals (e.g., Fe II, [Fe II], [O I]) with simultaneous broad absorption features of high-excitation lines.

The number of confirmed B[e]SGs is small. In the Galaxy, it is difficult to assign a star a firm supergiant status, due to the often uncertain distances, hence luminosities. Previously classified stars might also suddenly display a variable character, which then requires re-classification of the object (e.g., Aret et al. 2016). It might thus be advisable only to speak of candidates, and there are currently about 16 such Galactic B[e]SG candidates known (for a list see Kraus 2009, plus HD 62623 and AS 381).

The Magellanic Clouds host the most well-known B[e]SG sample. Here, the proper luminosity assignment is not an issue. We know 15 confirmed members (Zickgraf 2006), of which 11 reside in the Large Magellanic Cloud (LMC) and 4 in the Small Magellanic Cloud (SMC). In addition, a few new B[e]SG candidates were discovered: 3 in the LMC (see Dunstall et al. 2012; Levato et al. 2014) and 4 in the SMC (see Wisniewski et al. 2007; Graus et al. 2012). Moreover, Kamath et al. (2015) recently reported a new sample of B[e] candidates in the LMC. Whether supergiants are also included in this sample still needs to be investigated.

The identification of B[e]SGs in other galaxies is difficult, because these objects are generally rather faint, due to the large distances. Nevertheless, optical spectroscopic surveys of evolved massive stars in Local Group Galaxies hinted at a number of possible candidates (e.g., Massey et al. 2007; Clark et al. 2012). Kraus et al. (2014) performed follow-up IR observations of a few selected candidates. Based on the IR appearance of the stars, they discovered the first two B[e]SGs in the Andromeda galaxy. This demonstrates that a large number of these peculiar objects might still be identified in the Local Group with a more systematic search.

2. General Properties of B[e] Supergiant Stars' Disks

The hybrid spectrum of B[e]SGs was discovered by Zickgraf et al. (1985). These authors proposed that B[e]SGs might have a hybrid wind, consisting of a classical (i.e., low-density, fast) line-driven wind in polar direction together with an equatorial high-density, slow outflow. For these hybrid winds, a density contrast in the range 100–1000 between the equatorial and the polar wind components was found (Zickgraf et al. 1989), and the equatorial wind was henceforth dubbed the "outflowing disk".

There is a great deal of evidences for the presence of dense and cool disk-like structures around B[e]SGs. Their spectral energy distributions display strong IR emission in excess of a pure free-free contribution from a stellar wind or ionized gas disk (see, e.g., Zickgraf et al. 1986; Bonanos et al. 2009, 2010). It is thus attributed to large amounts of circumstellar dust. As the IR emission peaks in the near-IR region, this dust must be rather hot (~ 1000 K). The spatial distribution of the dust cannot be spherically symmetric because Magalhaes (1992) discovered intrinsic optical linear polarization in all the observed objects. The good correlation between the degree of polarization and the intensity of the dust emission he assigned to dusty disks seen under different inclination angles. Other studies confirmed the often high degree of intrinsic polarization, and detailed investigations suggest that it is caused by the combined effect of electron scattering plus scattering by dust in a disk-like structure (see Zickgraf & Schulte-Ladbeck 1989, and Seriacopi et al., this volume).

A dense disk is also considered the ideal environment for the hot molecules that were discovered in B[e]SGs. The most prominent species is carbon monoxide (CO). Its first-overtone band emission arises in the near-IR and was detected in many B[e]SGs (McGregor et al. 1988a,b, 1989; Morris et al. 1996; Oksala et al. 2012, 2013). The excitation of these bands requires gas temperatures in excess of 2000 K, implying that CO band emission originates from circumstellar regions closer to the star than the dust is. With a dissociation temperature of ~ 5000 K, CO is the most stable molecule in the universe, and no other molecule can exist closer to a hot, luminous star than CO. Hence, the detection of CO band emission from an object is typically regarded as the ultimate tracer for the inner rim of the circumstellar molecular gas. As the strong ultraviolet radiation field of hot stars destroys CO, the molecules are most likely located within a dense disk or ring, capable of self-shielding of the gas.

