Onsala Proposal

Beck 0108.F-9302

Charting Circumstellar Chemistry of Carbon AGB stars

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

Abstract

Our knowledge of the chemistry occurring in the stellar atmospheres and circumstellar envelopes of AGB stars is far from complete. Currently, theoretical chemical models are mainly based on constraints set by observations of the nearby, high-mass-loss-rate carbon-rich AGB star IRC+10216. We wish to study in detail five carbon-rich outflows, which we have selected for their brightness, molecular richness, similar outflow properties, and spread in carbon-isotopic ratio 12C/13C.

The requested spectral scans of four carbon-rich AGB outflows with APEX/SEPIA-B5 at 159-211 GHz will help probe the similarities and differences among a modest sample of carbon stars. Detailed radiative transfer modelling of the proposed APEX/SEPIA-B5 and earlier obtained APEX/PI230 surveys, ALMA surveys at 0.8 arcsec resolution over the range 85-115 GHz, and multiple auxiliary data sets will allow us to constrain the abundance profiles of the detected species. This will enable detailed comparisons and strong constraints on the chemical networks active in carbon-rich outflows.

Applicants

Name	Affiliation	Email	Country		Potential observer
Elvire De Beck	Chalmers University of Technology (Space, Earth and Environment)	elvire.debeck@chalmers.se	Sweden	Pi	Yes
Dr. Lars-Ake Nyman	ESO	nymanla@chalmers.se	Chile		
Hans Olofsson	Chalmers University of Technology (Space, Earth and Environment)	hans.olofsson@chalmers.se	Sweden		
Ramlal Unnikrishnan	Chalmers University of Technology (Space, Earth and Environment)	ramlal.unnikrishnan@chalmers.se	Sweden		Yes

Contact Author

Title		***Institute***	Chalmers University of Technology
Name	Elvire De Beck	***Department***	Space, Earth and Environment
Email	elvire.debeck@chalmers.se	***Address***	
Phone(first)	0046317725529	***Zipcode***	
Phone(second)		***City***	
Fax		***State***	
		Country	Sweden

Is this a long term proposal: No

Overall scheduling requirements

There are no strict scheduling requirements. IRC+10216 goes into Sun avoidance during the second half of the planned OSO observing run in September. The short total observing time needed for this target would make it possible to complete (if scheduled) in the first few days.

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	SEPIA180 (159-211 GHz)	4h (4h)	173	> 2 mm	06:00-19:00; 21:00-01:30	LSB centered at 161.0 GHz USB centered at 173.0 GHz Times calculated for 173.0GHz. None
B	APEX	SEPIA180 (159-211 GHz)	3h (3h)	168	> 2 mm	06:00-19:00; 21:00-01:30	LSB centered at 168.0 GHz USB centered at 180.0 GHz Times calculated for 168.0GHz. None
C	APEX	SEPIA180 (159-211 GHz)	4h (4h)	171.5	> 2 mm	06:00-19:00; 21:00-01:30	LSB centered at 171.5 GHz USB centered at 183.5 GHz Times calculated for 171.5GHz. None
D	APEX	SEPIA180 (159-211 GHz)	7h (7h)	176.5	> 2 mm	06:00-19:00; 21:00-01:30	LSB centered at 164.5 GHz USB centered at 176.5 GHz Times calculated for 176.5GHz. None
E	APEX	SEPIA180 (159-211 GHz)	2h (2h)	198.5	> 2 mm	06:00-19:00; 21:00-01:30	LSB centered at 186.5 GHz USB centered at 198.5 GHz Times calculated for 198.5GHz. None
F	APEX	SEPIA180 (159-211 GHz)	6h (6h)	190.0	> 2 mm	06:00-19:00; 21:00-01:30	LSB centered at 190.0 GHz USB centered at 202.0 GHz Times calculated for 190.0GHz. None
G	APEX	SEPIA180 (159-211 GHz)	3h (3h)	193.5	> 2 mm	06:00-19:00; 21:00-01:30	LSB centered at 193.5 GHz USB centered at 205.5 GHz Times calculated for 193.5GHz. None

Observing runs are continued on the last page

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
IRC +10216	09:47:57.40	+13:16:43.5	J2000	-26.5	10	A B C D E F G H	
AFGL 3068	23:19:12.60	+17:11:33.1	J2000	-30.9	440	A B C D E F G H	
IRAS 07454-7112	07:45:02.41	-71:19:45.8	J2000	-38.7	640	A B C D E F G H	
IRAS 15082-4808	15:11:41.43	-48:19:58.7	J2000	-3.3	470	A B C D E F G H	

