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Probing the structure and dynamics of B[e] supergiant stars' disks*

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Resumen / Las supergigantes B[e] son un grupo de estrellas masivas evolucionadas que se encuentran en una fase de transición de corta duración. Durante esta fase, estos objetos expulsan grandes cantidades de materia que se acumula formando anillos circunestelares o estructuras en forma de disco, que giran alrededor de las estrellas en órbitas keplerianas. En la mayoría de estos objetos, los discos circunestelares parecen presentar estructuras estables por décadas, por lo que resultan laboratorios ideales para estudiar la formación de moléculas y la condensación de polvo. La combinación de datos espectroscópicos de alta resolución, de las regiones ópticas e infrarrojas, permiten buscar características en emisión que sirvan como trazadores de la estructura, cinemática y composición química del disco a diferentes distancias de la estrella. Ciertas líneas en emisión de transiciones prohibidas de metales ionizados o neutros, tales como [Ca II] y [O I], son los trazadores ideales de las regiones gaseosas atómicas más internas del disco. Un poco más lejos de la estrella se forman las moléculas, donde el primer sobretono de las bandas de monóxido de carbono (CO) marca el borde caliente interior del disco molecular, por lo que se esperaría encontrar la formación de otras moléculas entre la región comprendida entre el CO y la zona de condensación de polvo. Se han iniciado varias campañas de observación en búsqueda de estas moléculas y de sus características de emisión, con el fin de construir una imagen global de las propiedades de los discos alrededor de las supergigantes B[e]. En este trabajo se presenta una visión general de nuestro actual conocimiento sobre la estructura y la cinemática de estos discos a partir de la información brindada por los diferentes elementos trazadores.

Abstract / B[e] supergiants are a group of evolved massive stars in a short-lived transition phase. During this phase, these objects eject large amounts of material, which accumulates in a circumstellar ring or disk-like structure, revolving around the star on Keplerian orbits. In most objects, the disks seem to be stable over many decades. This guarantees these disks as ideal chemical laboratories to study molecule formation and dust condensation. Combining high-resolution optical and infrared spectroscopic data allows to search for emission features that trace the disk structure, kinematics, and chemical composition at different distances from the star. Certain forbidden emission lines of singly ionized or neutral metals, such as [Ca II] and [O I], are ideal tracers for the innermost gaseous (atomic) regions. Farther out, molecules form. While first-overtone bands of carbon monoxide (CO) mark the hot, inner rim of the molecular disk, more molecules are expected to form and to fill the space between the CO emitting region and the dust condensation zone. Observing campaigns have been initiated to search for these molecules and their emission features, in order to construct a global picture of the properties of the disks around B[e] supergiants. This paper presents an overview of the status of our knowledge about the structure and kinematics of B[e] supergiant stars' disks, based on currently available information from different observational tracers.

Keywords / circumstellar matter — infrared: stars — stars: early-type — stars: massive — supergiants

1. Introduction

During the post-main sequence evolution, massive ($> 8\,\mathrm{M}_\odot$) stars can pass through several short-lived phases, in which they lose a substantial amount of mass via strongly enhanced mass loss, sometimes in the form of eruptions. The B[e] supergiants (B[e]SG), a sub-group of the B[e] stars, encompass one of these phases.

Initially, B[e] stars (or more precisely stars showing the B[e] phenomenon) were discovered by Geisel (1970), who found infrared (IR) excess emission in a sample of B-type emission-line stars with low-excitation emission lines (especially Fe II and [Fe II]). Follow-up infrared surveys (Allen & Swings, 1972; Allen, 1973, 1974; Allen & Glass, 1974, 1975) confirmed the findings by Geisel (1970) and revealed two distinct populations: (i) emission-line stars with normal stellar IR colors, and (ii) emission-line stars with IR excess emission due to hot dust. As it was unhandy to refer to stars in the latter group as "peculiar emission-line stars with forbidden lines and dust", the much shorter designation "B[e] stars" was introduced for these objects and utilized since then.

Subsequent identification of numerous objects with similar properties required the definition of general criteria. A classification scheme was introduced by Lamers et al. (1998), who proposed to sort the B[e] stars ac-

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cording to their evolutionary state. Besides pre-main sequence objects (Herbig Ae/B[e] stars), a few compact planetary nebula stars were found, as well as the high mass B[e]SGs. Also members of the group of symbiotic stars were identified. However, a large number of objects could not be assigned a proper evolutionary phase yet due to the lack of proper stellar parameters.