Other molecules detected from a few B[e]SGs are silicon oxide (SiO), whose first-overtone bands also arise in the near-IR region (Kraus et al. 2015b), and titanium oxide (TiO) with band emission from electronic transitions emitting at optical wavelengths (Zickgraf et al. 1989; Torres et al. 2012; Kraus et al. 2016). However, to date not many objects have been thoroughly searched for emission from molecules other than CO, and one might expect to find emission from hot molecules in many more B[e]SGs.

The development of optical interferometry facilities that operate in the near- and mid-IR wavelength regions, provided a great step forward in B[e]SG star research (see Meilland, this volume). The capability of these facilities to spatially resolve circumstellar environments down to small scales boosted the studies of B[e]SG star disks, at least for those Galactic objects that were close and IR bright enough to be observed interferometrically. With this powerful tool, the gaseous, dusty disks of several objects could be resolved, resulting in precise measurements of the disk sizes, the distances of the dust from the stars, and the disk inclination angles (see Domiciano de Souza et al. 2007, 2011; Millour et al. 2011; Cidale et al. 2012; Wang et al. 2012; Wheelwright et al. 2012a,b).

All this evidence imply that B[e]SGs are surrounded by disk-like structures, which must be geometrically thick to provide an ideal environment that is dense and cool enough for molecule and dust condensation. A proof that the material forming these disks was indeed ejected from the star during its post-main sequence evolution was provided by the discovery of enhanced ^{13}C, detected via strong ^{13}CO band emission (Liermann et al. 2010; Kraus et al. 2013b; Oksala et al. 2013). As stellar evolution models depict (see, e.g., Ekström et al. 2012), the enrichment of the stellar surface (and thus of the released circumstellar material) with this isotope, with respect to the main isotope ^{12}C, is a process that already starts during the main-sequence evolution of massive stars and continues gradually with the age of the object. Hence, detection of an enrichment in ^{13}CO in stars with circumstellar disks provides the ideal tool for estimating the evolutionary state, but also for discriminating between a pre-main sequence and an evolved nature of the object (e.g., Kraus 2009; Muratore et al. 2015).

3. Disk Formation Mechanisms

As B[e]SGs are hot, luminous objects, how can cool and dense disks form and survive in such a harsh environment? Several mechanisms have been proposed in the literature, which are briefly outlined in the following.

Most popular is certainly the binary scenario, in which a disk-like structure can form from the material ejected during phases of strong interaction, up to a full merger. To date, a companion has been identified in only six B[e]SGs. Four of them are Galactic objects (MWC 300, HD 62623, HD 327083, and GG Car), and in all of which the disk is circumbinary (Wang et al. 2012; Millour et al. 2011; Wheelwright et al. 2012a; Kraus et al. 2013b). The remaining two objects (LHA 115-S 6 and LHA 115-S 18) reside in the SMC, and these objects show clear differences from the Galactic binary sources. LHA 115-S 6 was thought to be a post-merger candidate in an original triple system (Langer & Heger 1998; Podsiadlowski et al. 2006), while LHA 115-S 18 was identified as the optical counterpart of a high-mass X-ray source (Clark et al. 2013; Maravelias et al. 2014). The latter object is particularly interesting as it shows strong photometric and spectroscopic variability and displays time-variable Raman scattered emission (Torres et al. 2012), which is typically only seen in symbiotic systems (e.g., Leedjärv et al. 2016). The features and variabilities of the SMC B[e]SG binary candidates clearly separate these objects from the remaining B[e]SG sample in the Magellanic Clouds. Together with the fact that no binary has been identified in the LMC B[e]SG sample so far, we might conclude that binary interaction or merger might be a reasonable scenario for a minority of objects, but it is most likely not the universal disk-formation mechanism.