Charting Circumstellar Chemistry of Carbon AGB stars

1 Scientific rationale

The chemical evolution of matter in the Universe crucially depends on the different "polluters". Asymptotic giant branch (AGB) stars, cool evolved stars of low to intermediate birth mass, are among the major contributors. They nucleosynthesise heavy elements and release these in steady stellar winds, depositing up to half of the stellar mass in gas and newly formed dust into the interstellar medium (ISM). The physical properties of the wind are crucial to the description of the mass-loss process and evolution of the majority of stars. The chemical characterisation of the winds is crucial to understand the overall enrichment of galaxies and to understand astrochemical networks, in particular those that lead to the formation of complex species, like polyaromatic hydrocarbons (PAHs), and eventually microscopic dust particles in the outflows. This forms an important complement to studies of astrochemistry in the ISM and proto-planetary disks.

Molecular spectroscopy at (sub)millimeter wavelengths is an extremely powerful tool to study gas-phase species present in the outflows of evolved stars. Observations of CO have led to their basic physical characterisation (wind speed v_∞, mass-loss rate $\dot{M}$, temperature). Targeted observations of molecules such as SiO, HCN, and H_2O have helped to further constrain e.g. wind acceleration, geometry, and depletion of certain species from the gas phase into dust grains. An excellent and comprehensive way to sample the outflows' chemical content is to perform spectral surveys covering available spectral windows without confining oneself to a few pre-selected molecular transitions. This has been done for only very few objects, including the carbon-rich IRC +10216 and IRAS 15194-5115, the oxygen-rich IK Tau and R Dor, and the intermediate (S-type) W Aql (e.g. Cernicharo et al. 2000; De Beck et al. 2015; De Beck & Olofsson 2018, 2020; Smith et al. 2015; Velilla Prieto et al. 2017; Woods et al. 2003). In all cases, the surveys have led to unexpected detections and a significant extension of our chemical inventory, with the notable example of W Aql, for which De Beck & Olofsson (2020) recently found from an unbiased survey that the outflow is much more carbon-rich than thought before based on a range of targeted molecular observations. The current and coming generations of instrumentation on e.g. APEX and ALMA are quickly improving the efficiency at which such surveys can be carried out, sounding in a new era for astrochemistry studies.

Much of our knowledge about molecular line emission and chemistry in outflows from carbon-enriched AGB stars is based on the results obtained for a single object, the nearby, high-mass-loss-rate carbon star IRC +10216. This rather extreme object is well-studied, both with single-dish and interferometry observations (e.g. Patel et al. 2011; Cernicharo et al. 2000, 2010, 2013, 2015). To understand the chemistry and morphology in carbon-rich outflows in a comprehensive way, we need to probe a sample of such environments to uncover possible differences linked to the outflow density, evolutionary stage, or stellar parameters such as temperature and variability.

Our initial sample consists of five stars, selected for their high luminosities, high mass-loss rates ($\dot{M} \approx 10^{-5}\,M_\odot$/yr), similar densities $\dot{M}/v_\infty$, and richness in molecular lines based on earlier observations (e.g. Nyman et al. 1993; Woods et al. 2003; Smith et al. 2015). One clear difference between the sources is their estimated isotopic ratio $^{12}C/^{13}C$, which is 4, 6, 17, 35, and 45 for AFGL 3068, IRAS 15194-5115, IRAS 07454-7112, IRAS 15082-4808, IRC +10216 respectively (Woods et al. 2003; Kahane et al. 2000; De Beck et al. 2010). From the PI230 observations we obtained in P104, we preliminarily derive $^{17}O/^{18}O$ values of 0.6, 0.6, 0.3, 1.4, and 1.5. These isotopic ratios indicate a diversity in stellar initial masses and nucleosynthetic histories, i.e. evolutionary status. The differences in physical and chemical properties between these outflows, and how these are linked to the intrinsic diversity needs further investigation and requires an extension of the observed spectrum.

