Onsala Proposal

Liseau 0115.F-9301

Hunting O2 with SO+ -- continued

Semester: feb2025 **Science Cat.: ISM and star formation**

Abstract

We use SO+ as a substitute for O2 to identify sources that potentially contain molecular oxygen. However, so far, the "statistics" are based on only a few sources. We thus propose to use for SO+ the nFLASH230 and SEPIA180 receivers to survey sources which have been observed with Odin, SWAS and Herschel for O2 . In this case, also O2 upper limits will prove meaningful. This proposal is a resubmission/continuation to complete proposal 0113.F-9302.

We ask for 20 hours of telescope time.

Applicants

Name	Affiliation	Email	Country		Potential observer
Dr. Anders Olof Henrik Olofsson	Chalmers University of Technology (Space, Earth and Environment)	henrik.olofsson@chalmers.se	Sweden		Yes
Dr.Prof.em. Rene Liseau	Chalmers University of Technology (Space, Earth and Environment)	rene.liseau@chalmers.se	Sweden	Pi	
Dr. Bengt Larsson	Stckholm University (Astronomy)	bem@astro.su.se	Sweden		

Contact Author

Title	Dr.	***Institute***	Chalmers University of Technology
Name	Anders Olof Henrik Olofsson	***Department***	Space, Earth and Environment
Email	henrik.olofsson@chalmers.se	***Address***	Onsala Space Observatory
Phone(first)	+46-31-7725564	***Zipcode***	SE-43992
Phone(second)		***City***	Onsala
Fax		***State***	
		Country	Sweden

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	nFLASH230 (200-270 GHz)	10h (8h)	208.8	1-2 mm	00-24	Line frequencies: 208590.0163 and 208965.4203 MHz
B	APEX	SEPIA180 (159-211 GHz)	10h (8h)	163.3	> 2 mm	00-24	Line frequencies: 162198.5980 and 162574.0580 MHz Use the same receiver set-up as in the 097.F-9305 OTF program with coverage is in the LSB: 161.3-165.3 GHz and in the USB: 173.3-177.3 GHz

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
M17	18:20:22.10	-16:12:37.0	J2000	0.0	62	A B	
M17SW	18:20:23.10	-16:12:47.0	J2000	0.0	62	A B	
Sgr_B2_M	17:47:19.70	-28:24:02.0	J2000	0.0	62	A B	
W33	18:14:15.10	-17:55:25.0	J2000	0.0	62	A B	
rhoOphD	16:28:28.90	-24:19:19.0	J2000	0.0	62	A B	
rhoOphA_1	16:26:26.40	-24:23:24.0	J2000	0.0	62	A B	
L429	18:17:05.10	-08:13:40.0	J2000	0.0	62	A B	
W49	19:10:13.50	+09:06:29.0	J2000	0.0	62	A B	
L134N_NH3	15:54:08.50	-02:52:48.0	J2000	0.0	62	A B	
NGC63341	17:20:53.40	-35:47:02.0	J2000	0.0	62	A B	
G34.3	18:53:18.30	+01:14:58.0	J2000	0.0	62	A B	
L694_2	19:41:04.50	+10:57:02.0	J2000	0.0	62	A B	
rOphA_O1	16:26:25.70	-24:23:24.0	J2000	0.0	62	A B	
S68FIRS1	18:29:50.30	+01:15:19.0	J2000	0.0	62	A B	
IRAS16293	16:32:22.80	-24:28:35.0	J2000	0.0	62	A B	
Sgr_B2	17:47:19.70	-28:23:07.0	J2000	0.0	62	A B	
L134N	15:54:06.50	-02:52:19.0	J2000	0.0	62	A B	
rhoOphA_2	16:26:23.40	-24:23:02.0	J2000	0.0	62	A B	
W51	19:23:43.00	+14:30:38.0	J2000	0.0	62	A B	

Abstract We use SO^+ as a substitute for O_2 to identify sources that potentially contain molecular oxygen. However, so far, the "statistics" are based on only a few sources. We thus propose to use for SO^+ the nFLASH230 and SEPIA180 receivers to survey sources which have been observed with ODIN, SWAS AND HERSCHEL for O_2. In this case, also O_2 upper limits will prove meaningful. This proposal is a resubmission/continuation to complete proposal 0113.F-9302. We ask for 20 hours of telescope time.