Here, we focus on the B[e]SGs. According to the classification scheme of Lamers et al. (1998), a star belongs to the group of B[e]SGs if it fullfills the following characteristics: a high luminosity of $\log L/L_{\odot} \geq 4.0$, indications of mass loss in the optical spectra, chemically processed material indicating an evolved nature, small photometric variability, 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 best-known sample of B[e]SGs resides in the Magellanic Clouds with 15 confirmed members (11 in the Large Magellanic Cloud (LMC) and 4 in the Small Magellanic Cloud (SMC), see Zickgraf, 2006) and seven new candidates, three in the LMC (see Dunstall et al., 2012; Levato et al., 2014) and four in the SMC (see Wisniewski et al., 2007; Graus et al., 2012). In the Galaxy, there are currently about 16 known B[e]SG candidates (see Kraus, 2009, plus the stars HD 62623 and AS 381). Here, the assignment of a supergiant status is typically hampered by the uncertain distances hence luminosities and by the sometimes variable character of the star requiring re-classification (e.g., Aret et al., 2016). In other galaxies, these objects are difficult to identify. So far, only two B[e]SGs were discovered in the Andromeda galaxy (Kraus et al., 2014), while spectroscopic surveys of evolved massive stars in Local Group galaxies hint towards many more possible candidates (e.g., Massey et al., 2007; Clark et al., 2012).

2. Observational evidence for disks around B[e]SGs

Based on the spectral characteristics, Zickgraf et al. (1985) proposed the so-called hybrid-wind model, in which the stars possess a classical (i.e., fast, low-density) line-driven wind in polar direction and a slow, high-density wind in equatorial direction. The latter was assigned the term “outflowing disk”.

Besides the hybrid character of their spectra, B[e]SGs display spectral energy distributions with an IR excess emission (see, e.g., Zickgraf et al., 1986) that is much stronger than what is expected from pure free-free emission from a stellar wind or from an ionized disk as in classical Be stars (see Bonanos et al., 2009, 2010). This excess emission must hence be attributed to a large amount of hot or warm dust.

Optical linear polarization observations by Magalhaes (1992) revealed intrinsic polarization in all objects, which indicates a non-spherically symmetric geometry of their circumstellar envelopes. In some objects the intrinsic polarization values were very high, supporting the suggestion of a disk-like structure, which is seen under different viewing angles. Based on the good correlation between the amount of intrinsic polarization and the strength of the dust infrared excess, Magalhaes (1992) suggested that the circumstellar dust probably causes the optical polarization. Follow-up studies found that the observed intrinsic polarization would be in better agreement with electron scattering (Melgarejo et al., 2001) or a combination of electron scattering and scattering by dust (Zickgraf & Schulte-Ladbeck, 1989). In any case, a wind with a density contrast of 100 to 1000 between the equatorial and polar components was required, in fair agreement with results from spectroscopic observations (Zickgraf et al., 1989).

Additional support for the need of a high-density medium in the vicinity of the central object came from the detection of molecular emission. Besides indication for emission from the TiO bands at optical wavelengths in a few objects (Zickgraf et al., 1989; Torres et al., 2012), the near-IR CO first-overtone bands were the most prominent molecular features seen in many B[e]SGs (McGregor et al., 1988a,b, 1989; Morris et al., 1996). Until that time, CO band emission was predominantly reported from the hot, inner regions of pre-main sequence accretion disks (e.g., Geballe & Persson, 1987; Carr, 1989; Chandler et al., 1993). The excitation of the first-overtone bands requires a dense medium with temperatures between 2000 K and 5000 K, where the upper limit corresponds to the dissociation temperature of the molecule. With such a high dissociation temperature value, CO is the most stable molecule and can hence exist much closer to a (hot and luminous) star than any other molecule in the Universe. The emission from CO first-overtone bands is, therefore, regarded as a tracer for the inner rim of circumstellar molecular disks (e.g., Kraus et al., 2000).

With the advent of optical interferometry operating in the near- and mid-IR regimes, it became possible to spatially resolve gaseous and dusty environments, with focus on circumstellar disks. The current capability of interferometry is limited to IR bright objects. Therefore, only a few bright Galactic B[e]SGs could be observed (see also the recent summary by de Wit et al., 2014). These observations revealed that B[e]SGs are indeed surrounded by gaseous and dusty disks (see Domiciano de Souza et al., 2007, 2011; Millour et al., 2011; Cidale et al., 2012; Wang et al., 2012; Wheelwright et al., 2012,?). The high angular resolution technique involved in long baseline interferometry provides thus a powerful tool to study the structure of circumstellar environments of this type of objects.

3. Disk formation mechanisms

The evidences presented in the previous section imply that the disk material must be dense and cool enough to facilitate efficient molecule and dust condensation. As B[e]SGs are clearly evolved, the disks cannot be remnants from the pre-main sequence phase. Consequently, they must have formed from material released from the stellar surface. To test this hypothesis, the disk should contain material that was processed during earlier stages of the star’s evolution.

