Probing the Ejecta of Evolved Massive Stars in Transition:

A VLT/SINFONI *K*-band spectral survey

M.E. Oksala[1], M. Kraus[1], L.S. Cidale[2], M.F. Muratore[2], & M. Borges Fernandes[3]

[1] Astronomical Institute, ASCR, Czech Republic; [2] Universidad Nacional de La Plata, Argentina; [3] Observatório Nacional, Brazil

Introduction

Transition Phases: Evolved massive star phases defined by large episodes of mass loss, not yet incorporated into stellar evolution models.

- **Yellow Hypergiants (YHGs):** cool, post-Red Supergiant objects surrounded by dense shells of material, expelled by pulsational instability, located on the cool side of the "Yellow Void", where surface gravity is particularly low
- **B[e] Supergiants (B[e]SGs):** surrounded by dense disks or rings of material, with narrow forbidden emission lines, molecular emission, and evidence for large amounts of dust, formation mechanism for circumstellar material is currently unknown
- **Luminous Blue Variables (LBVs):** expel large amounts of mass via eruption, likely due to proximity to Eddington luminosity limit, traverse across the HRD due to expansion and cooling of the stellar photosphere during

CO emission: At high densities (>10^{10} cm^{-3}) and warm temperatures (2000-5000 K), CO molecules are predicted to be abundant enough to form spectral band head features. The first overtone band heads are ideal to determine disk temperature and column density. The presence and strength of ^{13}CO emission can determine the evolutionary stage of the star.

Motivation

- **Determine the evolutionary phase of objects suggested or suspected to be evolved massive stars.**
- **Determine the conditions in the circumstellar environments of these stars.**
- **Search for evidence for the evolutionary relation between evolved massive stars.**

Observations

- We acquired **high-quality medium resolution (R=4500) *K*-band (1.95-2.45 μm) spectra of 25 evolved massive stars in transition** using the Spectrograph for Integral Field Observation in the Near Infrared (SINFONI) on the VLT UT4 telescope.
- The survey sample included 16 B[e]SGs, 2 YHGs, 6 LBVs, and 1 Peculiar Oe star. The objects are located in the Galaxy, Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC).