Motivation In spite of many recent observational advances, we are still not able to account for all the interstellar oxygen (van Dishoeck et al. 2021). As discussed in that paper, the constituents of interstellar UDO (Unidentified Depleted Oxygen, of which some 100 to 200 ppm are unaccounted for) have yet to be identified. This adds to the puzzle and scarcity of detectable molecular oxygen, O_2, in the ISM (Inter-Stellar Medium): The large efforts of Odin, Swas and Herschel came finally up with merely 2 firm detections (ρ Oph A and Ori A) and 1 tentative detection (NGC1333 IRAS 4). Maybe, there exists a related, but easier to detect, species that permits us to track down any hidden oxygen[1].

In molecular clouds, the primary formation route for O_2 is

$$O + OH \rightarrow O_2 + H. \tag{1}$$

An analogue formation process involves another chalcogen, viz. sulfur of the oxygen family, and is (see Turner 1992, and references therein)

$$S^+ + OH \rightarrow SO^+ + H. \tag{2}$$

It seems thus feasible that we may use SO^+ to track O_2 in molecular clouds. First evidence for this was provided by our Herschel observations of O_2 and SO^+ in ρ Oph A and these were also followed up with APEX (Fig. 1, Larsson et al. 2025). For all positions in that map, the scaling between the SO^+ and O_2 line intensities, having the same widths, is a single constant factor, i.e. $T_{\rm mb}(O_2) = {\rm const} \times T_{\rm mb}(SO^+)$. Similar is observed towards four positions in Orion (H_2 peak 1, Ori A, South and Bar; Larsson et al. 2025). If this linearity is found to be a general result of the proposed APEX observations, one should in principle be able to derive the desired relation $X(O_2) \propto X(SO^+)$ for any given source.

Proposal part 1: pwv ≤ 2mm. Of the original list of 34 sources suitable for observation from APEX (ODIN-SWAS-HERSCHEL data set for O_2), 15 sources were observed in 2024 (see Fig 2). Since SO^+ has so far only been observed in a few O_2 targets, which gives rather poor statistics, we propose that the remaining 19 sources should also be observed (Table 1). As for the previous observations, we propose to use the nFLASH receiver to observe its 208 GHz Λ-doublet, viz. $^2\Pi_{1/2}, v=0: J=9/2 \rightarrow 7/2$ 208590.0163 MHz and 208965.4203 MHz. The telescope beam is HPBW $= 30''$. Regarding the O_2 487 GHz and the SO^+ 208 GHz lines, one notes that both the O_2 and SO^+ transitions originate from an upper level energy of $E_{\rm up}/k = 26$ K.

Consequently, observations of these SO^+ transitions would be optimally suited to infer the O_2 - SO^+ relation. At good atmospheric transparency, these lines constitute our primary goal. We intend to achieve the same noise level as in the original map of ρ Oph A (0101.F-9300(A), Fig. 1), i.e. $T_{\rm rms}$= 30 mK. Note that the intensity of the 0101.F-9300(A) SO^+ line in the figure is scaled down by a factor of 17 to fit the O_2 line, and so is the $T_{\rm rms}$ (< 2 mK) shown in the figure. We have split our proposal into two parts: part 1 in good weather conditions and part 2, when the weather is not fully optimal.

Observing time estimate part 1: pwv ≤ 2mm. We have used the ON-OFF observing time calculator at APEX V7.3 to estimate the total time needed to achieve our goal. Using NFLASH230 tuned to 208.8 GHz in the LSB, selecting a spectral resolution of 0.0877 $\mathrm{km\,s^{-1}}$ and assuming a typical source elevation of 45° and a typical PWV of 2 mm, we could get down to a noise level of 30 mK [T_A^*] in 33.5 minutes (including telescope and calibration overheads).

