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Similarities in the Structure of the Circumstellar Environments of B[e] Supergiants and Yellow Hypergiants

A. Aret,[1] I. Kolka,[1] M. Kraus,[1,2] and G. Maravelias[2]

[1]*Tartu Observatory, 61602 Tõravere, Tartumaa, Estonia;* aret@to.ee
[2]*Astronomický ústav AVČR, v.v.i., Ondřejov, Czech Republic*

Abstract. Yellow hypergiants (YHGs) and B[e] supergiants (B[e]SGs), though in different phases in their evolution, have many features in common. This is partly due to the fact that both types of objects undergo strong, often asymmetric mass loss, and the ejected material accumulates in shells, rings, or disk-like structures, giving rise to emission from warm molecules and dust. We performed an optical spectroscopic survey of northern Galactic emission-line stars aimed at identifying tracers for the structure and kinematics of circumstellar environments. We identified two sets of lines, [O I] and [Ca II], which originate from the disks of B[e]SGs. The same set of lines is observed in V1302 Aql and V509 Cas, which are both hot YHGs. While V1302 Aql is known to have a disk-like structure, the kinematical broadening of the lines in V509 Cas suggests a Keplerian disk or ring around this star like their hotter B[e]SG counterparts.

1. Introduction

Despite their different evolutionary phases, B[e] supergiants (B[e]SGs) and yellow hypergiants (YHGs) share a number of common properties regarding their circumstellar environments. Both types of stars experience phases of strongly enhanced mass-loss, and the released material accumulates in multiple shells, bipolar nebulae, and/or disk-like structures, often veiling the central object. Moreover, the physical conditions in the envelopes of these stars are ideal for molecule and dust condensation. Warm molecular gas is obvious from CO band emission (e.g., McGregor, Hyland, & Hillier 1988; Gorlova et al. 2006; Oksala et al. 2013), and the dust is traced by its infrared excess emission (Zickgraf et al. 1986; Oudmaijer et al. 1996). While the enhanced mass-loss and eruptions in YHGs are probably caused by an increased pulsation activity, the physical mechanism leading to the formation of the dense winds and Keplerian disks and rings observed in B[e]SGs is yet unknown, although pulsations might play a role as well (Kraus et al. 2016).

The evolutionary state of B[e]SGs is also still unclear. Based on the observed enrichment in ^{13}C in their disks, Oksala et al. (2013) proposed that B[e]SGs have just evolved off the main sequence. On the other hand, their dense dusty environments seem to speak in favor of a post-red supergiant (post-RSG) evolutionary phase. YHGs may have passed through the RSG phase and evolved back to the blue, hot side of the Hertzsprung-Russell diagram (HRD). On their journey, they encounter the Yellow Void region where their envelopes become unstable and are successively ejected during a series of outbursts (e.g., Lobel et al. 2003; Oudmaijer et al. 2009). While the progenitor stars of B[e]SGs spread over the full mass range of massive stars ($M > 8\,M_\odot$), YHGs are only found in the mass range $25\,M_\odot < M < 50\,M_\odot$. Nevertheless, it has been suggested that YHGs may be evolving toward the B[e] supergiant phase (Davies, Oudmaijer, & Sahu 2007). Such a possible evolutionary link in this specific mass range should be investigated.

2. Observations

During the years 2010–2015, we carried out an optical spectroscopic survey of a large sample of Galactic northern emission-line stars in diverse evolutionary states (pre-main sequence stars, classical Be stars, B[e] stars including two B[e]SGs, compact planetary nebulae, and YHGs). This survey was aimed at identifying characteristic emission features that help to study the structure and kinematics of dense circumstellar environments. Motivated by the results from previous studies (Kraus, Borges Fernandes, & de Araújo 2007, 2010; Aret et al. 2012), we focused on the strategic forbidden emission lines of [O I] and [Ca II], whose appearance requires high-density environments combined with large emitting volumes, conditions that are typically met in geometrically thick and dense circumstellar disks (Aret, Kraus, & Šlechta 2016).

The observations were obtained using the Coudé spectrograph attached to the Perek 2 m telescope at Ondřejov Observatory (Šlechta & Škoda 2002). Spectra were taken in three different wavelength regions: around Hα (6250–6760 Å, $R \simeq 13\,000$) in the region of the [Ca II] $\lambda\lambda$7291, 7324 Å lines (6990–7500 Å, $R \simeq 15\,000$) and in the region of the Ca II IR triplet (8470–8980 Å, $R \simeq 18\,000$). The H α region also encloses the two [O I] $\lambda\lambda$6300, 6364 Å lines.

Table 1. Identification of disk tracers in B[e]SGs (top) and YHGs (bottom).

