Onsala Proposal

Andrews 0108.F-9304

Investigation into the molecular content of the circumstellar envelopes of red supergiants and yellow hypergiants

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

Abstract

Mass-loss and outflows from evolved massive stars are important as feedback mechanisms of both mechanical and chemical feedback to their surroundings. Understanding the outflows and structures of the stellar winds and envelopes of massive evolved stars can help shed a light on the creation of asymmetric structures around their evolutionary descendants, core-collapse supernovae. The proposed study aims to investigate the circumstellar envelopes around two red supergiants, Betelgeuse and VX Sgr, and two yellow hypergiants, AFGL2343 and IRAS 17163, in order to determine the presence of asymmetry and structure in their outflows from SiO and HCN line profiles.

Applicants

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Is this a long term proposal: No

No overall scheduling requirements

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	SEPIA180 (159-211 GHz)	16h	175.5	> 2 mm	0:30 - 07:30 (VX Sgr), 02:00 - 08:00 (AFGL2343), 3:00 - 07:00 (IRAS17163), 03:00 - 20:00 (Betelgeuse)	We propose the two sidebands to be split, with 173.5 - 177.5 covered in the LSB and 161.5 - 165.5 covered in the USB.

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
WRAY 15-1676	17:19:49.30	-39:10:37.9	J2000	70.0	234	A	
VX Sgr	18:08:04.04	-22:13:26.6	J2000	5.0	234	A	
Betelgeuse	05:55:10.30	+07:24:25.4	J2000	4.0	234	A	
AFGL2343	19:13:58.60	+00:07:31.9	J2000	95.0	234	A	

Investigation into the molecular content of the circumstellar envelopes of red supergiants and yellow hypergiants

Scientific Rationale

Motivations: Mass-loss and outflows from evolved massive stars are important as feedback mechanisms of both mechanical and chemical feedback to their surroundings. Understanding the outflows and structures of the stellar winds and envelopes of massive evolved stars can help shed a light on the creation of asymmetric structures around their evolutionary descendants, core-collapse supernovae (SNe) (Chiotellis et al. 2020).

Understanding evolved stars and their mass-loss through stellar winds is important for a wide range of astrophysical phenomena. Evolved stars are a main chemical driver of the universe, providing direct enrichment from dust and gas outflows via their stellar winds. The chemical enrichment caused by these stars may in turn then influence the triggering and formation of giant molecular clouds (GMCs), involved in generating the next generation of stars. Massive stars, with initial masses of 10 - 40 $M_{\odot}$, experience violent phases of enhanced mass-loss during their lifetimes, characterised by the cool evolved stellar stages of red supergiants (RSGs) and yellow hypergiants (YHGs). However, examples of these stages are rare due to the short stellar lifetimes of these phases at 10,000 years. During these phases, mass-loss rates may reach up to 10^{-3} $M_{\odot}$ yr^{-1}. These powerful stellar winds are also responsible for depositing up to half of the stellar mass into the surrounding circumstellar medium, determining the end fate of the massive star and the nature of the eventual stellar remnant, as a neutron star (NS) or black hole (BH).

NSs and BHs have in recent years been found to be key sources for the presence of gravitational waves (Abbott et al. 2016). Outflows from massive stars impact the characteristics of the resultant core-collapse supernova (SN), with interactions between the CSE and the SN remnant influencing the resultant light curve and the observed morphology of the SN remnant (Orlando et al. 2020). Massive evolved stars, their outflows, and their mass-loss processes, also affect models, including stellar evolutionary codes (van Loon et al. 2005) and detailed photoionisation models of starburst galaxies (Levesque 2010). Despite the clear level of importance for these astrophysical objects, a full understanding of the chemical and physical processes at play for these stars and their stellar envelopes remains elusive. The molecular content of the extended envelopes and outflows of very few massive evolved stars have been studied in detail, with only the RSG VY CMa, studied extensively across multiple wavelength regimes, and a few line spectra surveys additionally carried out for the RSG NML Cyg and the YHG IRC+10420.

This Proposal: . The sources of interest proposed here are Betelgeuse, VX Sgr, AFGL2343, and IRAS17163, two RSGs and two YHGs, all found to have previous evidence of the presence of multiple component outflows (see the previous observations section below).

We aim to carry out a pathfinder study at these wavelengths on these four sources to determine more about the different outflows present around these sources that may be traced by the SiO J = 4 - 3 and HCN J = 2 - 1 molecular lines. By tracing these lines, it will also allow for different regions of the circumstellar envelopes to be traced. The HCN line should provide a tracer for all outflow regions. As SiO is expected to condense into dust particles closer to the star, then it will primarily trace only the spherical wind.