For single B[e]SGs, Bjorkman & Cassinelli (1993) proposed a model in which the winds emanating from the two hemispheres of a rapidly rotating star were predicted to collide in the equatorial plane, forming a compressed, outflowing disk. However, these authors did not include the non-radial forces that arise from the flattening of a rapidly rotating star that prevent the formation of a disk (Owocki et al. 1996). Alternatively, critical stellar rotation may form an outflowing disk via the magneto-rotational instability mechanism (Krtička et al. 2015; Kurfürst et al. 2014, and this volume). This model works well for classical Be stars, which are known to rotate close to the critical velocity.

To test whether the material in the equatorial plane can actually recombine in the vicinity of a hot, luminous supergiant, ionization structure calculations were performed in hybrid-wind models. Based on a heuristic approach for the latitudinal density distribution, recombination in the equatorial plane occurred, but only in models with (unrealistically?) high values for the equatorial mass-loss rates (Kraus & Lamers 2003; Zsargó et al. 2008). Inclusion of rapid stellar rotation in the calculations revealed that owing to the effects of gravitational darkening, the equatorial wind regions are depleted, resulting in hydrogen-neutral equatorial zones that are less dense than the polar regions (Kraus 2006). This is the opposite of what is observed.

A way out of this dilemma is provided by the rotationally induced bi-stability mechanism (Pelupessy et al. 2000), which utilizes the fact that ions recombine at a certain latitude, due to the latitude dependence of the temperature in the wind of a rapidly rotating star. Of particular importance is the recombination from Fe IV to Fe III at a temperature of $\sim$ 25 000 K, because Fe III possesses many more transitions suitable to drive a dense wind in the cooler, i.e., equatorial regions. The drawback of this mechanism is, however, that the density contrast between equatorial and polar wind that can be achieved is a factor of 10–100 below the observed values. The situation can be improved by combining the bi-stability mechanism with the slow-wind solution discovered by Curé (2004, see also Curé, this volume). In this model, proper density enhancements in the equatorial direction were achieved (Curé et al. 2005); however, the resulting wind velocities in the equatorial plane (200–300 $\mathrm{km\,s^{-1}}$) were too high compared to the observed values, which are on the order of 10–30 $\mathrm{km\,s^{-1}}$ and can display a slow-down with increasing distance from the star (e.g., Kraus et al. 2010).

To summarize, all single-star models presented have significant drawbacks and have as a major prerequisite that B[e]SGs should be rotating at a substantial fraction of their critical velocity.

4. On the Rotation Velocities of B[e]SGs

The rotation velocities of stars, projected to the line of sight, are typically extracted from the profiles of their photospheric absorption lines. As most B[e]SGs are deeply embedded in their dense winds, their typically pure emission-line spectra hamper the proper establishment of their rotation speeds. Only in four Magellanic Cloud stars one or more photospheric lines were detected that were used to estimate the rotation velocity, projected to the line of sight. These are LHA 115-S 65 (Zickgraf 2000; Kraus et al. 2010) and LHA 115-S 23 (Kraus et al. 2008) in the SMC, and LHA 120-S 73 (Zickgraf 2006) and LHA 120-S 93 (Gummersbach et al. 1995) in the LMC. The inclination angle is often unknown or uncertain, so that only lower limits of their real rotation velocities are obtained. For LHA 120-S 93, a value of ∼ 40% of its critical rotation speed was estimated, whereas for the other objects a value on the order of 75% was proposed. Although these high values are tempting and have been used in the past as the basis for the theoretical models presented above, their reliability has recently been questioned.

For the LMC star LHA 120-S 73, Zickgraf (2006) determined a value of $\upsilon \sin i = 50\,\mathrm{km\,s^{-1}}$ from the photospheric He I λ 5876. This line was also seen in the spectra taken between 1999 and 2015. However, Kraus et al. (2016) have shown that its profile was clearly asymmetric and time variable. Moreover, comparison with an artificial rotationally broadened line profile revealed that the core of the observed line is in most cases much narrower than the theoretical one, meaning that the value of $\upsilon \sin i = 50\,\mathrm{km\,s^{-1}}$, and hence of 75% critical, are significantly overestimated. The He I λ 5876 line is thus not suitable to reliably determine $\upsilon \sin i$ in this object. In light of these findings, a revision of the $\upsilon \sin i$ values of the other three objects appears inevitable.

