Onsala Proposal

Beck **0108.F-9303**

Molecular emission from massive evolved stars

Semester: may2021 **Science Cat.: Late stages of stellar evolution**

Abstract

The evolution of massive stars is poorly understood and critically linked to mass loss. Post-main sequence massive stars shed several solar masses of material in violent episodes. Their eruptive mass loss creates morphologically complex outflows. We now know the outflows of blue massive evolved stars to also be rich in molecular gas and dust, possibly comparable to the cooler yellow and red super- and hypergiants.

Only studies of the molecular gas can trace certain fundamental outflow parameters, such as gas-mass -loss rate and history, temperature, density, velocity, and chemical content. These are critical parameters to constrain models of stellar evolution, as well as models of supernova remnant formation. We propose an APEX pilot study of two candidate luminous blue variables and two blue supergiants in CO, SiO, and HCN, to explore these poorly studied molecular outflow components.

Applicants

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Is this a long term proposal: No

Overall scheduling requirements

None of the objects go into sun avoidance during the scheduled observing periods.

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	nFLASH230 (200-270 GHz)	7h (7h)	230.538	any	07-12, 14-22	12CO J=2-1 in USB 13CO J=2-1 in LSB
B	APEX	SEPIA345 (277-371 GHz)	5h (5h)	345.8	1-2 mm	07-12, 14-22	12CO J=3-2 in USB 13CO J=3-2 in LSB
C	APEX	SEPIA180 (159-211 GHz)	9h (9h)	175.5	1-2 mm	07-12, 14-22	SiO(4-3) and HCN(2-1) in USB

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
Hen 3-298	09:36:44.19	-53:28:01.2	J2000	0.0	175	A B C	
HD 168625	18:21:19.54	-16:22:26.0	J2000	0.0	15	A B C	
[GKF2010] MN 90	18:45:55.92	-03:08:29.7	J2000	0.0	260	A B C	
Hen 3-1453	17:41:35.43	-30:06:38.7	J2000	0.0	136	A B C	

Molecular emission around massive evolved stars

1 Scientific background

Chemical enrichment. The chemical evolution of galaxies and the Universe is driven largely by the mass loss of evolved stars. Stellar winds build up vast circumstellar envelopes (CSEs) of gas and dust and deposit up to more than half of their stellar birth mass into the interstellar medium (ISM), from where it is incorporated into new stellar and planetary systems. While low- to intermediate-mass stars of initial mass $M_\mathrm{i} \sim 0.8 - 8M_\odot$ evolve along the red and asymptotic giant branches (e.g. Marigo 2013), massive stars with $M_\mathrm{i} \sim 8M_\odot - 30M_\odot$ evolve into red supergiants (RSGs), perhaps also becoming yellow hypergiants (YHGs), blue supergiants with emission lines (sgB[e]), or Wolf-Rayet (WR) stars before terminating as core-collapse supernovae (SNe; e.g. Smith 2014; Meynet et al. 2015). During a phase of about $10^4 - 10^5$ yr, RSG and YHG stars eject gas and dust in strong, episodic, and often anisotropic mass loss with rates of up to $\sim 10^{-3}M_\odot$/yr (e.g. Danchi et al. 1994; Drout et al. 2012; Smith 2014; Jiang et al. 2018) in violent ejections. Given their fast evolution, the contribution of massive stars to the ISM enrichment of young starburst galaxies at high redshift is likely to be very important (e.g. Riffel et al. 2008) and accurate mass-loss rates of gas and dust, and dust properties in the CSEs of RSGs are required as input for photo-ionisation models of such low-metallicity starburst galaxies (Levesque 2010). To understand the properties, feedback, and role of massive evolved stars in the high-redshift Universe, it is essential to understand them also at galactic metallicity.

Stellar life and death. Strong mass loss drastically impacts stellar evolution itself. The relation between the RSG, YHG, sgB[e], and WR stages is still poorly understood, but the stellar evolutionary path is connected to the mass loss the stars experience (Smith 2014; Meynet et al. 2015). Which order these phases appear in, how many times a star will go through the different phases, and which of them is the most likely SN progenitor phase, are all questions in urgent need of answering. Furthermore, the usage of SNe to study stellar evolution across cosmic time hinges largely on understanding their progenitors.

Mass loss removes hydrogen from the stellar envelope, setting the initial conditions for the core-collapse SN explosion: an RSG progenitor most likely leads to a SNIIL, SNIIP, or SNIIn (Heger et al. 2003; Smith 2014; Anderson et al. 2012), whereas an sgB[e], a star stripped of most of its H envelope, ends as SNIIb (e.g. SN1987A ; Saio et al. 1988). RSGs are considered to be the main progenitors of SN IIP, which, according to the models, require progenitor masses of up to $25 - 30M_\odot$. However, RSGs that have been observed as direct SNe progenitors have $M_\mathrm{i} \leq 17M_\odot$ (the so-called 'RSG problem'; Smartt 2009), though Davies & Beasor (2018) suggest that unaccounted reddening from foreground extinction may provide a solution. Better characterisation of RSG outflows is required to solve this problem, especially since RSG mass-loss rates might be significantly overestimated in current stellar evolution models (Beasor et al. 2020).