Follow-on observations could then be carried out to further constrain the molecular content and physical structures of the stellar outflows for these sources, building a wider understanding of the stellar envelopes of YHGs, with potential further observations to focus on observations of $H^{13}CN$, ^{29}SiO, and excited SiO lines (v = 1, 2, 3, 4). Additionally, we expect the possible detections of SiS and NS, SO_2 and HCN. All but the NS line have been seen for O-rich AGBs R Dor and IK Tau (Velilla Prieto et al. 2017; De Beck & Olofsson 2018), and different transitions for the molecular species SiS and NS have previously been detected around another YHG, IRC+10420 (Quintana-Lacaci et al. 2016).

Additionally, we have submitted a proposal to OSO to observe four RSGs, to search for multiple component outflows from SiO, SO and HCN lines. These two proposals will complement each other in investigating the outflows of evolved massive stars, although this APEX proposal also serves as a stand-alone observation that is not reliant on the OSO proposal.

Previous Observations: This study is proposed as a follow-on of spectral surveys carried out in the range $68-116$ GHz on two northern hemisphere sources, the RSG NML Cyg and YHG IRC+10420 with the OSO 20m dish (Andrews & De Beck in prep). Extensive surveys have so far been carried out for only one RSG, VY CMa (Kamiński et al. 2013b,a; Ziurys et al. 2007; Muller et al. 2007; Tenenbaum et al. 2010; Adande et al. 2013; Alcolea et al. 2013; Matsuura et al. 2014), and more observations are required to build up a systematic data-sets containing multiple examples of stars experiencing this stage of stellar evolution.

Previous observations have been detected for CO transitions around all of the requested sources, as shown in Figures 1 and 2, all of which show evidence for the presence of multiple components in the stellar envelopes. IRAS 17163 has previous CO observations (shown in Figure 2, Wallström et al. (2015)) and has been found to have a similar optical spectra to the YHG IRC+10420 (Koumpia et al. 2020). An enhanced blue-shifted component is clearly visible indicating multiple outflows around this source, and more recent ACA observations linked this emission to the presence of a "spur" located to the south-east of the source (Wallström et al. 2017), which indicates the possible presence of a bipolar outflow.

AFGL 2343 has previously been observed with the IRAM 30m telescope with the 1mm ($\sim$ 230 GHz) and the 3mm band ($\sim$ 86 GHz) (Quintana-Lacaci et al. 2016). Maps of the HCN (J = 1 - 0) and ^{29}SiO (J = 2 - 1) lines around AFGL2343 show asymmetry in the emission (Quintana-Lacaci et al. 2008), likely indicative of a phase of enhanced mass-loss, though it could also be caused by a shocked region. AFGL2343 has also been observed at higher frequencies ($\sim$550 - 1840 GHz) (Teyssier et al. 2012), with a significant red-shifted component implying the presence of asymmetry in its outflows.

Betelgeuse has previously been observed at 172.4 - 173.6 GHz with APEX, with a tentative detection of H^{13}CN found at a sensitivity of σ = 8mK. With a $^{12}/^{13}$C ratio of $\sim$ 6, (De Beck et al. 2010), we expect the line strength to be sufficient for a strong detection of the HCN J = 2 - 1. Additionally, several water and CO lines have been detected for the star at higher wavelengths ($\sim$ 550 - 1800 GHz, Teyssier et al. (2012)). Infrared imaging and photometry of VX Sgr has already shown that this RSG has likely experienced variable epochs of enhanced mass-loss (Gordon et al. 2018; Shenoy et al. 2016). These two red supergiants are well-studied sources known to host O-rich envelopes formed by dust-driven radiative winds (Gail et al. 2020).

Observing Plan

We assume normal weather conditions for APEX. The preference for night-time sources is taken into account when considering appropriate sources for this study; IRAS17163 will be observable at LST 23:00 - 07:00, AFGL 2343 at LST 02:00 - 08:00, and VX Sgr at LST 00:30 - 07:30. Betelgeuse will be observable at LST 13:00 - 20:00. We have used the ON-OFF observing time calculator at APEX V7.2 to estimate the total time needed to achieve our goal. Using SEPIA180 tuned to 175.5 GHz in the USB and 163.5 in the LSB, selecting a spectral resolution of 5 km/s and assuming a typical source elevation of 45 deg and a typical PWV of 2.0 mm, this provides a required rms level of 2.5 mK[Ta*] in 3.9 hours for each source (including telescope and calibration overheads). This then leads to a total time requested on APEX of **15.6 hours**.

