Circumstellar environment and mass-loss history of evolved massive stars

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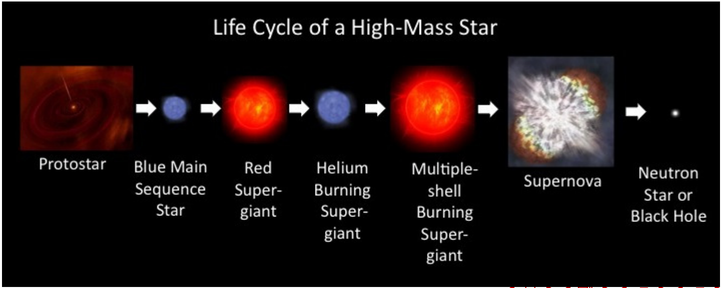
Motivation

Evolution of masive 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

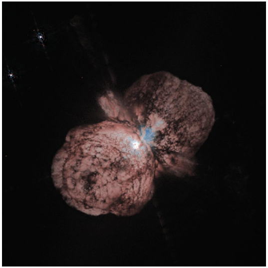
$\Longrightarrow$ deposit large amounts of momentum and energy into their surroundings and trigger galactic evolution



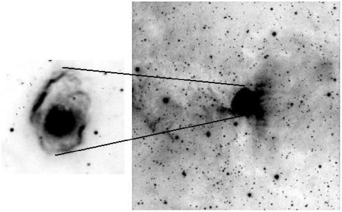
Motivation

- 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)

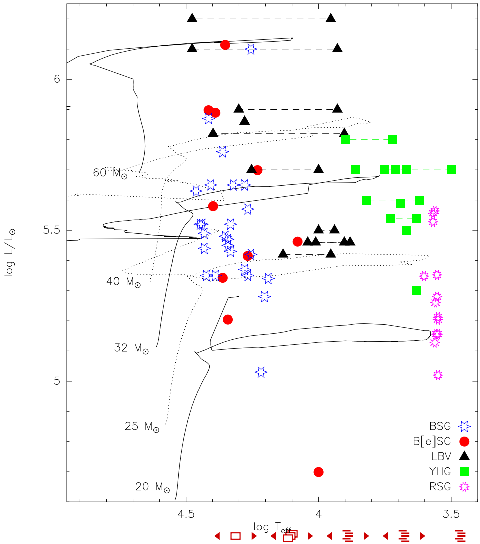


Fried Egg Nebula (YHG, ESO: E. Lagadec)

Motivation

Open questions

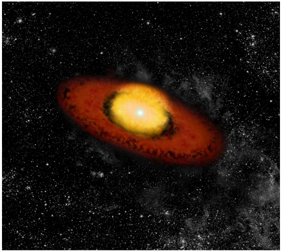
- When during the evolution of massive stars happen these phases?
- How much mass ist lost in these phases?
- What mechanism(s) trigger the eruptions?



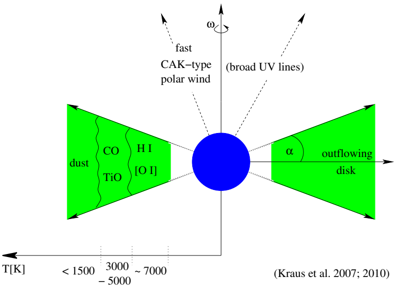
Motivation

The B[e] supergiants

- B-type supergiants ($T_{\rm eff} = 10\,000 - 25\,000$ 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

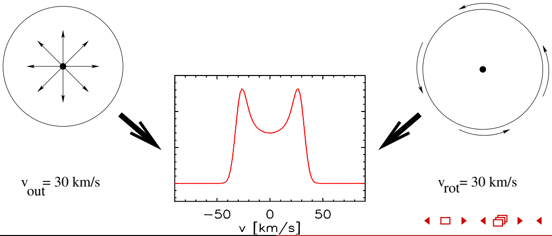
Strategy for our investigations

- 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 YHGs in the Local Group Galaxies to study the evolution of massive stars at different metallicities.

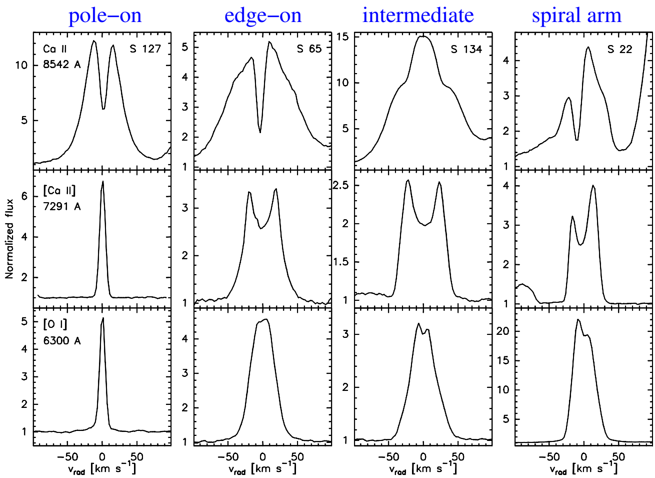
Structure and Kinematics of the Circumstellar Material

Tracers for ionized and neutral atomic gas regions

- High-resolution ($R \simeq 45\,000$) 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.
- [OI] and [CaII] lines mirror high-density regions with $N_{\rm [CaII]} \gtrsim N_{\rm [OI]}$ (Kraus et al. 2007, 2010; Aret et al. 2012).
- CaII IR triplet lines are composite: contributions from disk + wind.

