*The Origin of Outflows in Evolved Stars*
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# Environments of evolved massive stars: evidence for episodic mass ejections

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**Abstract.** The post-main sequence evolutionary path of massive stars comprises various transition phases, in which the stars shed large amounts of material into their environments. Our studies focus on two of them: B[e] supergiants and yellow hypergiants, for which we investigate the structure and dynamics within their environments. We find that each B[e] supergiant is surrounded by a unique set of rings or arc-like structures. These structures are either stable over time or they display high variability, including expansion and dilution. In contrast, yellow hypergiants are embedded in multiple shells of gas and dust. These objects are famous for their outburst activity. Moreover, the dynamics in their extended atmospheres imply an enhanced pulsation activity prior to outburst. The physical mechanism(s) leading to episodic mass ejections in these two types of stars is still uncertain. We propose that strange-mode instabilities, excited in the inflated envelopes of these objects, play a significant role.

**Keywords.** supergiants, circumstellar matter, stars: mass loss, stars: winds, outflows

## 1. Introduction

Massive stars ($M > 8\,\mathrm{M}_\odot$) are important cosmic engines. With their life-long mass loss they constantly supply material and energy into their environment, influencing and driving the chemical and dynamical evolution of their host galaxies. The post-main sequence evolution of massive stars bears many unsolved issues, one of them being the question of the triggering mechanism for eruptions and mass ejections occurring in several evolutionary transition phases. As mass loss is crucial for the fate of a massive star, understanding the mechanisms behind mass ejection phases and exploring the amount of mass lost during such events is essential. Our research focuses mainly on two groups of evolved massive stars, the hot B[e] supergiants (B[e]SGs) and the cool yellow hypergiants (YHGs). Both types of objects display clear indication for circumstellar material in form of disks, rings, or shells of material, which must have been released from the star.

## 2. The environments of B[e] supergiants

B[e] supergiants form a sub-group of the classical B-type supergiants. As such, their temperatures range from 10 000 K to 25 000 K, and they spread over the entire luminosity range of massive stars ($\log L/L_{\odot} \geq 4$). The major characteristics of B[e]SGs is their hybrid appearance (Zickgraf *et al.* 1986). The ultraviolet spectra imply a powerful, high-ionized wind driven by these luminous stars. In contrast to this, pronounced emission-line spectra at optical and infrared wavelengths, a strong infrared excess, and highly polarized emission suggest the co-existence of a dense, disk-like environment composed of low-ionized and neutral gas, along with a considerable amount of warm dust.

To unveil the density structure and dynamics of the circumstellar matter we first focused on molecules, which can be expected to form within the dense, disk-like environments. The most stable and most abundant molecule is CO. We have surveyed B[e]SGs in the $K$-band and detected intense emission from the CO first-overtone bands in the spectra of about 50% of the objects (Muratore *et al.* 2012; Oksala *et al.* 2013). Modeling of these emission bands provides column density, temperature, and kinematics of the molecular gas (Kraus *et al.* 2000). We found that in all objects the CO emission arises in a dense, rotating ring of gas. The CO temperatures were thereby found to be considerably lower than the CO dissociation temperature (Liermann *et al.* 2010; Cidale *et al.* 2012; Oksala *et al.* 2013), implying that the molecular gas must be localized in detached structures rather than being part of a continuous circumstellar outflowing disk.

Furthermore, in all objects displaying CO band emission we also found emission from the isotopic molecule $^{13}$CO. In all cases, the ratio $^{12}$C/$^{13}$C is significantly smaller than the initial, interstellar value of $\sim 90$, reinforcing that the circumstellar material has been released from the evolved supergiant star (Kraus 2009). In fact, the finding of circumstellar molecular gas enriched in $^{13}$CO in some B[e] stars could even be used to classify these objects as evolved supergiants (Muratore *et al.* 2015; Kraus *et al.* 2020).