Mass loss also impacts the angular-momentum evolution (spin-up) of the star, causing changes in outflow morphology with, e.g., massive circumstellar disks around near-critically rotating sgB[e] stars, changes in the stellar magnetic field embedded in the CSE into which the supernova remnant expands, changes in the internal mixing, and changes in the ultimate r-process yields (e.g. Heger & Langer 1998; Ignace et al. 1998; Prantzos et al. 2018; Maeder 1992; Maravelias et al. 2018; Martins et al. 2017; Meynet et al. 2015).

Mass loss creates a CSE with which the SN ejecta will interact, driving a reverse shock potentially destroying dust particles formed around the RSG, and causing hydrodynamical instabilities. The mass-loss history affects the SN light curve, and asymmetries in the CSE affect the morphology of the supernova remnant (Orlando et al. 2007, 2020). Anisotropies might also cause non-spherical explosions leading to newly born pulsars at anomalously high space velocities (Jura et al. 2001).

Mass loss is clearly decisive in the evolution of massive stars, and all the above points underscore the need to understand different aspects of mass loss: the mechanism(s) behind it, the rate and mass-loss history, the gaseous and dusty content, and the outflow dynamics and morphology.

2 Objective

We aim to address several of the points raised above by observing ^{12}CO, ^{13}CO, SiO, and HCN emission towards a number of massive evolved stars. The molecular component of their outflows has only recently become a topic of investigation. We know now that molecules can exist in these environments (e.g. Rizzo et al. 2014; Kraus 2009) and wish to constrain the properties of this outflow component to increase our overall understanding of these extreme environments. CO emission probes the density, temperature, mass-loss rate, and the outflow kinematics. SiO and HCN emission probe the kinematics and the chemical content. ^{12}CO and ^{13}CO line emission will allow us to probe ^{12}C/^{13}C, setting constraints on stellar evolution models (Kraus 2009). The proposed observations serve as a pilot study. Follow-up observations will expand the sample and targeted species, and will be developed based on the outcome of the proposed observations.

We include **2 candidate LBVs** (MN 90, HD 168625) in our sample. Line intensity estimates are based on the mass-loss rates and distances reported by Arneson et al. (2018) for the 2 cLBVs, and on the similarity in outflow parameters to known RSG/YHG sources. We also include **2 sgB[e] sources** (Hen 3-298, Hen 3-1453). The properties of the equatorial (disk) outflows of sgB[e] stars are also close to those of RSG/YHG sources, with densities 2-3 orders of magnitude higher and terminal wind velocities ($60 - 80$ km/s) at least ten times slower than their fast, line-driven polar winds (Zickgraf et al. 1996).

3 Observations

We wish to recover the CO and SiO and/or HCN lines at a signal-to-noise ratio of 30 and 10, respectively, at a velocity resolution of 4 km/s (cLBVs) or 8 km/s (sgB[e]), sufficient to reliably detect, identify, and measure emission with multiple bins across the profile. The high signal-to-noise ratio in CO will allow us to detect multiple components in the wind, if there are any. This multi-component nature is likely, when comparing to well-known massive evolved stars like VY CMa and IRC +10420 (De Beck et al. 2010; Quintana-Lacaci et al. 2016; Teyssier et al. 2012; Ziurys et al. 2007). We estimate intensities based on available masses, mass-loss rates and distances from the literature (e.g. Arneson et al. 2018; Pasquali et al. 2002).

^{12}CO($J = 2-1$) and ^{13}CO($J = 2-1$) can be observed simultaneously with nFLASH230, ^{12}CO($J = 3-2$) and ^{13}CO($J = 3-2$) can be observed simultaneously with SEPIA345. Considering the low values of ^{12}C/^{13}C in massive evolved stars (Kraus 2009, 2019), we aim to recover the ^{13}CO emission at signal-to-noise ratios $3 - 10$. SiO($J = 5-4$) and HCN($2-1$) can be observed simultaneously with SEPIA-B5. We prioritise the detection of CO line emission: if either of the two CO lines is observed at a signal-to-noise ratio above 10 at the requested rms noise level, we request to also carry out the SiO/HCN observation. The observational setup will be optimised to cover as many as possible likely emission lines for these targets (e.g. N-bearing species, given the N-enrichment of evolved massive stars).