This will allow us to capture two main lines of interest: the SiO (J = 4 - 3) line at 173.688 GHz, and the HCN (J = 2 - 1) line at 177.261 GHz. With a LSB range of 161.5 - 165.5 GHz and a USB range of 173.5 - 177.5 GHz, possible additional detections would include the SiS (J = 9 - 8), SO_2 (J = $5_{2,4}$ - $5_{1,5}$) and NS (J = $4_{1,4}$ - $3_{1,3}$) lines in the LSB, and SO_2 (J = $7_{2,6}$ - $7_{1,7}$) and HCN (J = 2 - 1, v_2 = 1) in the USB, if present. These lines are summarised in Table 1.

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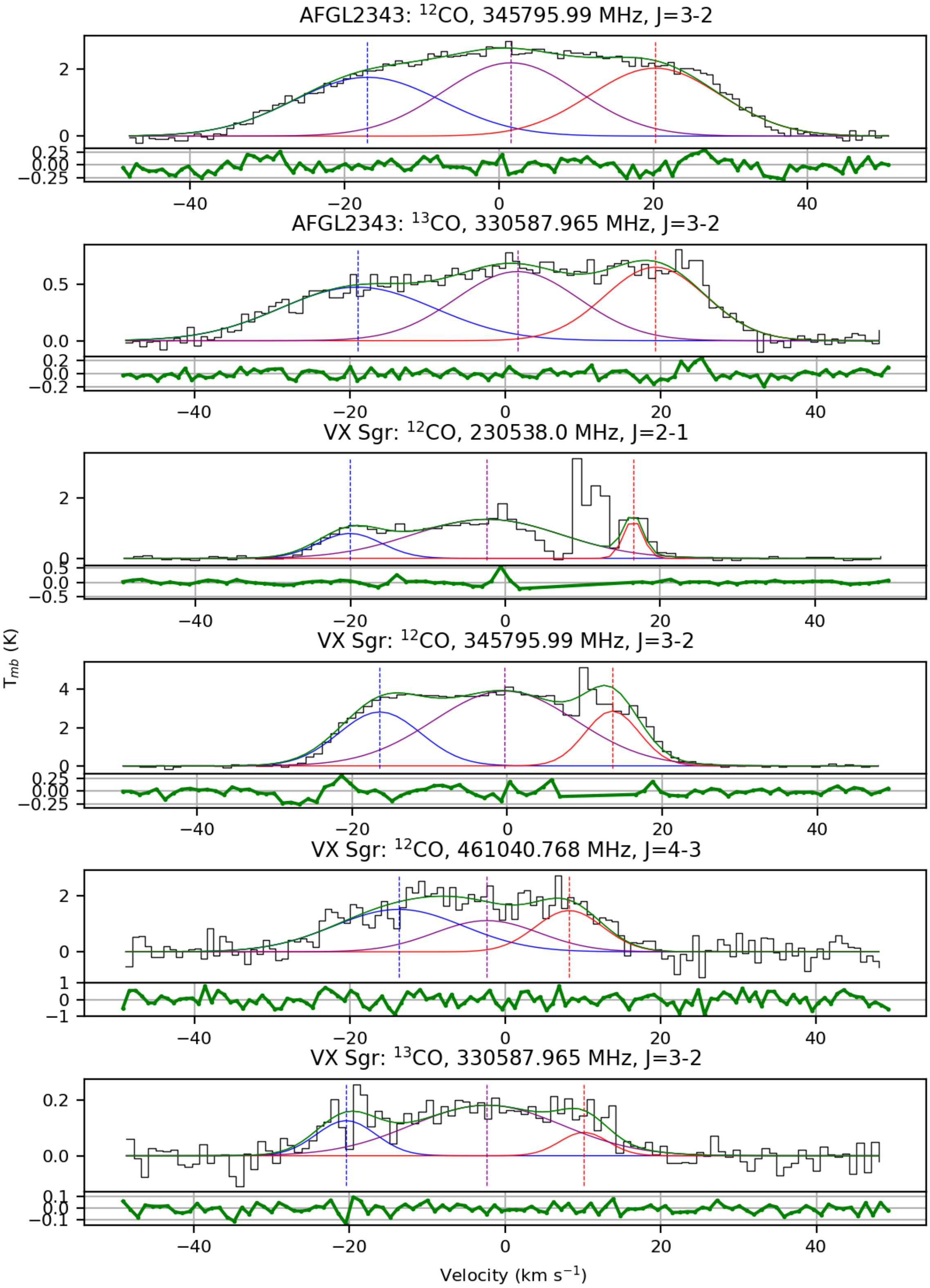
Figures

Table 1: Lines of interest.