The surface of massive stars is oxygen-rich (O/C $> 1$) and so is the material released into the environment. All excess oxygen that is not bound in CO can thus form other compounds with elements of high abundance and/or high binding energy, and so far we searched for and detected SiO first-overtone band emission in four B[e]SGs (Kraus *et al.* 2015a), and six objects possibly display TiO emission† (Zickgraf *et al.* 1989; Kraus *et al.* 2016; Torres *et al.* 2018). The physical conditions in the SiO band forming region, obtained from modeling of the emission spectra, support the scenario of detached rotating molecular gas ring(s). Modeling of TiO emission is in progress.

Neutral and low-ionized gas provides additional tracers for density and dynamics. These are the lines of [O I]$\lambda\lambda$5577, 6300, 6364 and [Ca II]$\lambda\lambda$7291,7324 (Kraus *et al.* 2010; Aret *et al.* 2012), which can be excited in relatively high-density environments. Their profiles provide further evidence for rotation in a (quasi-)Keplerian manner of the circumstellar matter. Detailed modeling of their profile shapes revealed that the gas is localized in a series of rings, in some cases co-existing with the molecules and with varying, often alternating density (Kraus *et al.* 2016; Torres *et al.* 2018). Moreover, the number of rings and their distribution around the stars is unique for each object (Maravelias *et al.* 2018). In some B[e]SGs, the emission from these rings decreases in strength with time, up to complete disappearance (Torres *et al.* 2012; Liermann *et al.* 2014; Kraus *et al.* 2020), suggesting expansion and dilution of the ejected material. In others, the profiles display asymmetries and time variability implying gaps in the rings or spiral-arm like structures (Maravelias *et al.* 2018; Torres *et al.* 2018), whereas in one

† But we want to caution that not all stars displaying CO band emission have been systematically searched for emission from other molecules yet (for an overview, see Kraus 2019).

object we noted a sudden appearance of CO band emission (Oksala *et al.* 2012), likely due to the accumulation of the steadily decelerating outflowing material (Kraus *et al.* 2010).

Compared to classical B supergiants, B[e]SGs are rare with currently 33 confirmed members and 25 candidates within the Milky Way and the closest Local Group galaxies (Kraus 2019). This could mean that B[e]SGs comprise a short transition phase in the evolution of massive stars, characterized by episodes of enhanced mass loss. In this respect it is noteworthy that a significant number of B[e]SGs display besides the molecular and dusty rings on small scales also nebulae and ejecta on much larger scales speaking for previous mass-loss events (Kraus *et al.* 2021; Liimets et al. in prep.).

## 3. Yellow Hypergiants and their outburst activity

Yellow hypergiants populate a region in the HR diagram that spreads from 4000 − 8000 K in temperature and from $5.4 \leq \log L/L_{\odot} \leq 5.8$ in luminosity. These stars have started their lives most likely with an initial mass of $\sim 20$–$40\,M_{\odot}$ and are now on their blue-ward evolution after having passed through the red supergiant (RSG) state. The number of currently known YHGs is small. Just a handful of objects in the Milky Way and its closest neighboring galaxies are confirmed YHGs, and a similar number of objects has the status of a YHG candidate (de Jager 1998; Kourniotis et al., submitted).

YHGs have developed a pronounced core-envelope structure, and their strongly inflated and rarefied envelopes make them susceptible to even tiniest disturbances. It is therefore not surprising that the YHG state is characterized by outbursts during which the stars shed large amounts of material into their environments. Each outburst is identified by a steep drop in stellar brightness accompanied by an apparent decrease in effective temperature so that the star seemingly undergoes an excursion back to the red, cool side of the HR diagram. With the dilution of the ejected material, the star finally re-appears with its real effective temperature. The ejected matter expands and cools, providing an ideal environment for molecule and dust formation. It is noteworthy that, alike the B[e]SGs, about half of the YHG stars and candidates display CO first-overtone bands in emission (e.g., Lambert et al. 1981; Davies *et al.* 2008; Oksala *et al.* 2013) indicating a dense and warm molecular environment. The significantly cooler circumstellar dust may also become observable in form of rings or shells around the star, as in the case of IRAS 17163-3907, which seems to have had three distinct mass-ejection episodes within a 100 year period leading to three shells encompassing the central object (Lagadec et al. 2011; Koumpia et al. 2020; Oudmaijer et al., these proceedings).