2 Sample, analysis & results

Our sample consists of five carbon-rich stars: IRAS 15194-5115, IRAS 15082-4808, IRAS 07454-7112, IRC +10216, and AFGL 3068. We have obtained PI230 surveys for all (during P104) and SEPIA-B5 observations for IRAS 15194-5115. The SEPIA-B5 surveys of the remaining four stars will provide us with emission lines of “simple” parent species formed close to the star (e.g. HCN, SiO, SiS, CS), of daughter species formed further (e.g. SiN, SiC_2, C_2H, C_4H, c-C_3H_2, HC_3N, HCP), and of several of their less abundant isotopologues. We also expect to recover emission from Na- and Al-bearing species (NaCl, AlCl, AlF), as is the case in the PI230 spectra (P104) and APEX/SHeFI spectrum of IRAS 15194-5115 (Figs. 1, 3). For reference: the SEPIA-B5 spectrum of IRAS 15194-5115 holds ~150 emission features and we found clear differences between the PI230 spectra (Figs. 3, 4), with in total ~300 features. And as with all of our previous surveys, we are likely to recover some unexpected line emission, at no extra cost.

The SEPIA-B5 observations will be complemented with available APEX and ALMA data and auxiliary data from previous studies (e.g. Woods et al. 2003). The available ALMA observations provide *(1)* access to a continuous frequency range that APEX does not cover (85 − 115 GHz), containing molecular emission lines with different excitation properties than probed with PI230 and SEPIA-B5, and as such necessary to constrain abundances, and *(2)* morphological information at roughly 0.8 arcsecond angular resolution (~500 AU scale; outflows are on several thousand AU scales), opening up the possibility to localise emission regions (Fig. 2) and strongly constrain the chemical networks spatially and temporally. We will also connect this to the ongoing study on IRAS 15194-5115 for which we have surveys covering 159 − 368 GHz (APEX) and 480 − 1122 GHz (Herschel/HIFI; De Beck et al., *in prep.*).

Our analysis will build on and refine outflow models constructed based on CO and dust emission (Woods et al. 2003). We will calculate non-LTE radiative transfer models for the observed molecular emission, using the codes presented by Schöier & Olofsson (2001); Maercker et al. (2008) and derive molecular abundance profiles from which we will be able to also derive accurate isotopic ratios (e.g. $^{12}C/^{13}C$, $^{17}O/^{18}O$) based on the multitude of detected isotopologues. Vlemmings et al. (2013); Saberi et al. (2017) have shown that one can find significantly different $^{12}C/^{13}C$ depending on the molecule studied, as their isotopologues can be differently affected chemically. Multiple molecules should therefore be probed to determine robust values.

The proposed observations will provide necessary constraints on molecular abundance profiles and will lead to the most complete molecular study of any sample of AGB stars, by sampling large spans in the excitation conditions for a large number of molecules. The direct comparison between the outflows will be instrumental in uncovering similarities and differences among this modest sample (see e.g. preliminary results in Figs. 3 and 4) and will set strong spatial and temporal constraints on the chemical networks in carbon-rich outflows, which constitute critical locations for the formation of PAHs and large amounts of dust. A natural continuation of this study will be to extend the sample to include lower-density, lower-mass-loss rate stars, to probe the chemical differences at varying densities.

3 Observations

We request to survey four outflows at 159 − 211 GHz with APEX/SEPIA-B5, at an rms corresponding to 0.15% of the CO(J=2 − 1) peak intensity, in line with the sensitivity of our SEPIA-B5 survey of IRAS 15194-5115 (Fig. 1), providing a homogeneous data set. The velocity resolution is target dependent, to ensure 6 bins across emission lines, for reliable detection and identification. An overlap with our PI230 data (205 − 211 GHz; no extra tuning needed) will allow us to check for calibration consistency and possible intrinsic variability of the observed molecular emission (from e.g. HC_3N, C_3N, C_4H, SiC, SiC_2), providing valuable input for our radiative-transfer analysis. A duplication of IRAS 07454-7112 observations (E-099.D-0750; PI: Danilovich) is necessary to reach the required sensitivity and we already identified strong variability for at least one SiC_2 line between the earlier SEPIA-B5 data and the PI230 data.

We calculated beam-switching times using the Observing Time Calculator assuming 2 mm PWV and 45 degrees elevation. The rms noise outside 178 − 189 GHz is the limiting factor, avoiding the high-rms effect in the 183 GHz window. Accounting for overhead time for tuning, pointing, and focussing, we request 36.6 hours of observing time.