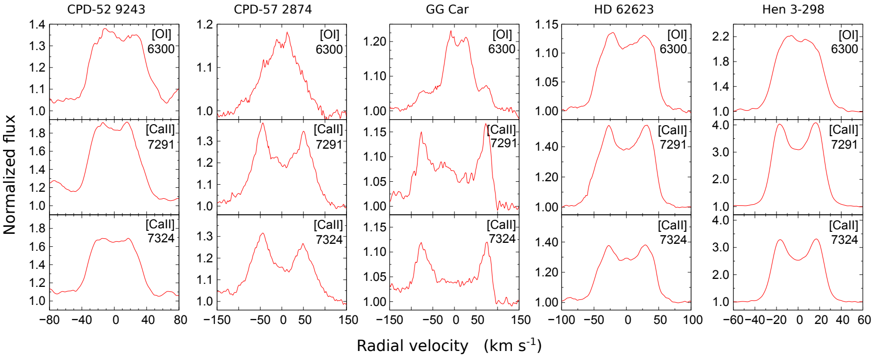


Structure and Kinematics of the Circumstellar Material



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

Structure and Kinematics of the Circumstellar Material

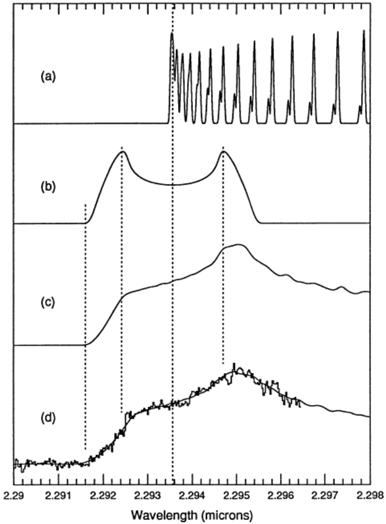


Disk tracers in FEROS spectra of Galactic B[e] supergiants
(Muratore et al. 2012)

Structure and Kinematics of the Circumstellar Material

Tracers for the molecular regions

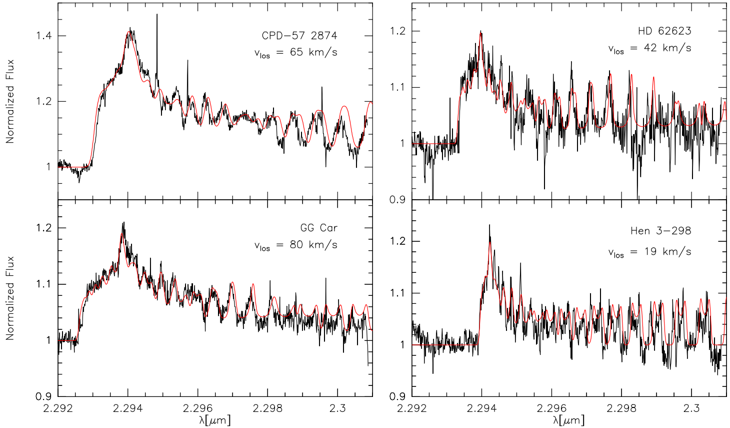
- We use medium-resolution ($R \simeq 4500$) and high-resolution ($R \simeq 50\,000$) near-infrared spectra obtained with SINFONI and CRIRES
- High-resolution spectra of the first CO band head displays kinematical (e.g. rotational) broadening (Kraus et al. 2000, 2013; Cidale et al. 2012)



Structure and Kinematics of the Circumstellar Material

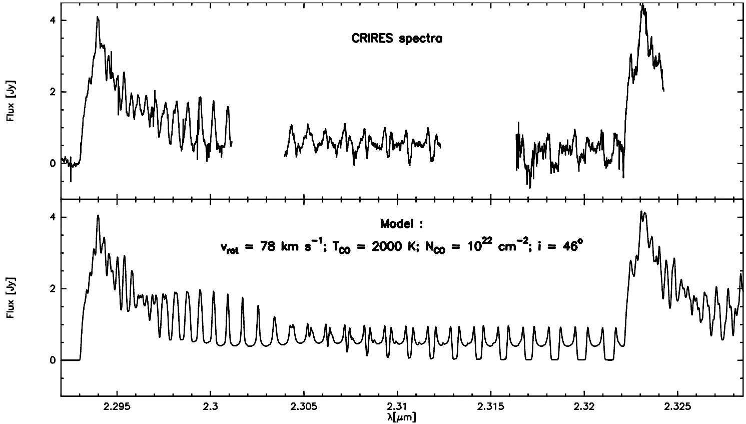
Kinematically resolved first CO bandheads of Galactic B[e] supergiants