A further YHG, famous for its outbursts, is the Galactic object $\rho$ Cas. It is one of the four northern Galactic YHGs that we monitor. The star underwent at least four outbursts since the mid 1940ies, with the most recent one occurring in 2013 (Kraus *et al.* 2019). The strength and intensity of these events is highly variable, and dust formation was recorded so far only in relation to the intense mass-ejection phase in 1945–1947 (Jura & Kleinmann 1990). During the quiescence phases the star undergoes cyclic light variability with quasi-periods between 200 and 400 days.

The temperature sensitive line ratio Fe I $\lambda$6431/Fe II $\lambda$6433 reveals that the atmospheric temperature closely follows the light variability. A temperature increase during stellar brightening phases and decrease during phases of stellar dimming resembles the behavior of radially pulsating stars. Additional support for pulsation activities in the envelope of $\rho$ Cas is provided by the measured radial velocity variations of absorption lines that form in different atmospheric depths. Noteworthy is the enhanced dynamical activity in the outermost layers prior to the 2013 eruption. The same behavior had been recorded before the outburst in 2000 (Lobel *et al.* 2003).

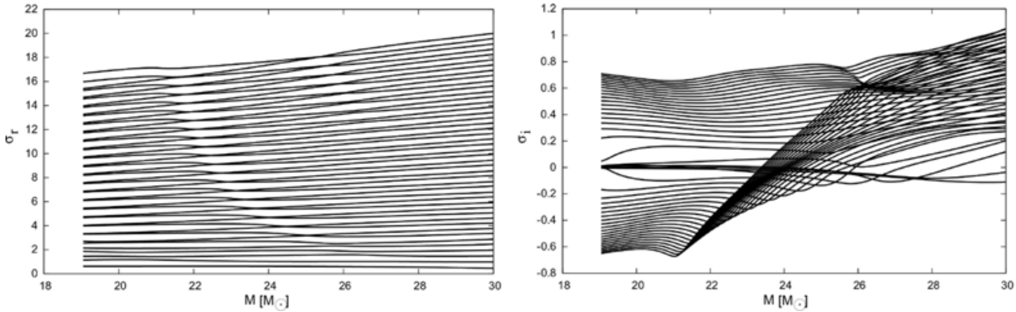


**Figure 1.** Real parts (= pulsation periods, left panel) and the imaginary parts (right panel) of the eigenfrequencies, which are normalized to the global free-fall time. Positive imaginary parts correspond to damped modes, and negative ones to unstable modes. The computations have been performed for $T_{\rm eff} = 7000$ K and $\log L/L_{\odot} = 5.7$, matching the observed values of $\rho$ Cas.

Our observations also revealed emission in some Fe I lines (e.g., Fe I $\lambda$6359) as well as in the lines of [Ca II]$\lambda\lambda$7291,7324 (Kraus *et al.* 2019). These narrow emission lines are static and are centered on the systemic velocity. They are most prominent during phases of maximum stellar brightness, that is when the star is hottest and hence compact, whereas strong atmospheric absorption conceals the emission during phases of minimum brightness. These findings reinforce the circumstellar nature of the line emission.

Finally, we have identified a trend of decreasing duration and time interval between individual outbursts (Maravelias & Kraus 2021). The increased activity might suggest that $\rho$ Cas is preparing for another major eruption.