5. Disk Structure and Kinematics

There could be two reasons why no common scenario has been identified so far for the disk formation in B[e]SGs. Either the mechanism is different in each object, or we have not found the proper one yet. To unveil possible disk formation mechanisms, suitable observational constraints regarding the structure and kinematics of the material surrounding B[e]SGs are indispensable. Spectroscopy provides the ideal tool for searching for features that trace the disk from its inner rim to far distances.

5.1. Dust

We start with the outer disk regions, dominated by dust. Infrared photometric observations over several decades displayed no evidence of variability. If the dust particles condense from an outflow, they should be formed continuously. However, as model computations have shown, the observed intense IR excess emission of B[e]SGs cannot be reproduced by such a scenario (Porter 2003). This means that not enough dust can form in situ in an outflowing disk. Instead, it seems more likely that the dust around B[e]SGs has accumulated with time. Support for such a scenario comes from observations with the *Spitzer Space Telescope*. The mid-IR spectra of the nine observed B[e]SGs in the Magellanic Clouds display emission features from crystalline silicates (Kastner et al. 2010). Their formation requires substantial grain processing in a stable, long-lived environment. Some of the objects show additional emission from polycyclic aromatic hydrocarbons (PAHs). This dual-dust chemistry, i.e., the co-existence of silicates with carbon-based grains, is a further strong indicator of a stable dusty environment in which non-equilibrium chemical processes had sufficient time to occur.

5.2. Molecules and Chemistry

The molecular gas region lies closer to the star, where the temperature exceeds the dust evaporation temperature of ~ 1500 K. As mentioned earlier, molecular emission, in particular from CO, was detected in many B[e]SGs. The intensity of the CO first-overtone bands, which arise in the near-IR regime redward of 2.293 μm, is extremely sensitive to the density and temperature of the CO gas (Kraus 2009). As CO is furthermore the most stable molecule, the observed CO band emission originates from the densest and hottest molecular region, which marks at the same time the transition from atomic to molecular gas and hence the inner rim of the hot molecular disk.

Using the SINFONI spectrograph at ESO, a *K*-band near-IR survey was performed to determine the physical parameters of the CO band emitting regions in a sample of Galactic and Magellanic Cloud B[e]SGs (Liermann et al. 2010; Oksala et al. 2013). This survey delivered two surprising results. The CO gas in each object had a different temperature, spreading from 1900 K to 3200 K, and these values are far below the CO dissociation temperature of 5000 K. If the gas were distributed in a homogeneous disk ranging from the stellar surface to far distances, the transition from the atomic to the molecular region should take place at a temperature close to the CO dissociation value. The rather cool CO temperature values found in all objects imply that no hotter molecular gas exists closer to the star. Consequently, the disks of B[e]SGs cannot be continuous structures.

The resolution of the SINFONI spectrograph is low ($R \sim 4500$). To resolve the kinematics stored in the shape of the first CO band head, high-resolution observations are required. So far, eight Galactic B[e]SGs have been observed with the CRIRES spectrograph at ESO, and another four Magellanic Cloud B[e]SGs with the Phoenix spectrograph at GEMINI-South. Both instruments provide a resolution of $R \sim 50\,000$. In all objects, the CO band head displayed a blue-shifted "shoulder" and a red-shifted maximum. Detailed modeling of the band head structures reveal that the individual lines forming the band head display a double-peaked profile, which corresponds to just one single line-of-sight velocity (see Muratore et al. 2012b; Wheelwright et al. 2012b; Cidale et al. 2012; Kraus et al. 2013b, 2016). Such a profile can originate either from a ring expanding with constant velocity, or from a very narrow rotating ring.

To determine whether the velocity seen in the CO bands is due to expansion or rotation, information from complementary tracers of the kinematics is needed. Most valuable would be other molecules that form at lower temperatures than CO and hence at greater distances from the star. Considering that B[e]SGs are massive stars that preserve an oxygen-rich surface composition throughout their lifetime, a very promising molecule that will form in such an oxygen-rich environment is SiO. This molecule has, together with TiO, the second highest dissociation temperature and can hence also be regarded as very robust. Moreover, Si has an abundance that is more than two orders of magnitude higher than that of Ti, guaranteeing that a sufficiently large number of SiO will be formed to produce observable amounts of emission.