Figures

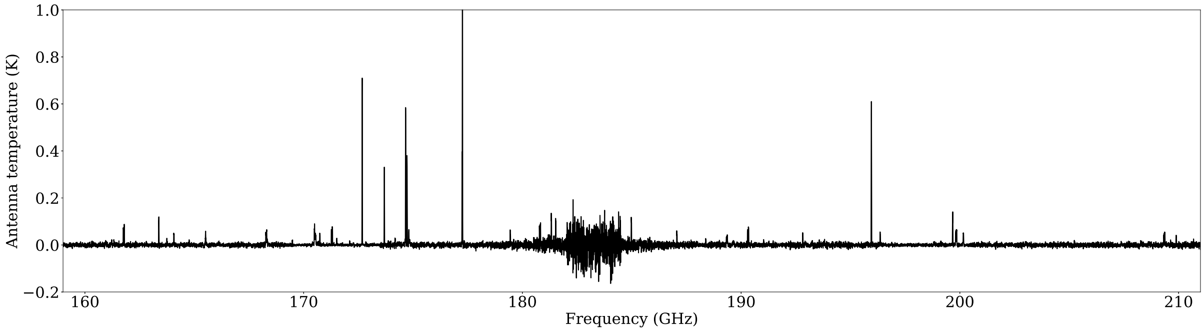

Figure 1: IRAS 15194-5115 in the range 159 − 211 GHz (De Beck et al., *in prep.*).

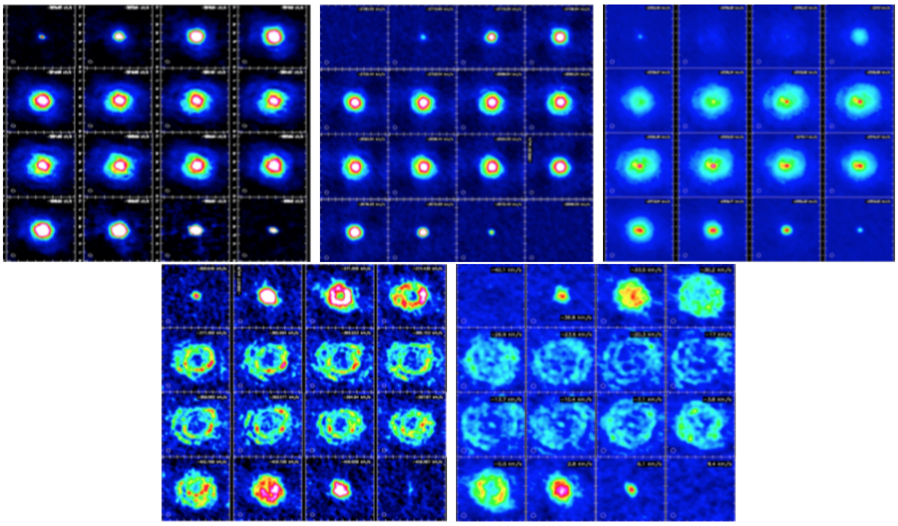

Figure 2: ALMA observations showing different morphologies in the emission from a selection of molecules. Top row: centrally peaked lines from CS, SiO, and HCN. Bottom row: shell morphology of HC_3N and SiC_2 emission.

References

Cernicharo, J., Daniel, F., et al. 2013, ApJ, 778, L25
Cernicharo, J., Guélin, M., & Kahane, C. 2000, A&AS, 142, 181
Cernicharo, J., McCarthy, M. C., et al. 2015, ApJ, 806, L3
Cernicharo, J., Waters, L. B. F. M., et al. 2010, A&A, 521, L8
De Beck, E., Decin, L., et al. 2010, A&A, 523, A18
De Beck, E., Kamiński, T., et al. 2015, in Astronomical Society of the Pacific Conference Series, Vol. 497, Why Galaxies Care about AGB Stars III: A Closer Look in Space and Time, ed. F. Kerschbaum, R. F. Wing, & J. Hron, 73
De Beck, E. & Olofsson, H. 2018, A&A, 615, A8
De Beck, E. & Olofsson, H. 2020, A&A, 642, A20
Kahane, C., Dufour, E., et al. 2000, A&A, 357, 669
Maercker, M., Schöier, F. L., et al. 2008, A&A, 479, 779
Nyman, L. A., Olofsson, H., et al. 1993, A&A, 269, 377
Patel, N. A., Young, K. H., et al. 2011, ApJS, 193, 17
Saberi, M., Maercker, M., et al. 2017, A&A, 599, A63
Schöier, F. L. & Olofsson, H. 2001, A&A, 368, 969
Smith, C. L., Zijlstra, A. A., & Fuller, G. A. 2015, MNRAS, 454, 177
Velilla Prieto, L., Sánchez Contreras, C., et al. 2017, A&A, 597, A25
Vlemmings, W. H. T., Maercker, M., et al. 2013, A&A, 556, L1
Woods, P. M., Schöier, F. L., Nyman, L. Å., & Olofsson, H. 2003, A&A, 402, 617