One important element is ^{13}C. As was shown by stellar evolution models (see, e.g., Ekström et al., 2012), the carbon isotope ratio $^{12}C/^{13}C$ rapidly decreases during the evolution of massive stars. Measuring this ratio in the disks of B[e]SGs would hence prove that the circumstellar material was indeed released from the stellar surface, and additionally provide information about the age of the star at the time of mass ejection. However, ^{13}C itself is difficult to detect; therefore, Kraus (2009) proposed to search for circumstellar emission from the isotopic molecule ^{13}CO in objects with confirmed ^{12}CO band emission. And in fact, ^{13}CO band emission was detected from all these B[e]SGs (Liermann et al., 2010; Kraus et al., 2013; Oksala et al., 2013), which was the ultimate proof for the enrichment of their circumstellar disks with processed material. Moreover, this ^{13}CO method has proven to be the ideal tool to disentangle unevolved (pre-main sequence) from evolved (B[e]SG) objects with circumstellar disks (e.g., Muratore et al., 2015).

However, the origin of a cool and dense disk in the close vicinity of the hot and luminous B[e]SGs is not understood yet. The most popular disk formation mechanism invokes binary interaction, up to merging. So far, a companion was identified in only six B[e]SGs, four Galactic (MWC 300, HD 327083, HD 62623, and GG Car) and two SMC objects (LHA 115-S 6 and LHA 115-S 18). No indication for binarity was found in any of the B[e]SGs in the LMC. In all four Galactic B[e]SGs, the disk is circumbinary (Wang et al., 2012; Millour et al., 2011; Wheelwright et al., 2012; Kraus et al., 2013), indicating that it could indeed originate from binary interaction. The situation is different for the SMC stars. LHA 115-S 6 was suggested to be a post-merger object in an original triple system (Langer & Heger, 1998; Podsiadlowski et al., 2006). The other object, 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). It is highly variable in both photometry and spectroscopy and displays Raman scattered emission (Torres et al., 2012), which is typically seen in symbiotic systems (e.g., Leedjärv et al., 2016, and references therein). Both SMC objects display variabilities and features in their spectra that clearly separate them from the other B[e]SGs in the Magellanic Clouds, in which no indication for binarity was found. Hence, binary interaction or merger seems to be a reasonable scenario for some objects, but is most likely not a universal mechanism.

Another possible scenario was the wind-compressed disk model of Bjorkman & Cassinelli (1993). It was proposed that the rapid rotation of a hot, massive star would cause a collision of the winds from both hemispheres in the equatorial plane, forming an outflowing disk. However, in that model the non-radial forces, e.g., due to the deformation of the stellar surface, were neglected, and follow-up investigations by Owocki et al. (1996) showed that these forces prevent the formation of a disk.

The observed hybrid-wind character of B[e]SGs also stimulated computations of wind ionization structures. Focus was thereby on the recombination of hydrogen in the equatorial wind, because the numerous emission lines from elements with low ionization potentials can only originate from regions in which hydrogen is predominantely neutral. In a heuristic approach with an artificial latitude dependence of the wind density, recombination of hydrogen could be achieved but high equatorial mass-loss rates were required (Kraus & Lamers, 2003; Zsargó et al., 2008). For a more realistic scenario of the wind structure of B[e]SGs, it was assumed that the stars might be (rapidly) rotating. The rotational distortion of the stellar surface results in the gravitational darkening of the equatorial regions, and hence the reduction of the number of ionizing photons in that region. However, at the same time the surface density decreases from the pole to the equator, resulting in hydrogen neutral equatorial zones, which are less dense than the polar regions —opposite of what is observed (Kraus, 2006).

A way out of the problematic depletion of the equatorial wind density was provided by the rotationally induced bistability mechanism (Pelupessy et al., 2000). Due to the latitute dependence of the wind temperature, Fe IV recombines into Fe III at a temperature of $\sim 25\,000$ K. Consequently, a different set of lines is driving the cooler wind, with a net effect of a sudden increase in mass flux towards the equatorial plane. However, the achievable density enhancement turned out to be a factor 10–100 too low compared to the observations. The situation is significantly better when the bistability mechanism is combined with the slow-wind solution discovered by Curé (2004). With such a scenario, proper density enhancements could be reached (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 (10–$30\,\mathrm{km\,s^{-1}}$).

A major prerequisite for all these models is rapid stellar rotation. Determination of proper rotation speeds of B[e]SGs is hampered by the absence of photospheric absorption lines in their mostly pure emission-line spectra. Hence, rotation velocities are currently known for only four objects. 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 latter object has a rotation speed of at least 40% and the rest of $\sim 75\%$ of their critical velocity, which is sufficiently high to initiate bistability. Whether all B[e]SGs are rapidly rotating is, however, unknown.