The spectral coverage is in the LSB: 202.8-210.7 GHz, and in the USB: 219.0-225.9 GHz. In the LSB, also the $H_2^{18}O\,(3_{13} - 2_{20})$ line at 203.40752 GHz will be admitted. In the USB, the $(J = 2 - 1)$ lines of the CO isotopologues $C^{18}O$, ^{13}CO and $C^{17}O$ should appear.

Proposal part 2: pwv > 2mm. At lower atmospheric transparency, we propose to use the SEPIA180 receiver to observe the SO^+ 162 GHz Λ-doublet, viz. $^2\Pi_{1/2}, v = 0 : J = 7/2 \rightarrow 5/2$ 162198.5980 MHz and 162574.0580 MHz, i.e. the same lines as mapped in ρ Oph A (Fig. 1) and to the same depth ($T_{\rm rms}$= 30 mK). These lines have their upper energy at $E_{\rm up}/k = 16$ K and together with the 208 GHz lines, this will provide a first handle on the SO^+ excitation; in particular, to what extent LTE (Local Thermodynamic Equilibrium) could provide a reasonable assumption[2].

Observing time estimate part 2: pwv > 2mm. We have used the ON-OFF observing time calculator at APEX V7.3 to estimate the total time needed to achieve our goal. Using SEPIA180 tuned to 163.3 GHz in the LSB, selecting a spectral resolution of 0.1121 $\mathrm{km\,s^{-1}}$ and assuming a typical source elevation of 45° and a typical PWV of 5.0 mm, we could get down to a noise of 30 mK [T_A^*] in 28.6 minutes (including telescope and calibration overheads).

This corresponds to the same receiver set-up as in the *0101.F-9300(A) program* and the spectral coverage is in the LSB: 161.3-165.3 GHz and in the USB: 173.3-177.3 GHz. The telescope half power beam width is HPBW = 38″.

Observing time summary: For either of the above scenarios, the observation of one object (or pointing) may require about half an hour of telescope time. The requested time of 20 hr should allow us to observe the missing 19 candidate sources on our list in both SO^+ transitions (162 GHz and 208 GHz).

Data Analysis After post-observing processing, the data will be analysed to find the relation $X(O_2) \propto X(SO^+)$. The in 2021 updated version of the PDR Meudon code (Photon Dominated Region, Le Petit et al. 2006) will provide adequate models of the run of temperature, density and molecular abundance (Fig. 3, Larsson et al. 2025). Based on these models, the radiative transfer[2], including line opacities, is calculated, using the recently determined value of the electric dipole moment for the $SO^+\,^2\Pi_{1/2}$ ground state ($\mu = 2.785$ Debye, Tinacci et al. 2021). The ionisation potential of S is about 3 eV below that of hydrogen, so that a substantial ionisation of S can be maintained also in a relatively modest PDR.

Our SO^+ survey of a wide variety of sources in the ISM with both APEX and OSO will be the first of its kind and provide valuable new data. Even if these observations should not result in any conclusive SO^+-O_2 relation, the SO^+ data may still eventually contribute to the understanding of the mysterious interstellar sulfur chemistry.

[1] In the ISM, all searches for $^{16}O^{18}O$ from the ground have hitherto been unsuccessful (e.g., Goldsmith et al. 1985, Liseau et al. 2010, Pagani et al. 2017, Taquet et al. 2018).

[2] For SO^+, no collision rates are available for either H, H_2 or e^-. Rate constants for collisions with electrons would be orders of magnitude larger, implying that these rates are sensitive to the electron density, i.e. the degree of hydrogen ionisation.