## 4. Pulsation instabilities as trigger for episodic mass ejections

Although B[e]SGs and YHGs populate distinct temperature regimes in the HR diagram, members of both classes display clear signs for episodic mass loss. The observed diversity of rings or arcs around B[e]SGs, and the outburst activity and resolved distinct circumstellar shells around some YHGs require a physical mechanism that is suitable to repeatedly lift matter from the stellar surface into the environments of these objects at detectable rates. Considering their high luminosity over mass ratios, evolved massive stars, particularly post-RSG stars, are ideal candidates for the excitation of strange-mode instabilities (Gautschy & Glatzel 1990; Glatzel 1994). These instabilities have been proposed to drive time-variable mass loss (Glatzel *et al.* 1999) and in fact, strange-mode pulsation and its correlation with phases of enhanced mass loss has been found in the $\alpha$ Cygni variable 55 Cyg from both an observational (Kraus *et al.* 2015b) and a theoretical approach (Yadav & Glatzel 2016). Motivated by these results, we have started to systematically investigate the entire upper HR diagram to identify constellations in stellar parameters that favor the excitation of strange-modes.

We first focused on the temperature and luminosity domain of the YHGs and performed a stability analysis with respect to linear nonadiabatic radial perturbations. A detailed description of these investigations will be published elsewhere. Here, we present our results for parameters matching $\rho$ Cas. We fixed the effective temperature at 7000 K, the stellar luminosity at $\log L/L_{\odot} = 5.7$, and computed models for a range of masses around the value of $24.1 \pm 4.7\,M_{\odot}$ estimated from observations. Each model provides a sequence of complex eigenfrequencies, $\sigma$, consisting of the fundamental and overtone modes. These eigenfrequencies, normalized to the global free-fall time, are shown in Figure 1. The left panel displays the real parts of $\sigma$, which represent the pulsation frequencies. For each mass we find that many, especially high-overtone modes are excited. Besides the expected homogeneous set of modes we note many modes that are crossing the regular

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ones. These crossing modes can be identified in the right panel of Figure 1 with negative imaginary parts of $\sigma$, meaning that these are all unstable with high growth rates. On the other hand, the homogeneous set of modes have all positive imaginary parts and are consequently stable, that is damped. It is noticeable that the instabilities set in around a stellar mass of $\sim 24\,M_{\odot}$, which is the most likely mass of $\rho$ Cas. In as how much these instabilities are indeed able to drive mass loss from the star needs to be investigated with the help of nonlinear simulations. This work is currently in progress, and first tentative test computations have shown that these instabilities occur also in the non-linear regime.

## 5. Conclusions

We have presented evidence for episodic mass loss in two types of evolved massive stars: B[e]SGs and YHGs, and we have proposed that strange-mode instabilities might be a suitable mechanism to trigger phases of enhanced mass loss and mass eruptions in these objects. Strange-mode instabilities have been detected in other types of blue supergiants such as the $\alpha$ Cygni variables underlining their suitability and supporting our hypothesis. As a prerequisite for the occurrence of strange mode instabilities a significantly decreased stellar mass (for a fixed luminosity) is favorable. This means that particularly stars in their blue-ward (e.g. post-RSG) evolution are ideal candidates, because massive stars typically lose large amounts of mass during their red-most evolutionary state. While YHGs are definitely post-RSG stars, the situation is less clear for the B[e]SGs. These objects typically display emission-line spectra, rendering it difficult to assess surface abundances and hence to constrain their evolutionary state. Moreover, it was possible to find indication for possible pulsation activity in only one B[e]SG so far (Kraus *et al.* 2016). Some B[e]SGs have been proposed to be indeed post-RSGs based on the strong enrichment of their circumstellar matter in $^{13}$CO. In addition, Davies *et al.* (2007) suggested that the mass loss in YHGs might change from initially spherical to axisymmetric at later states of the YHG phase so that YHGs might develop into B[e]SGs. While such a scenario will work only in the specific mass range of YHGs, this is still an interesting idea and needs to be investigated in more detail.

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