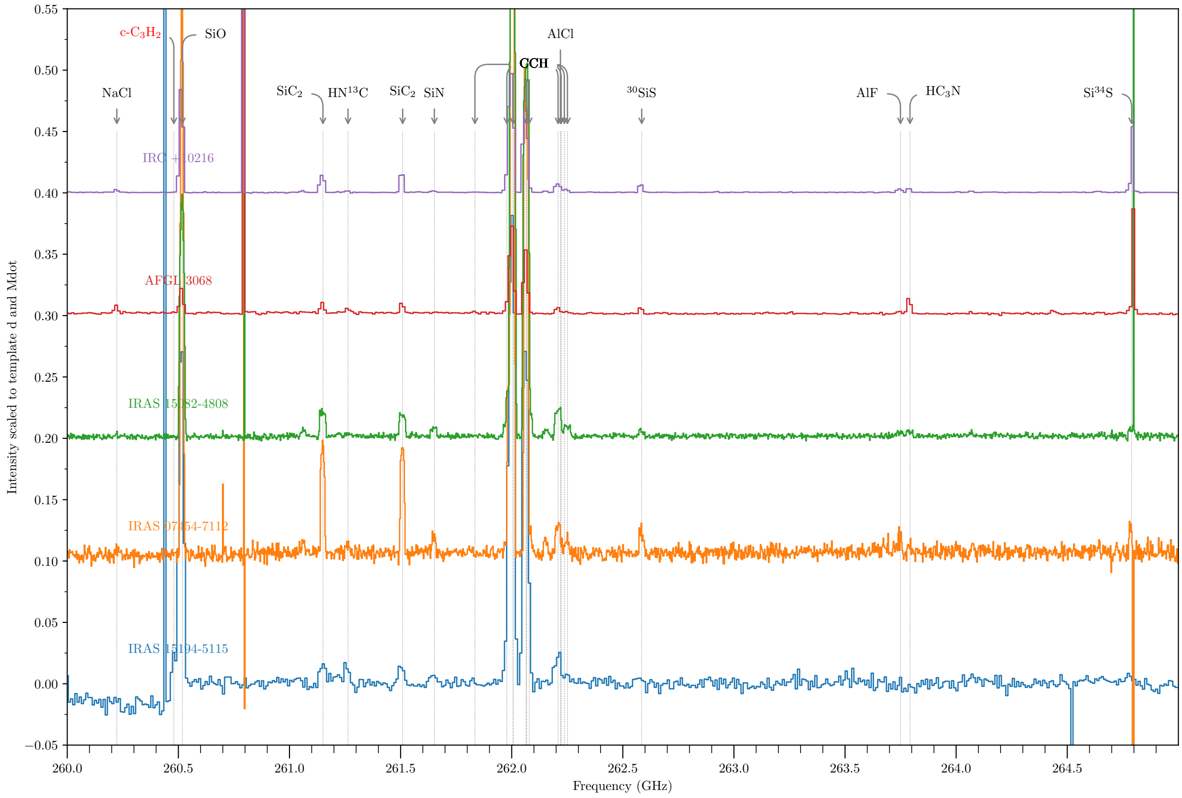

Figure 3: Observations with APEX at 260 – 265 GHz towards the sample. Spectra are offset vertically for visibility, and scaled with $\left(\frac{\dot{M}}{10^{-5}\mathrm{M}_\odot/\mathrm{yr}}\right) / \left(\frac{d}{600\mathrm{pc}}\right)^2$ to enable direct comparison.