To finish this section, another type of wind solutions, the delta-slow solutions, should be mentioned. The advantage of these solutions is that stars are not required to rotate at high speeds. So far, these solutions were found in the winds of A-type supergiants, where they were capable to properly reproduce the observed wind velocities and mass-loss rates (Curé et al., 2011). Extension of the search for delta-slow solutions in hotter, i.e., B-type supergiant star winds is underway.

4. Disk structure and kinematics

The difficulties in finding a common scenario for the formation of disks around B[e]SGs could have two reasons. Either there exists no common scenario so that for each

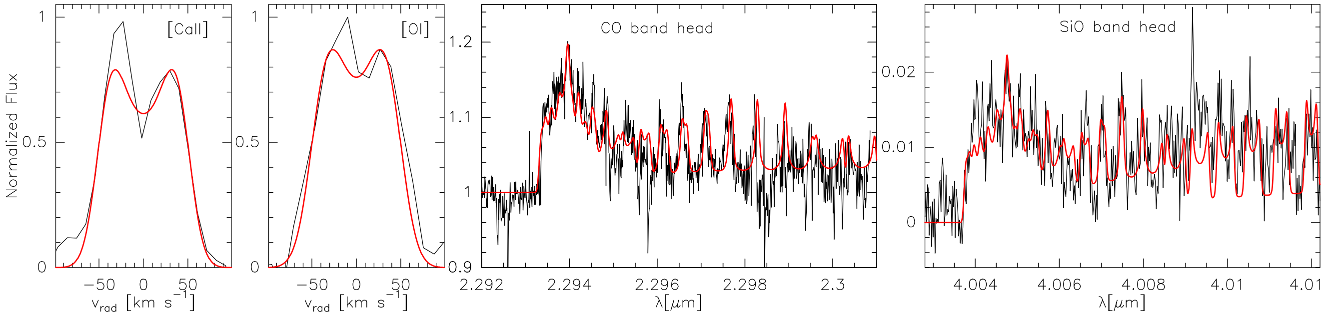

Figure 1: Model fits overplotted on the observed atomic and molecular tracers for the disk kinematics of HD 62623. Each emission feature represents a different gas ring revolving the star on a Keplerian orbit (see Table 1).

object a different (or a combination of more than one) mechanism might be at work, or we have not identified the correct scenario yet. Hence, to unravel possible disk formation mechanism(s), clearly more precise observational constraints are needed. Much effort has been made during the past decade to search for reasonable tracers that help to confine the real structure and, in particular, the kinematics of B[e]SG stars' disks.

4.1. Dust

Dust emission provides no kinematical information, but it can still be used to distinguish between different disk formation mechanisms via its total emission over the spectral energy distribution and distinct emission features resolved in IR spectra.

IR photometric observations over several decades showed no evidence for variability. If the dust particles condense from a wind or outflow, they should be formed continuously. Such a scenario disagrees with model computations of Porter (2003), who found that an equatorial wind, resulting for instance from the bi-stability mechanism, cannot reproduce the observed intense IR excess emission of B[e]SGs. This could indicate that the dust is not connected to an outflow but has accumulated at a certain distance from the star. Support for such an interpretation is provided by observations with the *Spitzer Space Telescope*. Kastner et al. (2010) collected mid-IR spectra of nine Magellanic Cloud B[e]SGs. All objects display crystalline silicate features, which result from grain processing within a long-lived, stable environment orbiting the central object. Moreover, in some objects additional emission from polycyclic aromatic hydrocarbons was identified. This dual-dust composition is a further proof for a stable dusty environment, in which non-equilibrium chemical processes had sufficient time to take place.

4.2. Molecules and chemistry

As mentioned earlier, molecular emission was detected from the disks of many B[e]SGs. As such, CO has proven to be particularly useful. Its first-overtone bands arise in the near-IR K-band regime, redwards of 2.293 μm. The intensity of the band emission is extremely sensitive to the temperature and density of the CO gas (Kraus, 2009), meaning that the observed emission typically originates from the hottest and densest region in which CO molecules can exist. With respect to a circumstellar disk, one would thus expect that the CO band emission marks the transition region between the molecular and the atomic disk parts and hence originates from a ring with a temperature close to the CO dissociation value.

The K-band near-IR surveys by Liermann et al. (2010) and Oksala et al. (2013), that were performed with the SINFONI spectrograph at the European Southern Observatory (ESO), were not only aimed at detecting emission from ^{13}CO, but also at determining the physical parameters (density, temperature) of the CO emitting rings. Surprisingly, modeling the molecular band emission delivered two important insights: (i) in each object the circumstellar CO gas has a different temperature spreading from 1900 K to 3200 K, and (ii) the values in all objects were far below the dissociation temperature of 5000 K. These results implied that the disks of B[e]SGs are not continuous structures extending from the stellar surface to far distances, hence refuting the outflowing disk scenario. Instead, the disk seems to be detached from the star, and the CO emission marks the inner rim of the molecular disk or ring.