Object		Sp.type	Class	[O I]	[Ca II]	Ca II IR
V1478 Cyg	MWC 349A	B0–B1.5 I	B[e]SG	+	+	emis
3 Pup	HD 62623	A2.7 Ib	A[e]SG	+	+	emis
V1302 Aql	IRC+10420	A2–F8 Ia	hot YHG	+	+	emis
V509 Cas	HR 8752	A7–G5 Ia	hot YHG	+	+	emis/abs
ρ Cas	HD 224014	F0–G7 Ia	cool YHG	–	+	abs
V1427 Aql	HD 179821	F3–G5 Ia	cool YHG	–	+	abs

The survey contains four YHGs, which we monitor to study variations in their environments and to trace their outburst activity during their journey through the Yellow Void instability region. They are discussed in the following in comparison to the two B[e]SGs (Table 1), which were presented and discussed in detail in Aret et al. (2016). The objects are listed in Table 1 together with a brief summary of the important spectral features. Portions of the optical spectra of the YHGs covering the strategic lines are shown in Fig. 1 in comparison to the spectrum of the A[e]SG star 3 Pup.

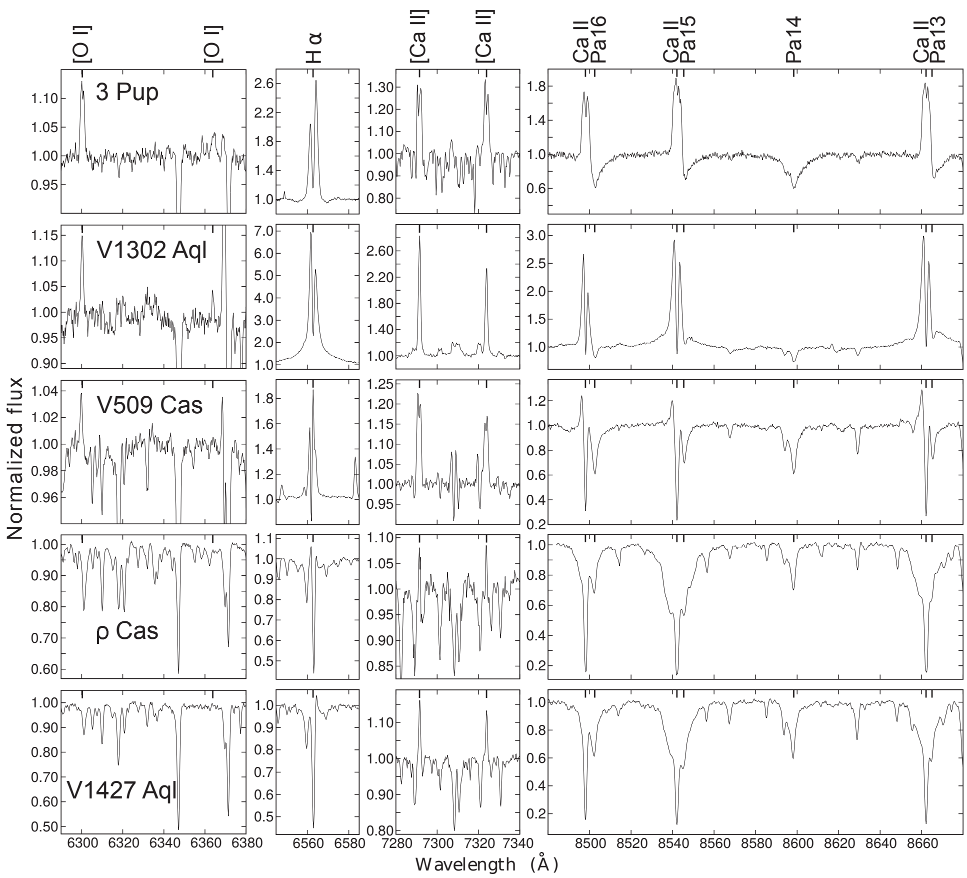

Figure 1. Spectra of the B[e]SG 3 Pup *vs* the hot YHGs V1302 Aql and V509 Cas and the cool YHGs ρ Cas and V1427 Aql.

3. Results

Our YHG sample splits into two categories, hot and cool. We define hot YHGs as those with spectral types A outside outburst. Two of our stars, V1302 Aql and V509 Cas, fall into this group, while the other two objects, ρ Cas and V1427 Aql, belong to the group of cool YHGs. They are characterized by spectral types F outside outburst.

