Circumstellar environment and mass-loss history of evolved massive stars

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Evolution of massive stars

- Massive stars ($M > 8 M_\odot$) serve as cosmic engines
  - Nuclear fusion of elements up to Fe
  - Mixing of chemically processed elements to surface
  - Release into the local ISM via strong stellar winds

$\Rightarrow$ deposit large amounts of momentum and energy into their surroundings and trigger galactic evolution
Motivation

- Short-lived evolutionary phases with enhanced mass-loss and eruptions
- Stars in such phases are luminous blue variables (LBVs), B[e] supergiants, and yellow hypergiants (YHGs)

η Car (LBV, HST)

MWC 137 (B[e] supergiant, Marston & McCollum 2008)

Fried Egg Nebula (YHG, ESO: E. Lagadec)
Open questions

- When during the evolution of massive stars happen these phases?
- How much mass is lost in these phases?
- What mechanism(s) trigger the eruptions?
The B[e] supergiants

- B-type supergiants ($T_{\text{eff}} = 10,000 - 25,000$ K; $\log L/L_\odot > 10^4$)
- Equatorially outflowing disks composed of gas and dust (infrared excess)
- Fast and dense polar winds
- Many forbidden emission lines ([OI], [CaII], [NII], [FeII], [SII], etc)

Artist’s view of a B[e] supergiant (credit: ESO)

(Kraus et al. 2007; 2010)
Motivation

Strategy for our investigations

- Reveal structure and kinematics of their circumstellar material (CSM) based on combined optical and near-infrared spectroscopic data
- Study mass-loss history and triggering mechanisms for phases of enhanced or eruptive mass loss
- Investigate evolutionary phase based on chemical and abundance analysis of the CSM
- Resolve populations of B[e] supergiants, LBVs, and YHGy in the Local Group Galaxies to study the evolution of massive stars at different metallicities.
Tracers for ionized and neutral atomic gas regions

- High-resolution \((R \approx 45\,000)\) optical spectroscopy obtained with FEROS
- Excellent tracers for kinematics are typically forbidden emission lines:
  - Line profiles display full kinematic information of their formation region.
  - Forbidden lines from different elements and ionization stages trace different temperature and density regions.
- \([\text{OI}]\) and \([\text{CaII}]\) lines mirror high-density regions with \(N_{\text{CaII}} \gtrsim N_{\text{OI}}\) (Kraus et al. 2007, 2010; Aret et al. 2012).
- \([\text{CaII}]\) IR triplet lines are composite: contributions from disk + wind.
Structure and Kinematics of the Circumstellar Material

- Motivation
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- Evolutionary phase
- Resolving massive star populations

Disk tracers in FEROS spectra of Magellanic Cloud B[e] supergiants (from Aret et al. 2012)

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Disk tracers in FEROS spectra of Galactic B[e] supergiants
(Muratore et al. 2012)
Tracers for the molecular regions

- We use medium-resolution ($R \approx 4500$) and high-resolution ($R \approx 50,000$) near-infrared spectra obtained with SINFONI and CRIRES.

- High-resolution spectra of the first CO band head displays kinematical (e.g. rotational) broadening (Kraus et al. 2000, 2013; Cidale et al. 2012).
Kinematically resolved first CO bandheads of Galactic B[e] supergiants

CRIRES spectra (Muratore et al. 2012)
CRIRES spectra for HD 327083 (Andruchow et al. in preparation)

Model:

$v_{\text{rot}} = 78 \text{ km s}^{-1}$; $T_{\text{CO}} = 2000 \text{ K}$; $N_{\text{CO}} = 10^{22} \text{ cm}^{-2}$; $i = 46^\circ$
CRIRES plus PHOENIX spectra for CPD-52 9243 (Cidale et al. 2012)

Model:

\[ v_{\text{rot}} = 33.5 \text{ km s}^{-1}; \quad T_{\text{CO}} = 2400 \text{ K}; \quad N_{\text{CO}} = 4 \cdot 10^{22} \text{ cm}^{-2}; \quad i = 50^\circ \]
Structure and Kinematics of the Circumstellar Material

Results

- Combined kinematics obtained from the three tracers [CaII], [OI], and CO (from inside out) indicate (quasi-)Keplerian rotation of the gas.
- CO band emission marks the inner edge of the molecular disk region.
- In all objects, temperatures are low ($T_{\text{CO}} < 3000$ K) compared to the CO dissociation temperature ($T_{\text{CO,diss}} \approx 5000$ K)

\[ \downarrow \]

B[e] supergiants are surrounded by detached, often multiple rings of gas and dust.

- The existence of gaps in the disks is also confirmed by interferometry (Wheelwright et al. 2012, 2013; Cidale et al. 2012).

\[ \downarrow \]

Contrary to former suggestions, the disks of B[e] supergiants are not formed and continuously supplied by an equatorially outflowing wind.
SINFONI K-band survey

- B[e] supergiants and YHGs display strong CO band emission; no CO in LBVs
- Fits to CO band and Hydrogen Pfund series emission from B[e] supergiants (Oksala et al. 2013).
- Discovery of $^{13}$CO band emission in B[e] supergiants and YHGs
- Enrichment of CSM with $^{13}$C during stellar evolution

$\downarrow$

The amount of $^{13}$CO reveals the stars’ age (evolutionary phase)
Results

$^{12}\text{CO}/^{13}\text{CO} = 10 - 20$ for the B[e] supergiants. This phase happens just beyond the main-sequence. YHGs are post-RSGs with $^{12}\text{CO}/^{13}\text{CO} = 5 - 10$. 

*Figure showing evolutionary tracks for stars in the Milky Way, LMC, and SMC.*
Why is it **important** to resolve massive star populations

- to increase samples of these rare objects, which is vital to improve our understanding of stellar evolution of massive stars and to study evolutionary connections
- to study the occurrence of these particular evolutionary phases as a function of metallicity

Why is it **difficult** to resolve massive star populations

- Typically, classification is based on optical spectra
  
  However:

- Difficult to ascertain in highly reddened regions (e.g., towards the center of the Galaxy)

- Optical spectra of LBVs in their hot (quiescent) phase are **indistinguishable** from those of B[e] supergiants

- Optical spectra of LBVs in their cool (eruptive) phase are **indistinguishable** from those of YHGs
B[e] supergiants, LBVs (hot and cool) and YHGs display clearly distinct characteristics in the near-infrared! (Oksala et al. 2013)
Summary and work in progress

Summary

- Studying the structure and kinematics of the CSM of B[e] supergiants revealed that they are surrounded by detached, multiple rings in Keplerian rotation.
- We discovered $^{13}$CO band emission, which allows us for the first time to locate the B[e] supergiant phase in the evolution of massive stars.
- We discovered that K-band spectra of massive stars are excellent indicators for their evolutionary stage.

Current projects at ESO

- Resolving the B[e] supergiant and LBV populations in M 33 using KMOS.
- Resolving the B[e] supergiant population in highly extincted regions and studying their molecular (CO) disk regions using SINFONI.
- Searching for emission from other molecules such as SiO, water and OH and resolving the kinematics in their line-forming disk/ring regions using CRIRES.