Clear paths for follow-up are to (1) map CO (with e.g. APEX to retrieve larger scales or ALMA to obtain higher angular resolution), (2) observe additional molecular species and/or transitions for the sources with detected lines, to better constrain the molecular chemistry, and (3) extend the sample to be observed in CO line emission, to probe the diversity among the circumstellar environments of massive evolved stars. These molecular studies should be put into direct relation to the results obtained from dust observations. Observations of the molecular ring nebulae around WR stars will also be a part of related future studies.

Time request Observing times (see Table 1) were calculated for beam switching at 3 mm PWV (nFLASH230) and 2 mm PWV (SEPIA345 and SEPIA-B5) and a source elevation of 45 deg. Accounting for overheads for tuning, pointing, and focussing, we request a maximum total observing time with APEX of 21.3 hours.

References

Anderson, J. P., Habergham, S. M., James, P. A., & Hamuy, M. 2012, MNRAS, 424, 1372
Arneson, R. A., Shenoy, D., Smith, N., & Gehrz, R. D. 2018, ApJ, 864, 31
Beasor, E. R., Davies, B., et al. 2020, MNRAS, 492, 5994
Danchi, W. C., Bester, M., et al. 1994, AJ, 107, 1469
Davies, B. & Beasor, E. R. 2018, MNRAS, 474, 2116
De Beck, E., Decin, L., et al. 2010, A&A, 523, A18
Drout, M. R., Massey, P., & Meynet, G. 2012, ApJ, 750, 97
Heger, A., Fryer, C. L., et al. 2003, ApJ, 591, 288
Heger, A. & Langer, N. 1998, A&A, 334, 210
Ignace, R., Cassinelli, J. P., & Bjorkman, J. E. 1998, ApJ, 505, 910
Jiang, Y.-F., Cantiello, M., et al. 2018, Nature, 561, 498
Jura, M., Velusamy, T., & Werner, M. W. 2001, ApJ, 556, 408
Kraus, M. 2009, A&A, 494, 253
Kraus, M. 2019, Galaxies, 7, 83
Levesque, E. M. 2010, New Astronomy Reviews, 54, 1
Maeder, A. 1992, A&A, 264, 105
Maravelias, G., Kraus, M., et al. 2018, MNRAS, 480, 320
Marigo, P. 2013, in IAU Symposium, Vol. 281, IAU Symposium, ed. R. Di Stefano, M. Orio, & M. Moe, 36–43
Martins, F., Simón-Díaz, S., et al. 2017, A&A, 599, A30
Meynet, G., Chomienne, V., et al. 2015, A&A, 575, A60
Orlando, S., Bocchino, F., et al. 2007, A&A, 470, 927
Orlando, S., Wongwathanarat, A., et al. 2020, arXiv e-prints, arXiv:2009.01789
Pasquali, A., Nota, A., et al. 2002, AJ, 124, 1625
Prantzos, N., Abia, C., et al. 2018, MNRAS, 476, 3432
Quintana-Lacaci, G., Agúndez, M., et al. 2016, A&A, 592, A51
Riffel, R., Pastoriza, M. G., RodrÃguez-Ardila, A., & Maraston, C. 2008, Monthly Notices of the Royal Astronomical Society, 388, 803
Rizzo, J. R., Palau, A., Jiménez-Esteban, F., & Henkel, C. 2014, A&A, 564, A21
Saio, H., Kato, M., & Nomoto, K. 1988, ApJ, 331, 388
Smartt, S. J. 2009, ARA&A, 47, 63
Smith, N. 2014, ARA&A, 52, 487
Teyssier, D., Quintana-Lacaci, G., et al. 2012, A&A, 545, A99
Zickgraf, F. J., Humphreys, R. M., et al. 1996, A&A, 315, 510
Ziurys, L. M., Milam, S. N., Apponi, A. J., & Woolf, N. J. 2007, Nature, 447, 1094

Figures & tables

	nFLASH230 $^{12}CO(2-1)$ $^{13}CO(2-1)$		SEPIA345 $^{12}CO(3-2)$ $^{13}CO(3-2)$		SEPIA-B5 $SiO(4-3)$ $HCN(2-1)$	
	T (K)	t (hrs)	T (K)	t (hrs)	T (K)	t (hrs)
cLBV						
HD 168625	0.29	0.1	0.71	0.1	0.08	0.1
MN 90	0.07	2.7	0.16	1.7	0.02	2.8
sgB[e]						
Hen 3-298	0.06	1.8	0.14	1.1	0.02	2.7
Hen 3-1453	0.06	1.4	0.15	0.9	0.02	2.1

Table 1: Sample overview with estimated peak antenna temperatures T and integration times t for different emission lines.

No PhD Students involved

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: Yes

This is an identical re-submission of 0107.F-9308, an approved proposal for the ongoing observing period. No observations have yet been carried out.

Additional remarks

ESO=edebeck

Observing run info :

Run: B backup strategy: In case of bad weather, we will limit our study to the CO J=2-1 observations and, if possible, the SiO/HCN observations