We identified the [Ca II] lines in all stars of our YHG sample, but the [O I] lines only in the hot YHGs. In addition, only the hot YHGs display the Ca II triplet lines in emission. To understand this behavior, we recall that the upper levels, from which the [Ca II] lines emerge, are the lower levels to which the triplet lines decay. In addition, the upper levels of the forbidden lines can be populated collisionally from the ground level. The fact that we observe the triplet lines in emission only in the hot YHGs indicates that the excitation mechanism of the [Ca II] lines is different in the two groups of stars, meaning that in the cool YHGs only collisional level excitation is at work. Moreover, the low effective temperature of the cool YHGs translates into a cooler temperature of the stars' environment, which suppresses effective collisional population of the levels of both Ca II and O I. This explains why the [Ca II] lines are much weaker and the [O I] lines are even absent in the spectra of these stars.

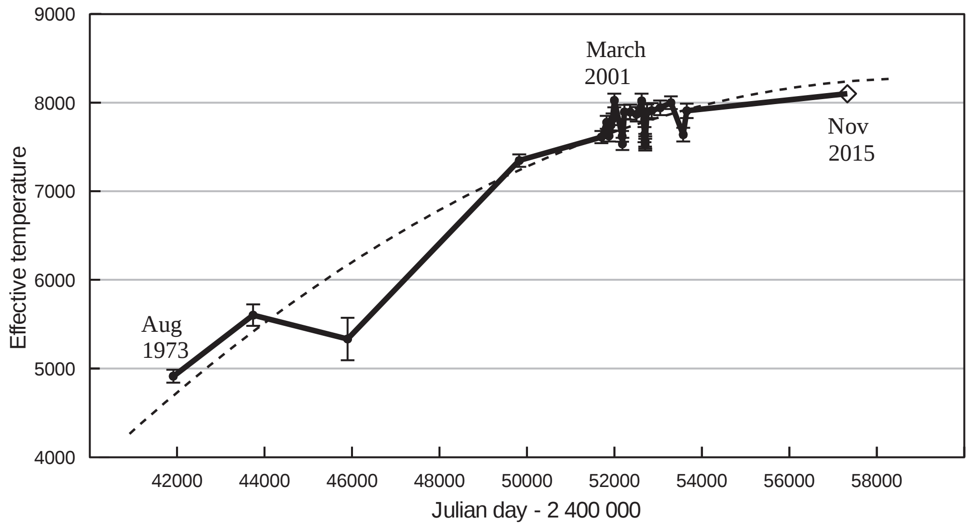

Figure 2. Bold line marks the temperatures of V509 Cas from Nieuwenhuijzen et al. (2012) with one point from our spectra (November 2015). The dashed line indicates a polynomial trend.

ρ Cas is famous for its outbursts (or shell episodes), when the star ejects large amounts of material (Lobel et al. 2003, Aret et al., this volume); however, no large-scale nebulosity has been detected (Schuster, Humphreys, & Marengo 2006). The situation is different for V1427 Aql, which has a clearly detached large-scale dust shell (Castro-Carrizo et al. 2007). Not much is known about the shape of the environments of these two objects on small scales. The profiles of their [Ca II] lines are single-peaked in both cool YHGs (Fig. 1). Hence, based on our data we have no information on the kinematics in their [Ca II] line-forming regions.

The presence of both sets of forbidden lines in the two hot YHGs indicates that the physical conditions in their environments could be similar to those in the B[e]SGs. The kinematics obtained from the [O I] and [Ca II] line profiles of the B[e]SG stars V1478 Cyg and 3 Pup agrees with an origin of the lines in Keplerian rotating rings (Aret et al. 2016). Thus, the same scenario might also hold for the hot YHGs.

The object V1302 Aql is surrounded by a large-scale spherical shell, a possible remnant from the previous RSG state. It is famous for its extreme infrared excess indicating large amounts of warm dust, and it loses mass at a very high rate in an axi-symmetric wind (Davies et al. 2007). Moreover, a disk-like structure, embedded in the innermost shell, was proposed by Castro-Carrizo et al. (2007), and an orientation of the star close to pole-on was suggested by Tiffany et al. (2010). Inspection of its forbidden emission lines (Fig. 1) reveals that all profiles are very narrow and single peaked. Despite the lack of kinematical information, such profiles are in agreement with their formation in the nearly pole-on seen disk.

Like ρ Cas, V509 Cas displays no evidence of large-scale shells or ejecta (Schuster et al. 2006), indicating that no high mass-loss events took place prior to 500–1000 years ago. From 1960 to 1980, the star was practically the spectroscopic twin of ρ Cas because it displayed the same emission and absorption features, which varied with the pulsation phase. It also underwent similar outbursts with the appearance of CO