The structure of the energy levels in SiO is very similar to CO, so that in a hot enough environment ($T > 1500$ K) the rotation-vibration bands are excited. The first-overtone SiO bands arise in the *L*-band, redward of 4.004 μm. Kraus et al. (2015b) selected four Galactic B[e]SGs with confirmed CO band emission, and observed these stars using CRIRES. All four objects displayed kinematically broadened emission of the first SiO band head. As the velocity projected to the line of sight was smaller than that derived from CO, the logical conclusion was that the molecular gas is rotating around the central stars, most likely on Keplerian orbits.

The successful detection of theoretically predicted SiO band emission from the environments of B[e]SGs encourages the search for further molecular species that would bridge the gap to the dust condensation zone and would help improve our knowledge of the physical properties and the kinematics of the molecular regions.

5.3. Optical Forbidden Lines

We turn now to the atomic gas, which is located between the stellar surface and the molecular CO ring. To study the gas kinematics, optically thin lines are required. This predestines forbidden lines because transitions from various elements and ionization states are excellent tracers of different density and temperature regimes (e.g., Kraus et al. 2005).

In addition, the numerous [Fe II] lines in the spectra of B[e]SGs, which trace low-density environments, the [O I] lines, which are present in all B[e]SGs, have proven to be extremely valuable. The optical spectral range hosts three of them: [O I] $\lambda\lambda$ 5577, 6300, 6364. However, the [O I] λ 5577 is often very weak or even absent. These lines had been ignored until Kraus et al. (2007) realized that they arise from regions in which the particle density can be high, as long as the electron density remains low. Such conditions prevail in regions where hydrogen is predominantly neutral. This is achieved for temperatures below $\sim$ 10 000 K. The [O I] lines in high-resolution optical spectra displayed double-peaked profiles in B[e]SGs with edge-on or intermediate orientation of their disks, while they displayed no kinematical broadening in pole-on oriented objects (Kraus et al. 2010; Aret et al. 2012; Muratore et al. 2012a). This implies that the [O I] line forming region lies within the dense, neutral (in hydrogen) regions of the gaseous disks. Moreover, the profile of the [O I] λ 5577 Å line is typically wider than the profile of, e.g., the [O I] λ 6300 Å line. As the [O I] λ 5577 Å line emerges from a higher energy level whose collisional population requires an environment with a higher electron density, the forming regions of the [O I] λ 5577 Å and [O I] λ 6300 Å lines are physically distinct. These findings agree with the idea that the [O I] lines form in a Keplerian rotating gas disk, in which the [O I] λ 5577 Å line forms at distances closer to the star where both the density and rotation speed are higher.

In addition to the [O I] lines, Aret et al. (2012) recently identified the two [Ca II] $\lambda\lambda$ 7291 and 7324 Å lines in the spectra of B[e]SGs. These lines form a valuable complementary set of tracers for the properties of the gas disk. Like the [O I] lines, the [Ca II] lines display double-peaked profiles, indicating rotational broadening, and in all studied objects the width of the [Ca II] line profiles was comparable to or even broader than that of the [O I] λ 5577 Å lines. This implies that the [Ca II] lines form at similar distances or even closer to the star than the [O I] λ 5577 Å line (Aret et al. 2012, 2016). This is in line with the higher critical electron density for [Ca II].

Recent detailed investigation of the [O I] and [Ca II] sets of forbidden lines reveal that their profiles cannot be modeled under the assumption of line formation in a single ring as was the case for CO. Instead, to properly reproduce the shapes of the profiles the emission must originate from at least two detached and physically distinct rings (e.g., Kraus et al. 2016; Maravelias et al. 2015, and this volume). This result appears surprising at first glance, but it is in line with the findings from the CO molecular emission, which also arises from a detached ring. Consequently, B[e]SGs cannot have disks formed from a continuous equatorially outflowing wind. Instead, all tracers hint toward multiple material concentrations in the form of rings of atomic and molecular gas, revolving the stars on stable orbits.