The spectral resolution of $R \sim 4500$ provided by SINFONI was too low to resolve the kinematics of the molecular gas ring. For this, high-resolution observations are required. However, such spectrographs are rare and not always mounted. Therefore, only a dozen B[e]SGs could be observed with high resolution so far. In a survey of B[e] stars, eight Galactic B[e]SGs were 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 $R \sim 50\,000$. The observations focused on the first band head, which is formed by the superposition of several individual rotation-vibrational CO lines. An example of a CO band head is shown in the third panel of Fig. 1. In all objects, the shape of this band head displayed a blueshifted shoulder and a redshifted maximum. This is the characteristic band head structure expected for a rotating gas ring (e.g., Carr, 1995). Modeling the shape of the band heads delivered the line-of-sight rotation velocity of the CO gas (for details, see Muratore et al. 2012; Wheelwright et al. 2012; Cidale et al. 2012; Kraus et al. 2013, and Torres et al., this volume), and hence a first milestone in the determination of the global disk parameters.

CO is not the only molecule that will form in the cool environments of the circumstellar disks. As B[e]SGs are massive, their surface composition remains oxygen-rich throughout their entire evolution. Consequently, the ejected material, from which the disks form, has an oxygen-rich composition as well. This means that the number of oxygen atoms greatly exceeds the number of carbon atoms. In such an environment, all carbon atoms are locked in CO molecules, while the excess oxygen atoms can form other molecules and compounds. Which molecules will form severely depends on the elemental abundances as well as on the stability of the molecule, i.e., its dissociation energy.

One very promising diatomic molecule that will form in an oxygen-rich environment is silicon oxide (SiO). Compared to other oxygen-based molecules, it has, together with TiO, the second highest (after CO) dissociation energy and is hence the second most stable oxygen compound. Moreover, compared to titanium, the abundance of silicon is more than two orders of magnitude higher, favouring the formation of SiO over TiO. Theoretical computations of its rotation-vibrational first-overtone bands revealed that their emission falls into the *L*-band redwards of $4.004\,\mu$m. Kraus et al. (2015) selected four Galactic B[e]SGs with confirmed CO band emission and collected high-resolution *L*-band observations utilizing the CRIRES spectrograph at ESO. In all four objects rotationally broadened SiO band emission was discovered, and in all stars the SiO emission originates from disk regions which are cooler and have a smaller rotational velocity compared to the CO emitting region (Kraus et al., 2015). This finding is in agreement with a Keplerian rotating disk scenario. An example of the first SiO band head emission is shown in the last panel of Fig. 1.

The successful detection of SiO band emission from the disks of B[e]SGs encourages to search for further molecular species, which would bridge the gap to the dust condensation zone. Possible and promising candidates are NO, SO, OH, and water. All these oxygen compounds form with elements of significantly high abundances, and the molecules still have reasonably high dissociation temperatures. This guarantees that they form in relatively hot gas, i.e., hotter than the dust evaporation temperature of $\sim 1500\,$K. Searching for band emission from these molecules is certainly challenging, but any detection would greatly enhance our knowledge on the properties of the molecular disk regions.

4.3. Forbidden lines

The observational indications presented so far disprove the outflowing disk scenario as a unique formation mechanism of B[e]SG stars' disks. Instead, the derived properties hint towards a long-lived, stable outer dusty disk region and a detached molecular disk or ring. This raises the question of the characteristics of the atomic gas, which is located between the stellar surface and the molecular CO ring. To study this region, forbidden lines appear to be a viable tool.

Forbidden emission lines are typically associated with low density gas, such as the diluted, extended shells or lobes of planetary nebulae. However, not all forbidden lines are necessarily restricted to low-density gas, and transitions from various elements and ionization states are excellent tracers for different density and temperature regimes (e.g., Kraus et al., 2005).

One of the defining characteristics of B[e]SGs are forbidden emission lines from neutral or low-ionized elements, and [O I] emission is an intrinsic property of all B[e] stars. In optical spectra, typically three lines can be identified: [O I] $\lambda\lambda\,5577$, 6300, 6364. These lines did not catch much attention until (Kraus et al., 2007) performed a detailed analysis of the physical conditions of their formation regions. Surprisingly, these authors found that these lines can arise from regions in which the particle density can be rather high. The only crucial parameter is the electron density, because the excitation of the levels, from which the [O I] lines emerge, happens primarily via collisions with free electrons. To estimate the amount of free electrons, one needs to bear in mind that oxygen has the same ionization potential as hydrogen. Consequently, the [O I] lines form within a region, in which the electron density is strongly diminished due to the recombination of hydrogen.