CO band head emission

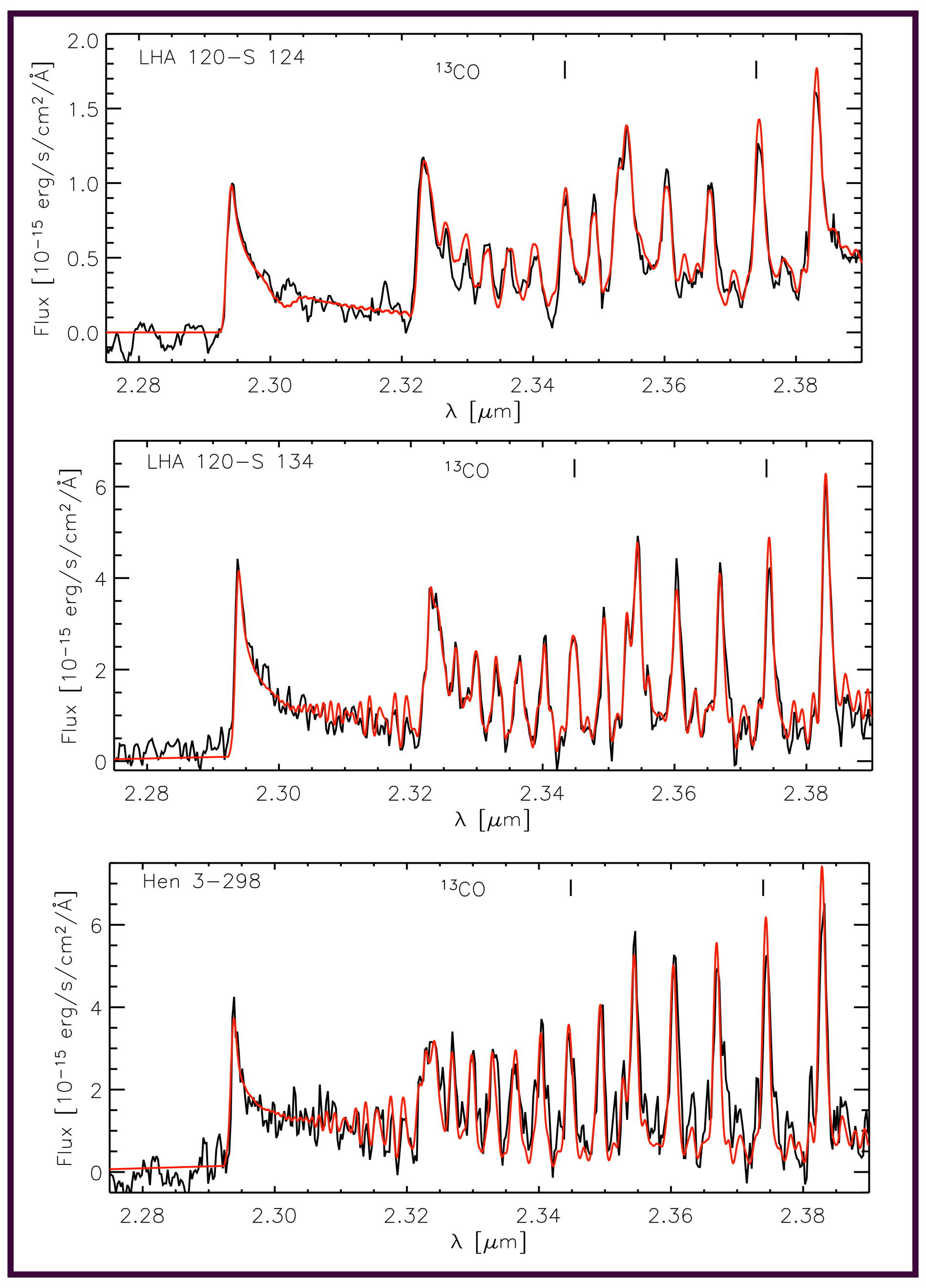

Figure 1: Examples of model (red) fits to the flux calibrated, continuum subtracted CO spectra (black) of three observed supergiants, S124, S134, and Hen 3-298. The location of the ^{13}CO band heads is indicated. Pfund emission pollutes the spectral region.

CO models: Code, developed based on Kraus et al. (2000, A&A, 362, 158) and Kraus (2009, A&A, 494, 253), computes **^{12}CO and ^{13}CO emission spectra for a ring of material in a rotating disk.** Gas is assumed to be in LTE, with constant temperature, column density, and rotational velocity.

> 50% of sample show CO emission, including 63% of B[e]SGs

Table 1: CO Model Best Fit Parameters

Object	T_{CO} (K)	N_{CO} (10^{21} cm^{-2})	$^{12}C/^{13}C$	$A_{CO} \cos i$ (AU^2)
LHA 115-S 6	2200±200	5±2	12±2	1.00±0.08
LHA 115-S 18	2000±200	8±3	20±5	8.9±0.6
LHA 115-S 65	3200±300	1.5±0.5	20±5	11.7±0.9
HD 269953	3000±200	2±0.5	10±1	41.5±1.1
LHA 120-S 12	2800±500	2.5±0.5	20±2	2.33±0.06
LHA 120-S 35	3000±200	2±0.5	10±2	1.16±0.06
LHA 120-S 73	2800±500	3.5±0.5	9±1	17.8±0.5
LHA 120-S 124	3000±400	9.5±0.5	20±5	0.90±0.02
LHA 120-S 134	2200±200	2±1	15±2	62±14
MWC 137	1900±200	5±2	25±5	1.86±0.27
GG Car	3200±200	5±3	15±5	0.58±0.05
Hen 3-298	2000±200	0.8±0.4	20±5	11±4

- **No CO emission was detected in any LBV.** CO was detected in both YHGs, the Peculiar Oe star, and in 10 of the 16 B[e]SGs.
- Each target with ^{12}CO emission also has ^{13}CO emission. Pre-main sequence levels of ^{12}CO/^{13}CO are not detectable at this resolution, indicating that all of our objects are **evolved past the end of the main sequence.**
- There do not appear to be any correlations between stellar properties and CO properties.
- Temperatures provided by all CO models are much **cooler** than the dissociation T_{CO} of 5000 K. The material is located in a region **detached** from the surface, likely in a ring or disk structure.
- There appears to be a lower luminosity limit of log $L/L_{\odot}$ = 5.0, below which CO emission is not detectable.
- **No metallicity effects** are detected in the formation of CO band head emission.

