The evolutionary phase of B[e] supergiants and unclassified B[e] stars

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Abstract. We present two classes of stars with yet unknown evolutionary phase: the B[e] supergiants and the so-called unclassified B[e] stars. While the B[e] supergiants are luminous post-main sequence stars with high mass progenitors, not much is known of the unclassified stars. We discuss how it might be possible to determine their evolutionary phases in the area of new large telescopes.

INTRODUCTION

Stars showing the B[e] phenomenon have several characteristics of their optical spectrum in common: they are of spectral type B, have strong Balmer emission lines, and many permitted and forbidden emission lines of predominantly low ionization metals like e.g. Fe II and O I. In addition, these stars are known to possess a strong near- or mid-infrared excess due to hot circumstellar dust. Since most of the characteristics are based purely on the optical spectrum, these stars can be of quite different evolutionary phase, and Lamers et al. [1] grouped all stars with the B[e] phenomenon accordingly. The different classes they found are: B[e] supergiants, Herbig Ae/B[e] stars, and compact planetary nebula B[e] stars. The biggest group, however, is formed by stars of unknown evolutionary phase, the so-called unclassified B[e] stars. In this paper we want to concentrate on two classes of B[e] stars: the supergiants and the unclassified stars. Both classes have in common, that their evolutionary phase is still unknown and we want to strengthen the need of large telescopes for the determination of the evolutionary phases of these stars.

THE B[E] SUPERGIANTS

B[e] supergiants are luminous (4 ≤ log L/L⊙ ≤ 6) post-main sequence objects. Their progenitors must have been massive (7 < M/M⊙ < 85) and probably rapidly rotating stars. The best known B[e] supergiants are located in the Magellanic Clouds. In the Milky Way only some candidates have been found. Here, due to large interstellar extinction the proper determination of distances and therefore luminosities is difficult. The optical spectra of B[e] supergiants show a hybrid character, i.e. a co-existence of very broad Balmer lines and extremely narrow forbidden and permitted low ionization metal lines. This hybrid character has led to the interpretation of two different winds: a normal line-driven (CAK-type) fast wind of low density in polar direction and a slow, high
density disk-forming wind in equatorial direction where the hot dust is located (see Zickgraf et al. [2]). Kraus & Lamers [3] performed ionization structure calculations in such non-spherical winds of B[e] supergiants using a latitude dependent mass flux that increases from pole to equator. They found that with such a model hydrogen can combine close to the stellar surface in the equatorial region leading to a hydrogen neutral disk-like structure around these luminous stars. High-resolution optical spectra of B[e] supergiants revealed strong emission of OI forbidden lines (see e.g. Kraus & Borges Fernandes [4]) which indicates the existence of a huge amount of neutral hydrogen since H and O have the same ionization potential. The additional detection of CO band emission in the near-infrared in several B[e] supergiants (e.g. McGregor et al. [5]; [6]; [7]) completes the picture of the circumstellar disk leading to the following schematic representation of its temperature structure (from inside out): \([\text{OI}] \text{ emission (10 000 K} \leq T \leq 6 000) – \text{CO band emission (5 000 K} \leq T \leq 2 000) – \text{dust emission (} T \leq 2000 \text{K).}

In the HR diagram, B[e] supergiants share their location with other massive post-main sequence stars like Wolf-Rayet stars and Luminous Blue Variables (LBVs). But the connection of B[e] supergiants with these other evolutionary states is still an unsolved problem and even newest stellar evolution calculations of massive stars cannot predict the B[e] supergiant phase (see e.g. Maeder & Meynet [8]; Maeder et al. [9]).

**UNCLASSIFIED B[E] STARS: THE EXAMPLE OF HEN 2-90**

The enigmatic galactic star Hen 2-90 belongs to the group of unclassified B[e] stars. It has been classified in the literature either as a compact planetary nebula (e.g. Costa et al. [10]; Lamers et al. [11]) or as a symbiotic object (Sahai & Nyman [11]; Guerrero et al. [12]). On an HST image (Sahai et al. [13]) a non-spherical wind structure is visible: a high-ionized polar wind, a low-ionized wind at intermediate latitudes and a (neutral) disk structure in equatorial direction.