CRIRES spectra (Muratore et al. 2012)



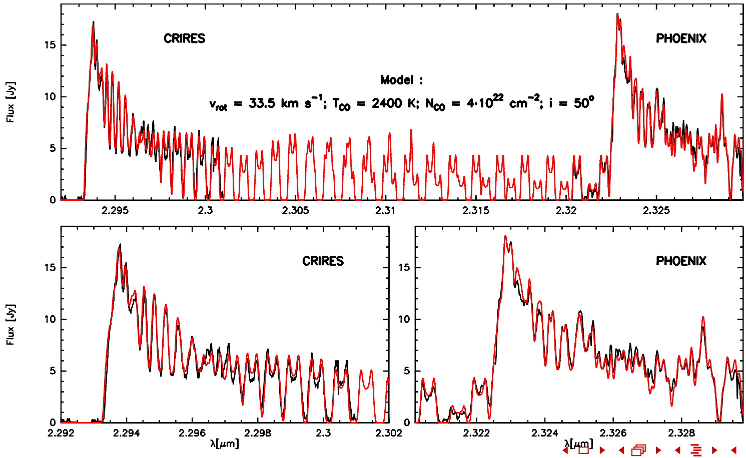
Structure and Kinematics of the Circumstellar Material

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



Structure and Kinematics of the Circumstellar Material

CRIRES plus PHOENIX spectra for CPD-52 9243 (Cidale et al. 2012)



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 ($T_{\rm CO} < 3000$ K) compared to the CO dissociation temperature ($T_{\rm CO,diss} \simeq 5000$ 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.

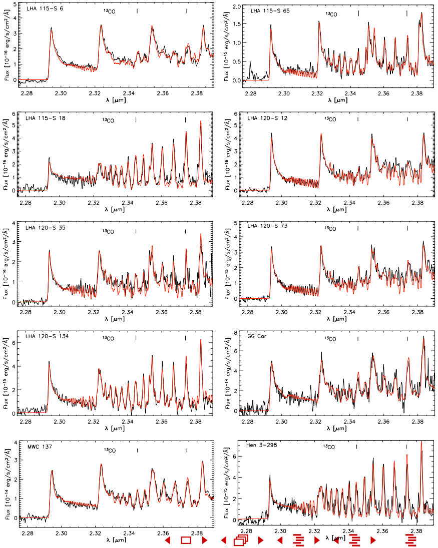
Evolutionary phase

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

⇓

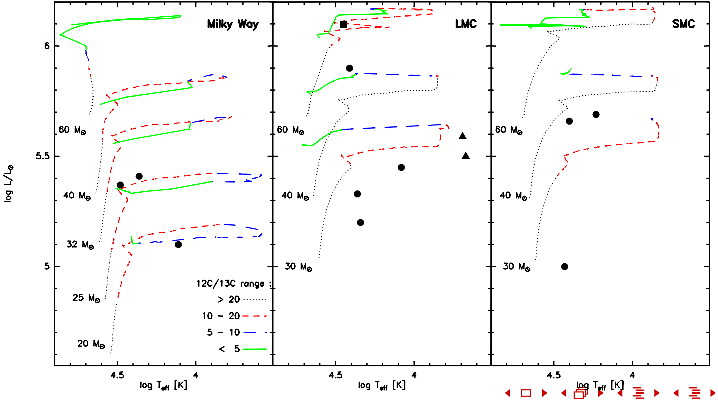
The amount of ^{13}CO reveals the stars' age (evolutionary phase)



Evolutionary phase

Results

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



Resolving massive star populations

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

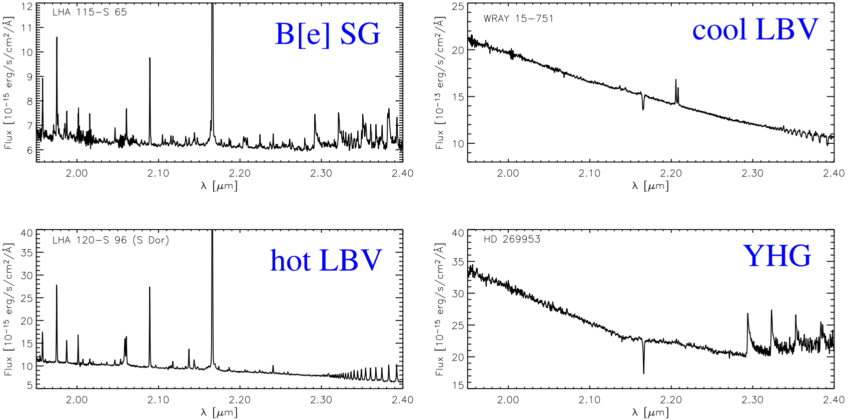
- Typically, classification is based on optical spectra

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

Resolving massive star populations

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