Line	Rest Frequency (GHz)	Transition	E_{upp} (K)	Sideband
SiS	161786.656	J = 9 - 8	39.2	LSB
SO_2	165144.651	J = $5_{2,4}$ - $5_{1,5}$	23.6	LSB
NS	161636.517	J = $4_{1,4}$ - $3_{1,3}$	16.7	LSB
SiO	173688.238	J = 4 - 3	20.8	USB
SO_2	175275.721	J = $7_{2,6}$ - $7_{1,7}$	35.5	USB
HCN	177238.655	J = 2_1 - 1_1 (v_2 = 1)	1037.1	USB
HCN	177261.11	J = 2 - 1	12.8	USB


AFGL2343: ^{12}CO, 345795.99 MHz, J=3-2
AFGL2343: ^{13}CO, 330587.965 MHz, J=3-2
VX Sgr: ^{12}CO, 230538.0 MHz, J=2-1
VX Sgr: ^{12}CO, 345795.99 MHz, J=3-2
VX Sgr: ^{12}CO, 461040.768 MHz, J=4-3
VX Sgr: ^{13}CO, 330587.965 MHz, J=3-2
T$_{mb}$ (K)
Velocity (km s^{-1})

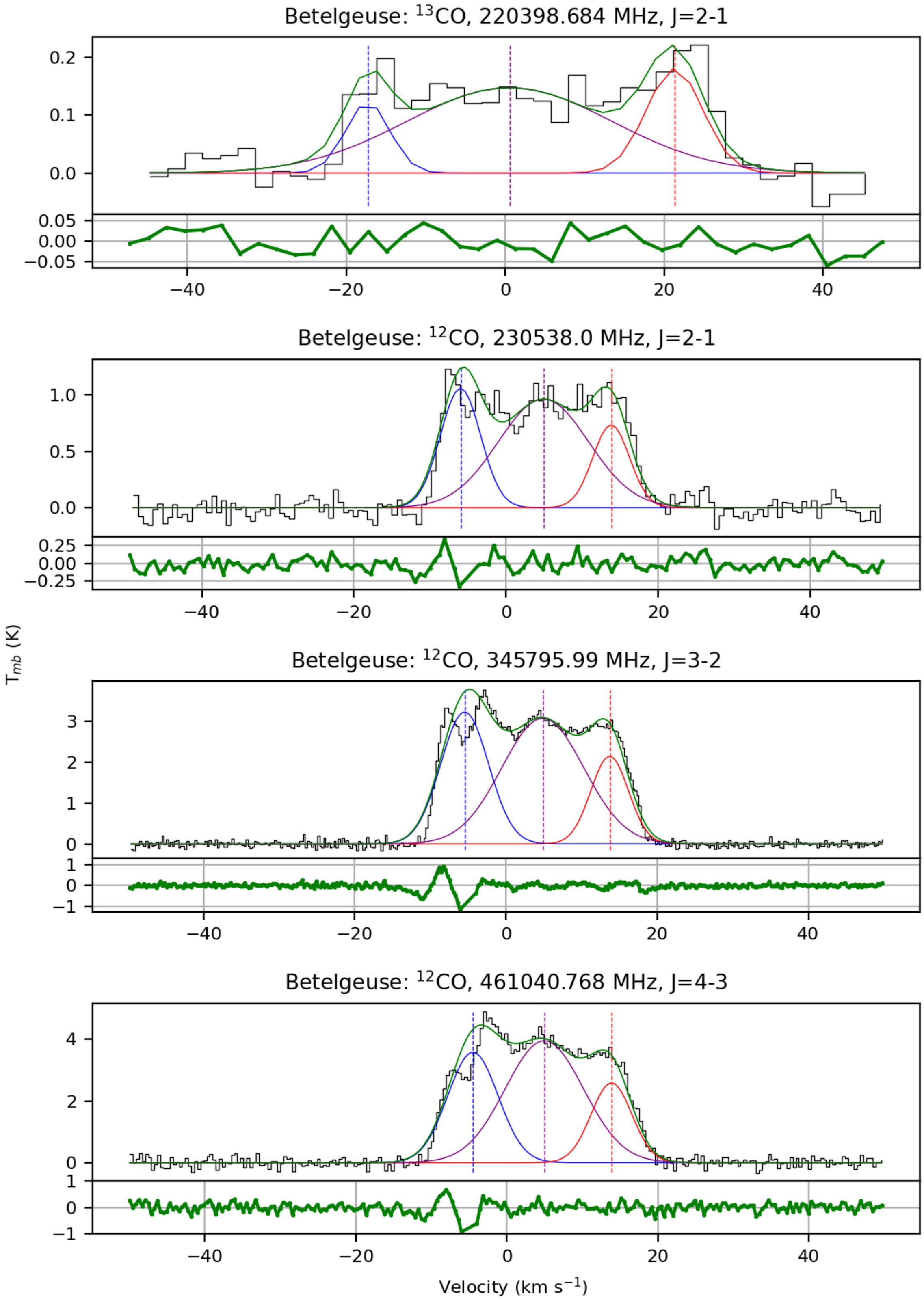


Figure 1: Multiple component Gaussian fits to CO lines from JCMT data for the YHG AFGL2343, and the RSGs VX Sgr and Betelgeuse. It can be seen clearly that blue-shifted and red-shifted components are required to explain the overall line profile shapes. Below each spectra the residuals on the overall combined fit found for the sum of the three Gaussians are shown.