A second important result of this analysis was the finding that the lines [O I] $\lambda\,5577$ and [O I] $\lambda\lambda\,6300$, 6364 are formed in physically distinct regions, because the excitation of the upper level, from which the [O I] $\lambda\,5577$ line emerges, requires significantly higher electron densities. In terms of a circumstellar Keplerian disk, this result implies that the line [O I] $\lambda\,5577$ should be formed closer to the star and should hence display a higher rotational velocity. And in fact, it was confirmed observationally, that the rotationally broadened double-peaked profiles of the [O I] $\lambda\,5577$ lines are wider than those of, e.g., the [O I] $\lambda\,6300$ lines (Kraus et al., 2010; Aret et al., 2012; Muratore et al., 2012).

Besides [O I], the [Ca II] $\lambda\lambda\,7291$, 7324 lines were recently identified by Aret et al. (2012) as an additional essential tracer for the gaseous inner disk regions. The ionization potential of Ca II is much higher than for O I. Hence, the emission of [Ca II] might originate from regions in which hydrogen is not necessarily neutral. Alike for [O I], the [Ca II] lines in the studied stars displayed double-peaked profiles indicating rotational broadening. Moreover, in all objects the width of the profiles was comparable to or even broader than the one of the [O I] $\lambda\,5577$ lines. This implies that also the atomic gas disk is in Keplerian rotation and that the [Ca II] lines originate from disk regions closer to the star than [O I] $\lambda\,5577$ (Aret et al., 2012, 2016). The forbidden emission lines of [O I] and [Ca II] thus form a valuable, complementary set of tracers for the properties of the gas disk close to the star.

The best studied object to date is HD 62623. For this star, the kinematics of its disk could be determined from several tracers (see Fig. 1): from the [Ca II] and [O I] lines for the atomic gas disk, and from the CO and SiO band heads for the molecular disk. Moreover, the detached Keplerian rotating gas disk as well as the dusty disk

Table 1: Velocity and distance of the rings around HD 62623.

Tracer	$v_{\rm rot}$ [km s^{-1}]	r [au]	Reference
[Ca II] λ 7324	72	1.67	Aret et al. (2016)
[O I] λ 6300	68	1.87	Aret et al. (2016)
CO	53	3.08	Muratore et al. (2012)
SiO	48	3.75	Kraus et al. (2015)
Dust		4.20	Millour et al. (2011)

were resolved by interferometry (Millour et al., 2011). For a distance to the object of 700 pc (Chentsov et al., 2010), a disk inclination of 38°(Millour et al., 2011), and a mass of about 10 $M_\odot$ (Aret et al., 2016), the rotational velocities and the corresponding distances from the star were computed and listed in Table 1.

These results suggest that, at least from a kinematical point of view, HD 62623 is surrounded by a disk spreading from the inner, ionized region traced by the lines of [Ca II] all the way out to the dusty region. That this scenario cannot be correct follows from the lack of hot CO gas. As no CO band emission with a gas temperature close to the CO dissociation temperature is observed, the only logical explanation is that the atomic and molecular regions are confined into individual rings.

The scenario of multiple rings is supported by the profiles of the forbidden emission lines resolved in high-resolution spectra. These clearly showed indication for multiple components (Muratore et al., 2012). In addition, a detailed analyis for the object LHA 120-S 73 revealed that the profiles of each of the two sets of forbidden lines consist of contributions from two physically distinct rings (Torres et al., this volume).

5. Variability and inhomogeneities

The findings of multiple gas rings around LHA 120-S 73 is not the only peculiarity. This object also shows indications for density inhomogeneities in the molecular ring, which is evident from strong variations in the CO band intensity while the rotation velocity remains unchanged (Torres et al., this volume).

Although K-band observations of B[e]SGs are sparse, variability in the CO bands was seen in four more objects. Torres et al. (in preparation) found that the CO band intensity in the SMC star LHA 120-S 35 has decreased by about a factor of two compared to observations of Oksala et al. (2013) taken two years earlier. A sudden appearance of previously undetected CO bands was reported from the SMC star LHA 115-S 65 (Oksala et al., 2012) and from the Galactic object CI Cam about one month after its spectacular outburst in 1998 (Clark et al., 1999). While in the latter object the CO band emission has disappeared again (Liermann et al., 2014), nothing is known about the current state of these emission bands in the former object. And the Galactic object HD 327083 displayed variations in its CO band heads within a period of one month (Kraus et al., 2013). These variations are caused by changes in the peak intensities in the asymmetric double-peaked rotation-vibration lines, most likely associated with a clumpy, molecular rotating ring similar to LHA 120-S 73.