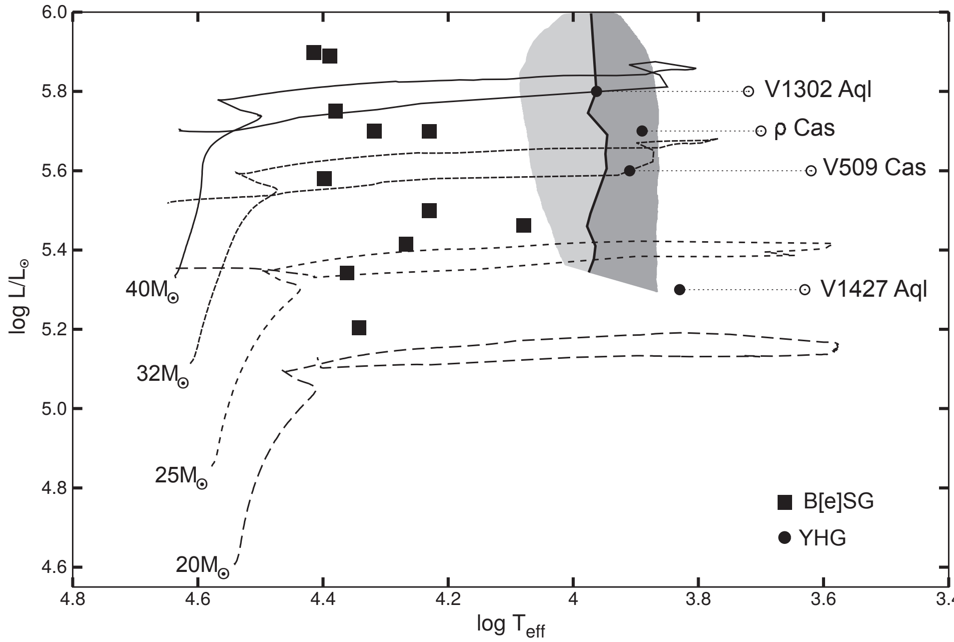

Figure 3. Upper part of the HRD illustrates a possible evolutionary link between YHGs (circles) and B[e]SGs (squares). For the hypergiants horizontal excursions due to $T_{\rm eff}$ variations are shown. Evolutionary tracks are taken from Ekström et al. (2012). The Yellow Void is drawn as in de Jager & Nieuwenhuijzen (1997), the first instability region is darker and its high-temperature boundary is marked by a solid line (Nieuwenhuijzen et al. 2012).

emission, which turned into absorption and then disappeared with the expansion and dilution of the ejected material (Gorlova et al. 2006). However, in contrast to ρ Cas, from 1980 on V509 Cas started to gradually heat up until about 2001 (Fig. 2). Concerning the structure of the small-scale environment, not much is currently known. The forbidden lines in our spectra (Fig. 1) show clearly double-peaked profiles for the [Ca II] lines, while the [O I] lines appear single-peaked at our spectral resolution. This behavior is also seen in the B[e]SGs (Kraus et al. 2010; Aret et al. 2012, Maravelias et al. this volume) and might be assigned to a (Keplerian) rotating disk or rings, in which the [Ca II] lines are formed closer to the star than the [O I] λ6300 Å line. If true, V509 Cas would be the second YHG with a clear indication of an inner disk.

4. Discussion and Conclusions

The fact that the hot YHGs in our sample seem to have disk-like structures, whereas the cool ones lack such evidence, might indicate a drastic change in the mass-loss behavior during the passage of the star through the Yellow Void from spherical to axisymmetric mass loss. As pulsations are believed to be the main mechanism responsible for enhanced mass loss and eruptions in YHGs (see the overview by de Jager 1998), this would require a change in the pulsation habit of the stars, which might be checked based on long-term observing campaigns.

During the past few decades, V1302 Aql (Klochkova et al. 2002) and V509 Cas (Nieuwenhuijzen et al. 2012) have displayed a considerable increase in their effective temperature, which seems to have slowed down or even stopped. Klochkova et al. (2016) reported that the kinematic picture and effective temperature of V1302 Aql have been stable during 2001–2014. Our spectra from 2015 show that the effective temperature of V509 Cas has remained at the same level as in the beginning of 2001 (Fig. 2). These findings may indicate that these objects are approaching the high-temperature boundary of the first instability region in the Yellow Void (Nieuwenhuijzen et al. 2012). Such a conclusion is in line with the current position of the stars in the HRD (Fig. 3).

The presence of disks around these hot YHGs has further implications. As these objects will continue to lose mass during their passage through the second part of the Yellow Void instability domain, the accumulation of material in the equatorial plane might continue. As soon as the star reaches the blue, stable edge of the Yellow Void, it could have deposited enough material into the disk (or rings) to appear as a B[e]SG. Such an evolutionary link was already suggested for V1302 Aql by Zickgraf (1998) and Davies et al. (2007). But in light of the new proposition of a Keplerian disk or rings around V509 Cas based on the profile shapes of its forbidden emission lines, it seems to be a valid suggestion even for a larger sample of hot YHGs.

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