We took high- and low-resolution optical spectra with slit centered on this non-spherical wind structure. The spectra contain very strong Balmer lines and lots of forbidden emission lines from e.g. S, N, O, Ar, Cl, Fe in different ionization states. We detected neither emission from HeII nor TiO absorption bands, which are both the main characteristics of a symbiotic object. In addition, we performed a detailed analysis of almost all observed forbidden emission lines and found that C and O are depleted, which means that Hen 2-90 should be an evolved object. Our conclusions are therefore, that Hen 2-90 is most probable a compact planetary nebula (Kraus et al. [14]).

There are, however, a few puzzling details that have to date not been solved: (i) Hen 2-90 shows a jet like structure with many knots being ejected regularly on both sides of the star and perpendicular to the disk. (ii) The velocity profiles of the different emission lines hint to a much more complex structure of the circumstellar material than might be explained with a simple wind model. (iii) We also found from our modeling that N is depleted, which cannot be understood in terms of a normal single star evolution so that probably a binary nature of this star needs to be taken into account (Kraus et al. [15]). More observations are certainly needed to disentangle the nature of this fascinating object.
HOW CAN WE DETERMINE EVOLUTIONARY PHASES?

The determination of the evolutionary phases of B[e] supergiants and unclassified B[e] stars strongly depends on the interplay of theory with observations. Here, we want to mention some of the methods we are using to fix stellar and circumstellar parameters necessary for the classification.

- **Abundance determinations:**
  The determination of elemental abundances is one key project when dealing with stellar evolution. It is thereby necessary to determine abundances in the circumstellar matter as well as on the stellar surface. The circumstellar material mirrors the surface abundance at the time of matter ejection, while the surface itself gives the actual abundance of the star. The surface abundance can be quite different from the circumstellar abundance if (i) the star was ejecting its complete hydrogen rich outer layers leaving a He rich surface behind, or (ii) the star is rapidly rotating leading to rotationally induced mixing of the internal material which results in a continuous surface enrichment of processed material. Since rapidly rotating stars have high mass loss rates, the mixing leads to an abundance gradient in the wind material.

- **Determination of the geometry and kinematics of the circumstellar matter:**
  The geometry of the system is a crucial point, especially if no direct imaging is available or possible. As discussed in the previous section, the appearance and strength of specific (e.g. forbidden) emission lines can hint to a non-spherical density distributions and even to neutral material close to the hot star. A detailed analysis of forbidden (and permitted) emission lines is needed to derive the ionization structure in non-spherical winds and disks. Especially in the case of B[e] stars we know that in polar direction highly-ionized, line-driven winds of rather high velocity emanate, while from equatorial directions the narrow emission lines of low-ionized or even neutral metals are observed. Both types of profiles will be present in high-resolution spectra.

  Besides the atomic and ionic lines also molecular emission, like e.g. the CO bands can be used to determine the kinematics of the emitting gas. Especially for several B[e] supergiants the CO bands which arise in the near-infrared have been observed. High-resolution observations of the CO $2 \rightarrow 0$ band head display the complete velocity information of the CO emitting gas. This band head shows e.g. a red peak and a blue shoulder in case of rotation. By modeling the high-resolution, high signal-to-noise $2 \rightarrow 0$ band head structure one can discriminate contributions coming from rotation and/or outflow (see e.g. Kraus et al. [16]).

- **Determination of the mass loss history:**
  The analysis of the forbidden emission lines can also be used to derive (non-spherical) mass fluxes and therefore the total mass loss rate of a star as has been shown by Kraus et al. [14] for the unclassified B[e] star Hen 2-90. Mass loss rates of the B[e] supergiants and unclassified B[e] stars can then be compared with those available in the literature for stars of different initial conditions and in different evolutionary phases to find agreements and therefore a possible evolutionary stage of each star.
OBSERVATIONS NEEDED

For the modeling of the CO bands high-resolution NIR spectra are needed. PHOENIX, the new high-resolution near-infrared spectrograph at Gemini-South is most suitable for these observations.

For the determination of terminal velocities, the mass loss history and the surface and circumstellar matter abundances we need mainly high-resolution optical (and UV) observations. Since many of the unclassified B[e] stars are southern objects and most of the nowadays known B[e] supergiants are located in the Magellanic Clouds, the new South African Large Telescope (SALT) will be the ideal tool to guarantee the success of our projects. Its major targets will be the Magellanic Clouds (see contributions by David and William in this volume) allowing us to retrieve the high-resolution optical spectra which are needed for a proper classification of B[e] stars.

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