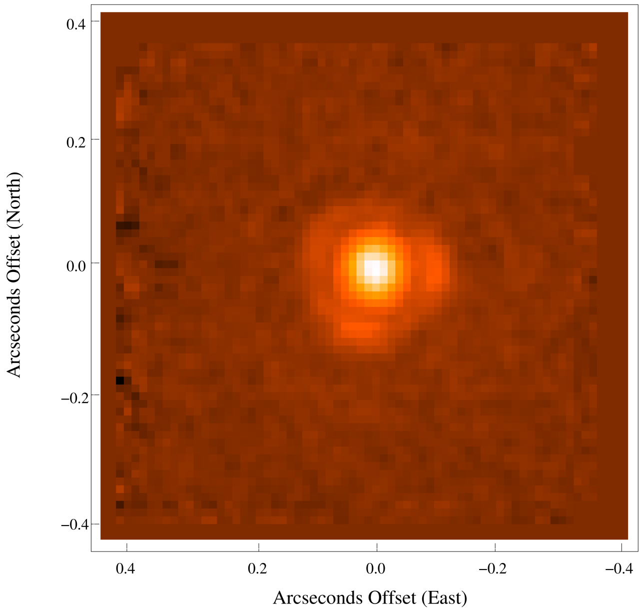

Figure 2: Spatially resolved first-overtone CO band emission around MWC 137 indicating that the circumstellar molecular gas is distributed within multiple, clumpy ring structures.

Finally, the Galactic object MWC 137 was recently observed in the K-band with SINFONI at ESO in high spatial resolution mode (Kraus et al., in preparation). Based on the Integral Field Unit (IFU) capabilities of SINFONI, the spatial distribution of the molecular emission was resolved. Clearly, the CO band emission originates from multiple, clumpy ring structures (see Fig. 2). These observations imply that the circumstellar environments of B[e]SGs have highly complex structures.

6. Conclusions and future perspectives

The thorough studies devoted to the structure and kinematics of the circumstellar environments of B[e]SGs revealed that these objects appear to be surrounded by multiple rings of gas an dust. The kinematics derived from the profiles of the forbidden lines and the shapes of the molecular band head structures suggest that these rings are most likely revolving the objects on Keplerian orbits. Moreover, density inhomogeneities seem to be a common property, especially within the molecular rings.

This raises the question of the origin of these (clumpy) ring structures. Whether they result indeed from interactions in (close) binary systems with yet unidentified companions, or maybe from instabilities within the base of the wind, maybe triggered by stellar pulsations as was recently found in a classical blue supergiant (Kraus et al., 2015), requires further detailed investigations.

The currently available observational data for B[e]SGs is still rather incomplete. In particular, high-resolution near- and mid-IR spectroscopic observations (including IFU or imaging) for all objects are vital to search for complementary molecular and dust emission features, based on which a better comprehension of the properties of the circumstellar environments beyond the CO band emitting region can be achieved. Only with the complete information on the global structure and dynamics within the circumstellar envelopes of B[e]SGs it will become possible to identify specific formation paths, which will help to improve our understanding of the evolution of these enigmatic objects.