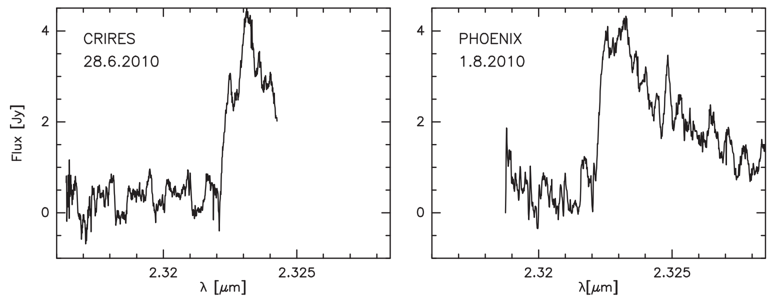

Figure 1. Variation in the CO band emission observed in HD 327083.

6. CO Variability and Inhomogeneities

Despite their importance, observations in the (near) IR are sparse. While most B[e]SGs were observed at least once in the *K* band during the past 30 years (McGregor et al. 1988a,b, 1989; Morris et al. 1996; Oksala et al. 2013), most spectra were taken with different (mainly low) resolution. These low-resolution observations hamper precise comparison of the strength and shape of the band heads and are inadequate for kinematical studies. Follow-up high-resolution observations exist only for a few objects, but even with this small set of data, notable variabilities in the CO band emission were identified in six objects.

The CO variabilities seen in two objects were exceptional. The first one is the Galactic object CI Cam, which experienced a spectacular outburst in 1998. And about one month later, CO band emission was discovered (Clark et al. 1999), which disappeared again with the expansion and dilution of the ejected material (Liermann et al. 2014). The second is the SMC star LHA 115-S 65, which suddenly displayed intense CO band emission in October 2011, while all previous observations resulted in non-detections (Oksala et al. 2012). Whether the appearance of CO band emission in LHA 115-S 65 was also caused by an outburst event, and whether the emission disappeared again, is unknown.

The variabilities seen in the other objects are less dramatic, but still of high importance. The LMC star LHA 120-S 35 had displayed a factor of 2 increase in CO intensity within two years (Torres et al., in preparation). LHA 120-S 73 exhibited a decrease in CO intensity between 2004 and 2009, while in 2010 the intensity had partly recovered (Kraus et al. 2016). And the Galactic B[e]SG HD 327083 displayed variations in its CO band heads within a period of one month (Kraus et al. 2013a, see Fig. 1). In the latter two objects the observed varibilities can be explained with density inhomogeneities (i.e., clumps) within the molecular gas ring. This scenario is supported by the spatially resolved integral-field unit *K*-band images of the Galactic object MWC 137, which revealed multiple, clumpy molecular ring structures (Kraus et al., this volume).

7. Conclusions and Future Perspectives

Although B[e]SGs have been investigated for several decades, they are still puzzling. Thorough analysis of their optical and IR spectroscopic appearance has led to the conclusion that these objects have multiple, often clumpy ring structures revolving the star on presumably stable orbits, meaning that the original suggestion of an outflowing disk needs to be discarded. Another important conclusion refers to the rapid (close to critical) rotation speeds of B[e]SGs. Based on the recent findings of Kraus et al. (2016), the values found in the literature might be significantly overestimated. A revision of all presently known $v \sin i$ values is thus imperative.

The next big question that needs to be addressed concerns the origin of the circumstellar rings. While in some objects they might result from binary interaction, most B[e]SGs are not known (yet) to have a close companion. For these stars an alternative formation mechanism is required. A possible approach might involve stellar pulsations, which were recently discovered in classical blue supergiants and α Cygni variables (Saio et al. 2013; Kraus et al. 2015a). Whether specific pulsation modes might facilitate periodically triggered equatorial mass-loss is certainly worth investigating in more detail.

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