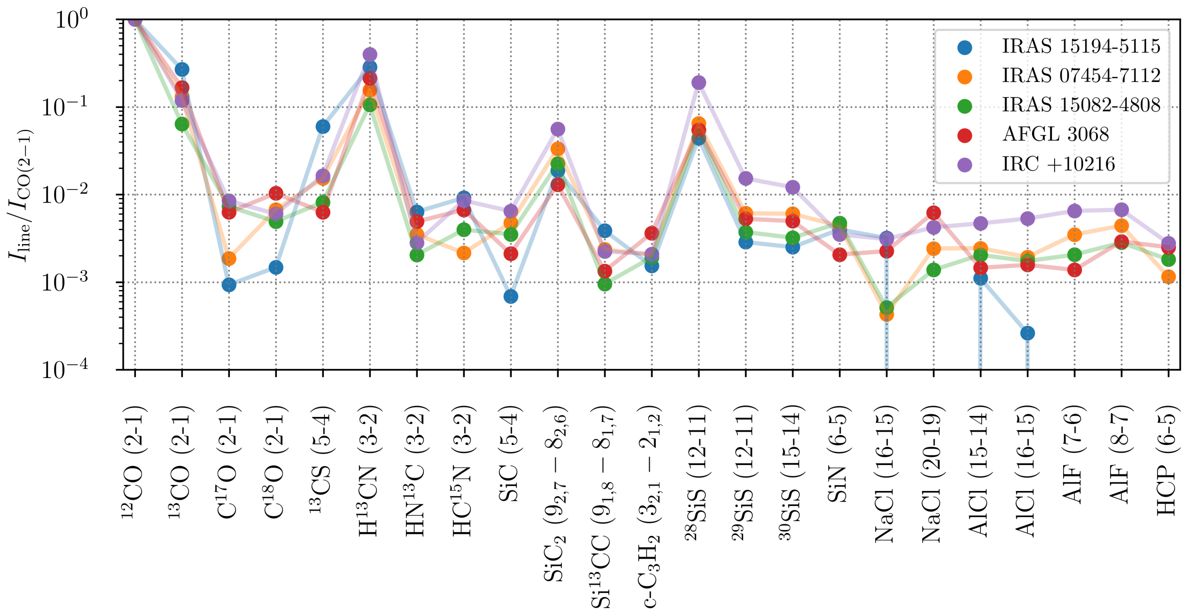

Figure 4: Integrated line intensities of selected molecular transitions scaled to the integrated intensity of the respective source's CO (2 – 1) emission line. The plot reflects, for example, a ^{13}C-enrichment towards IRAS 15194-5115 and AFGL 3068, and possibly a lower Al- and/or F-abundance towards IRAS 15194-5115 (AlF was observed towards all sources, and not detected towards IRAS 15194-5115). Like Fig. 3, this indicates relative differences in molecular abundances across the sample which need to be solidified with the measurement and analysis of additional emission lines.

Students involved

Student	Level	Applicant	Supervisor	Applicant	Expected completion date	Data required
Ramlal Unnikrishnan	Doctor	No	Elvire De Beck	Yes	2024/10	Yes

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-9310, an approved proposal for the ongoing observing period. No observations have yet been carried out.
O-099.f-9306, O-0100.f-9303: The effect of wind density on the chemistry around AGB stars; 41 hours, APEX/SEPIA-B5, PI De Beck; data obtained, reduced, analysis ongoing
E-099.D-0750: A spectral survey of lower mass-loss rate carbon stars; 40 hours, APEX/SEPIA-B5; PI Danilovich; data obtained, reduced, analysis ongoing
O-087.F- 9319A-2011, O-094.F-9318A-2014, O-098.f-9303: Spectral surveys of R Dor and II Lup with APEX; data obtained, reduced, analysis ongoing for II Lup, in combination with Herschel/HIFI survey (49hours); publication on R Dor: De Beck & Olofsson (2018), De Beck & Olofsson (in prep.) for II Lup
O-0104.f-9305: APEX/PI230 observations 205-265GHz - will be integrally combined with the proposed data in the PhD project of R. Unnikrishnan

Additional remarks

ESO=edebeck

Observing run info :

Run: A backup strategy: Calculations for 2mm PWV, 45 deg elevation, beam switching.
Run: B backup strategy: Calculations for 2mm PWV, 45 deg elevation, beam switching.
Run: C backup strategy: Calculations for 2mm PWV, 45 deg elevation, beam switching.
Run: D backup strategy: Calculations for 2mm PWV, 45 deg elevation, beam switching.
Run: E backup strategy: Calculations for 2mm PWV, 45 deg elevation, beam switching.
Run: F backup strategy: Calculations for 2mm PWV, 45 deg elevation, beam switching.
Run: G backup strategy: Calculations for 2mm PWV, 45 deg elevation, beam switching.
Run: H backup strategy: Calculations for 2mm PWV, 45 deg elevation, beam switching.

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
H	APEX	SEPIA180 (159-211 GHz)	2h (2h)	197.0	> 2 mm	06:00-19:00; 21:00-01:30	LSB centered at 197.0 GHz USB centered at 2.09.0 GHz Times calculated for 197.0GHz. None