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References

Allen D. A., 1973, MNRAS, 161, 145
Allen D. A., 1974, MNRAS, 168, 1
Allen D. A., Glass I. S., 1974, MNRAS, 167, 337
Allen D. A., Glass I. S., 1975, MNRAS, 170, 579
Allen D. A., Swings J. P., 1972, Astrophys. Lett., 10, 83
Aret A., et al., 2012, MNRAS, 423, 284
Aret A., Kraus M., Šlechta M., 2016, MNRAS, 456, 1424
Bjorkman J. E., Cassinelli J. P., 1993, ApJ, 409, 429
Bonanos A. Z., et al., 2010, AJ, 140, 416
Bonanos A. Z., et al., 2009, AJ, 138, 1003
Carr J. S., 1989, ApJ, 345, 522
Carr J. S., 1995, Ap&SS, 224, 25
Chandler C. J., et al., 1993, ApJL, 412, L71
Chentsov E. L., Klochkova V. G., Miroshnichenko A. S., 2010, Astrophysical Bulletin, 65, 150
Cidale L. S., et al., 2012, A&A, 548, A72
Clark J. S., et al., 2013, A&A, 560, A10
Clark J. S., et al., 2012, A&A, 541, A146
Clark J. S., et al., 1999, A&A, 348, 888
Curé M., 2004, ApJ, 614, 929
Curé M., Cidale L., Granada A., 2011, ApJ, 737, 18
Curé M., Rial D. F., Cidale L., 2005, A&A, 437, 929
de Wit W. J., Oudmaijer R. D., Vink J. S., 2014, Advances in Astronomy, 2014, 10
Domiciano de Souza A., et al., 2011, A&A, 525, A22
Domiciano de Souza A., et al., 2007, A&A, 464, 81
Dunstall P. R., et al., 2012, A&A, 542, A50
Ekström S., et al., 2012, A&A, 537, A146
Geballe T. R., Persson S. E., 1987, ApJ, 312, 297
Geisel S. L., 1970, ApJL, 161, L105
Graus A. S., Lamb J. B., Oey M. S., 2012, ApJ, 759, 10
Gummersbach C. A., Zickgraf F.-J., Wolf B., 1995, A&A, 302, 409
Kastner J. H., et al., 2010, AJ, 139, 1993
Kraus M., 2006, A&A, 456, 151
Kraus M., 2009, A&A, 494, 253
Kraus M., Borges Fernandes M., de Araújo F. X., 2007, A&A, 463, 627
Kraus M., Borges Fernandes M., de Araújo F. X., 2010, A&A, 517, A30
Kraus M., et al., 2005, A&A, 441, 289
Kraus M., et al., 2008, A&A, 487, 697
Kraus M., et al., 2014, ApJL, 780, L10
Kraus M., et al., 2013, in Massive Stars: From alpha to Omega Tracing the mass-loss history of B[e] supergiants. p. 160
Kraus M., et al., 2015, A&A, 581, A75
Kraus M., et al., 2000, A&A, 362, 158
Kraus M., Lamers H. J. G. L. M., 2003, A&A, 405, 165
Kraus M., et al., 2015, ApJL, 800, L20
Kraus M., et al., 2013, A&A, 549, A28
Lamers H. J. G. L. M., et al., 1998, A&A, 340, 117
Langer N., Heger A., 1998, in Hubert A. M., Jaschek C., eds, B[e] stars Vol. 233 of Astrophysics and Space Science Library, B[e] Supergiants: what is Their Evolutionary Status?. p. 235
Leedjärv L., et al., 2016, MNRAS, 456, 2558
Levato H., Miroshnichenko A. S., Saffe C., 2014, A&A, 568, A28
Liermann A., et al., 2010, MNRAS, 408, L6
Liermann A., et al., 2014, MNRAS, 443, 947
Magalhaes A. M., 1992, ApJ, 398, 286
Maravelias G., et al., 2014, MNRAS, 438, 2005
Massey P., et al., 2007, AJ, 134, 2474
McGregor P. J., Hyland A. R., Hillier D. J., 1988a, ApJ, 324, 1071
McGregor P. J., Hyland A. R., Hillier D. J., 1988b, ApJ, 334, 639
McGregor P. J., Hyland A. R., McGinn M. T., 1989, A&A, 223, 237
Melgarejo R., et al., 2001, A&A, 377, 581
Millour F., et al., 2011, A&A, 526, A107
Morris P. W., et al., 1996, ApJ, 470, 597
Muratore M. F., et al., 2012, in Carciofi A. C., Rivinius T., eds, Circumstellar Dynamics at High Resolution Vol. 464 of Astronomical Society of the Pacific Conference Series, Unveiling the Structure and Kinematics of B[e] Stars' Disks From FEROS and CRIRES Spectra. p. 67
Muratore M. F., Kraus M., de Wit W. J., 2012, BAAA, 55, 123
Muratore M. F., et al., 2015, AJ, 149, 13
Oksala M. E., et al., 2012, MNRAS, 426, L56
Oksala M. E., et al., 2013, A&A, 558, A17
Owocki S. P., Cranmer S. R., Gayley K. G., 1996, ApJL, 472, L115
Pelupessy I., Lamers H. J. G. L. M., Vink J. S., 2000, A&A, 359, 695
Podsiadlowski P., Morris T. S., Ivanova N., 2006, in Kraus M., Miroshnichenko A. S., eds, Stars with the B[e] Phenomenon Vol. 355 of Astronomical Society of the Pacific Conference Series, Massive Binary Mergers: A Unique Scenario for the sgB[e] Phenomenon?. p. 259
Porter J. M., 2003, A&A, 398, 631
Torres A. F., et al., 2012, MNRAS, 427, L80
Wang Y., et al., 2012, A&A, 545, L10
Wheelwright H. E., et al., 2012, A&A, 538, A6
Wheelwright H. E., et al., 2012, A&A, 543, A77
Wisniewski J. P., et al., 2007, ApJ, 670, 1331
Zickgraf F., 2000, in Smith M. A., Henrichs H. F., Fabregat J., eds, IAU Colloq. 175: The Be Phenomenon in Early-Type Stars Vol. 214 of Astronomical Society of the Pacific Conference Series, The Connection with B[e] stars. p. 26
Zickgraf F.-J., 2006, in Kraus M., Miroshnichenko A. S., eds, Stars with the B[e] Phenomenon Vol. 355 of Astronomical Society of the Pacific Conference Series, B[e] Supergiants in the Magellanic Clouds. p. 135
Zickgraf F.-J., Schulte-Ladbeck R. E., 1989, A&A, 214, 274
Zickgraf F.-J., et al., 1986, A&A, 163, 119
Zickgraf F.-J., et al., 1989, A&A, 220, 206
Zickgraf F.-J., et al., 1985, A&A, 143, 421
Zsargó J., Hillier D. J., Georgiev L. N., 2008, A&A, 478, 543