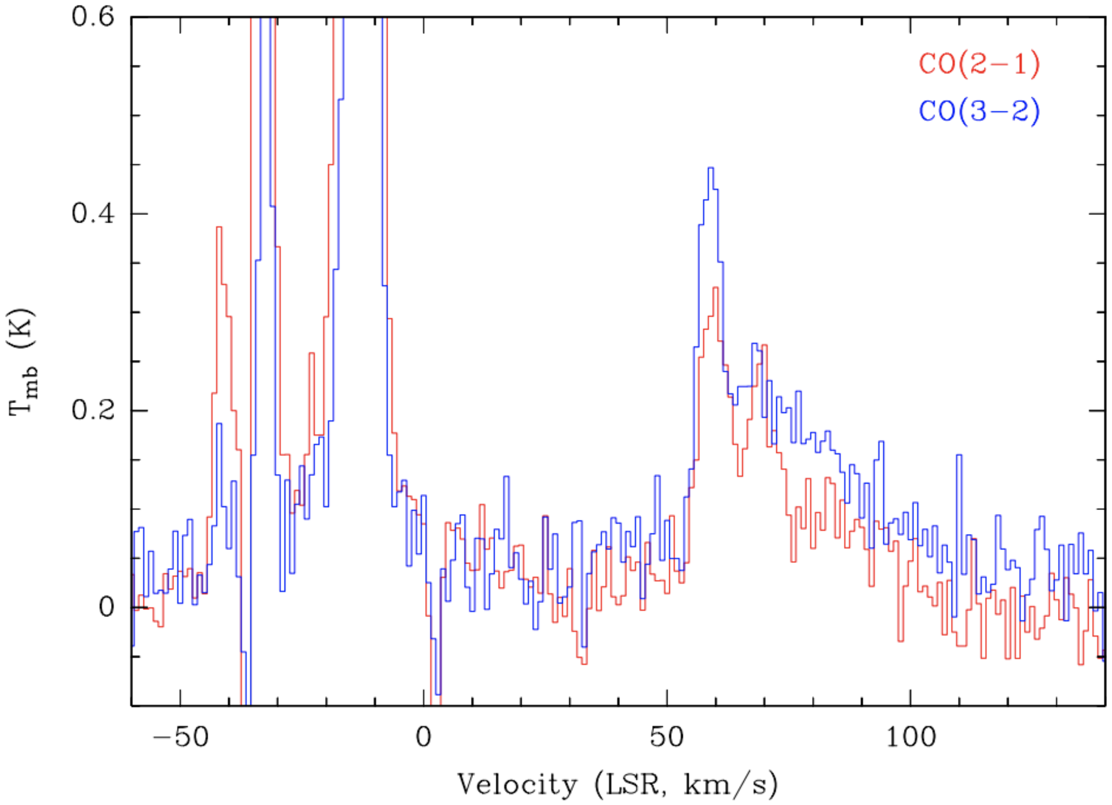


Figure 2: APEX spectra of the CO $J = 2 - 1$ (red) and $J = 3 - 2$ (blue) line emission around the YHG IRAS 17163, showing clear evidence of multiple components in the profiles for both lines. The emission detected at negative velocities is interstellar, with the emission between 50 and 110 km s^{-1} is attributed to IRAS17163. Taken from Wallström et al. (2015).

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-9311, an approved proposal for the ongoing observing period. No observations have yet been carried out.
The original proposal is linked to an accepted proposal, O2020b-06, for the Onsala 20m dish investigating northern RSG sources, including Betelgeuse as also included here, to search for multiple component outflows from SiO, SO and HCN lines. These two proposals will complement each other in their scientific aims.

Additional remarks

ESO=<handrews>

Observing run info :