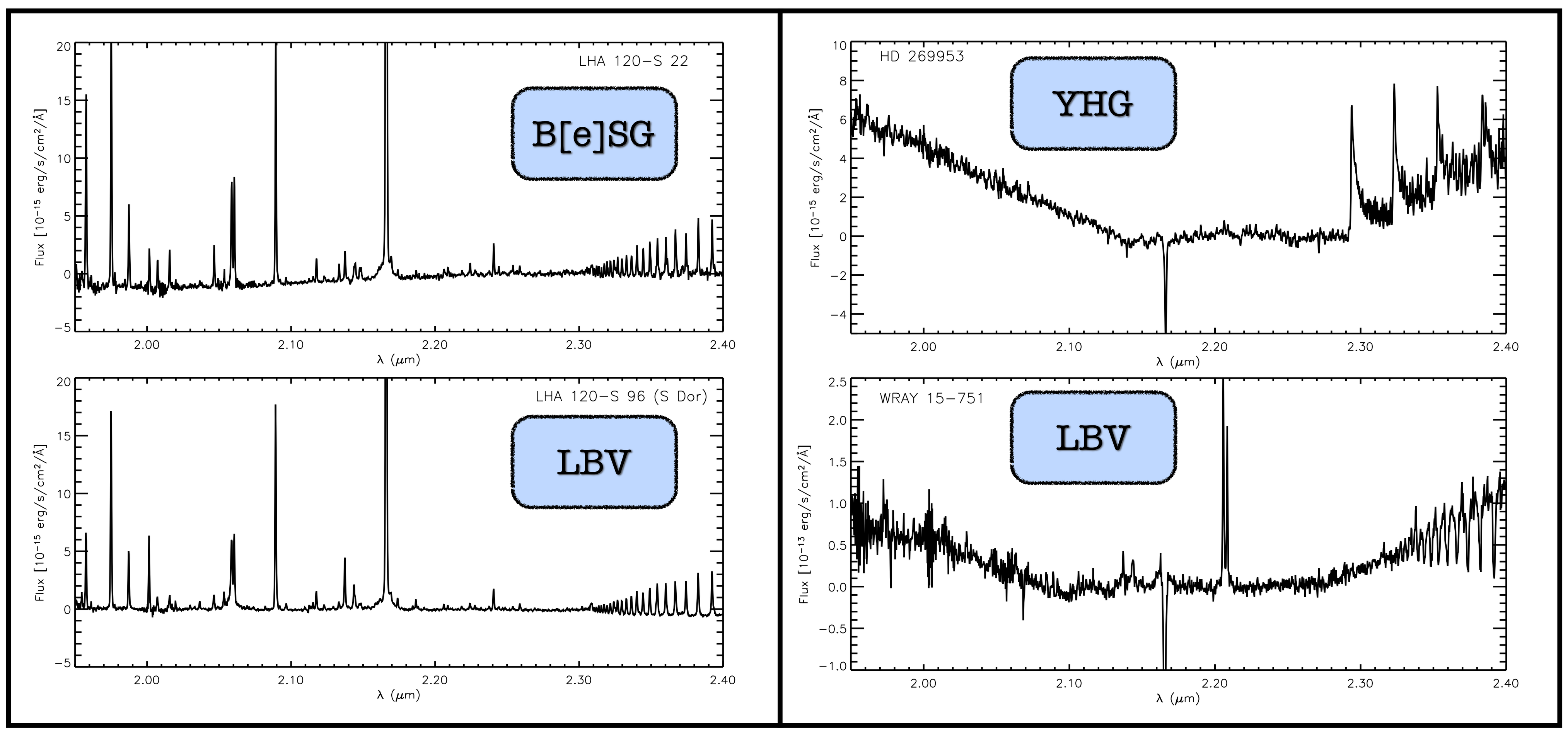

Figure 2: Flux-calibrated, continuum subtracted SINFONI *K*-band spectra. The **left** panel shows two examples of the group of objects in our survey with **straight continuum and a large variety of spectral emission lines**. The **top** spectrum, LHA 120-S 22 (HD 34664), is a known B[e]SG, while the **bottom** spectrum, S Dor, is a prototypical LBV. The **right** panel shows two examples of the group of **objects with kinked continuum and few, mostly absorption lines**. The spectrum of the YHG HD 269953 is on the **top**. The spectrum on the **bottom** is the LBV WRAY 15-751.

- In our sample, 4 LBVs display the **kinked continuum** shown above and are in their **active (visual maximum) phase**. The cool appearance of these stars is due to a "pseudo-photosphere" created by an expanding photosphere. The other LBVs with the **flat continuum** are in their **quiescent (visual minimum) phase**.

Results

- The *K*-band spectra of LBVs are similar to either B[e]SGs if they are in their quiescent phase, or to YHGs if they are in their active phase (with the exception of CO emission, see Figure 2).
- 13 targets with detected CO emission, 3 of which are initial discoveries, and a lower luminosity limit was found, below which no CO was detected.
- Model fits reveal detached ring or disk structures. All objects with ^{12}CO also have ^{13}CO, indicating an evolved nature. B[e]SGs (with detected CO emission) appear to be pre-RSG; YHG are post-RSG.
- YHGs may be the progenitors of LBVs as they evolve from their extremely cool positions back across the HRD.
- Several B[e]SG *K*-band spectra are indistinguishable from those of bonafide LBVs, lacking CO emission and indicating that they may be LBV candidates.