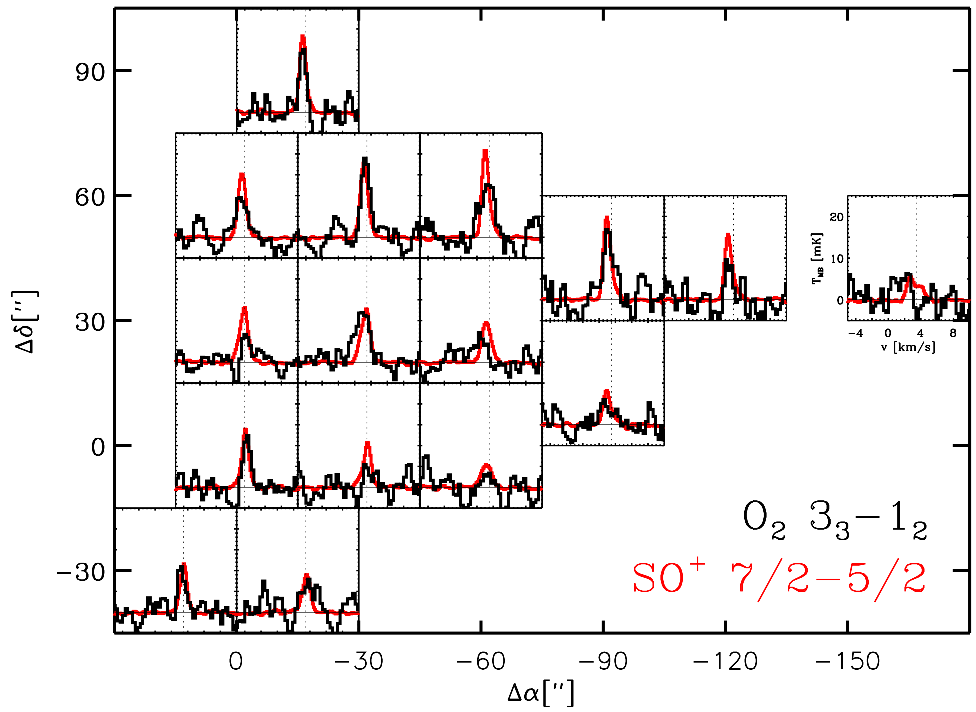

Figure 1: A maplet of O_2 487 GHz and SO^+ 162 GHz emission in ρ Oph A (Herschel and APEX data, respectively). The beam sizes are 44″ and 38″, respectively. The frame to the outmost right shows the units along the axes: the abscissa is $v_{\rm LSR}$ in km s^{-1}, the ordinate is $T_{\rm mb}$ in milli-Kelvin. All intensities of the SO^+ lines have been scaled down by the single constant factor of 17. The dotted vertical line is at $v_{\rm LSR} = 3.5$ km s^{-1}.

References

Chen et al. 2014, ApJ 793, 111: Che 14
Fuente et al. 2003, A&A 406, 899: Fue 03
Goicoechea et al. 2017, A&A 601, L9: Goi 17
Goldsmith et al. 1985, ApJ 289, 617
Goldsmith et al. 2000, ApJ 539,L123: Goi 00
Goldsmith et al. 2011, ApJ 737, 96: Gol 11
Larsson et al. 2007, A&A 466, 999: Lar 07
Larsson & Liseau 2017, A&A 608, 133: Lar 17
Larsson et al. 2025, in preparation
Le Petit et al. 2006 ApJS 164,506 (http://ism.obspm.fr)
Liseau et al. 2010, A&A 510, A98
Liseau et al. 2012, A&A 541, A73: Lis 12
Melnick et al. 2012, ApJ 752, 26: Mel 12
Möller et al. 2021, A&A 651, A9: Möl 21
Nummelin et al. 1998, ApJS 117, 427: Num 98
Pagani et al. 2003, A&A 402, L77: Pag 03
Pagani et al. 2017, A&A 604, A32
Rivière-Marichalar et al. 2019, A&A 628, A16: Riv 19
Taquet et. al. 2018, A&A, 618, A11
Tinacci et al. 2021, ApJS 256, 35
Turner 1992, ApJ 396, L107
van Dishoeck et al. 2021, A&A 648, A24
Wirström et al. 2016, ApJ 830, 102: Wir 16
Yildiz et al. 2013, A&A 558, A58: Yil 13

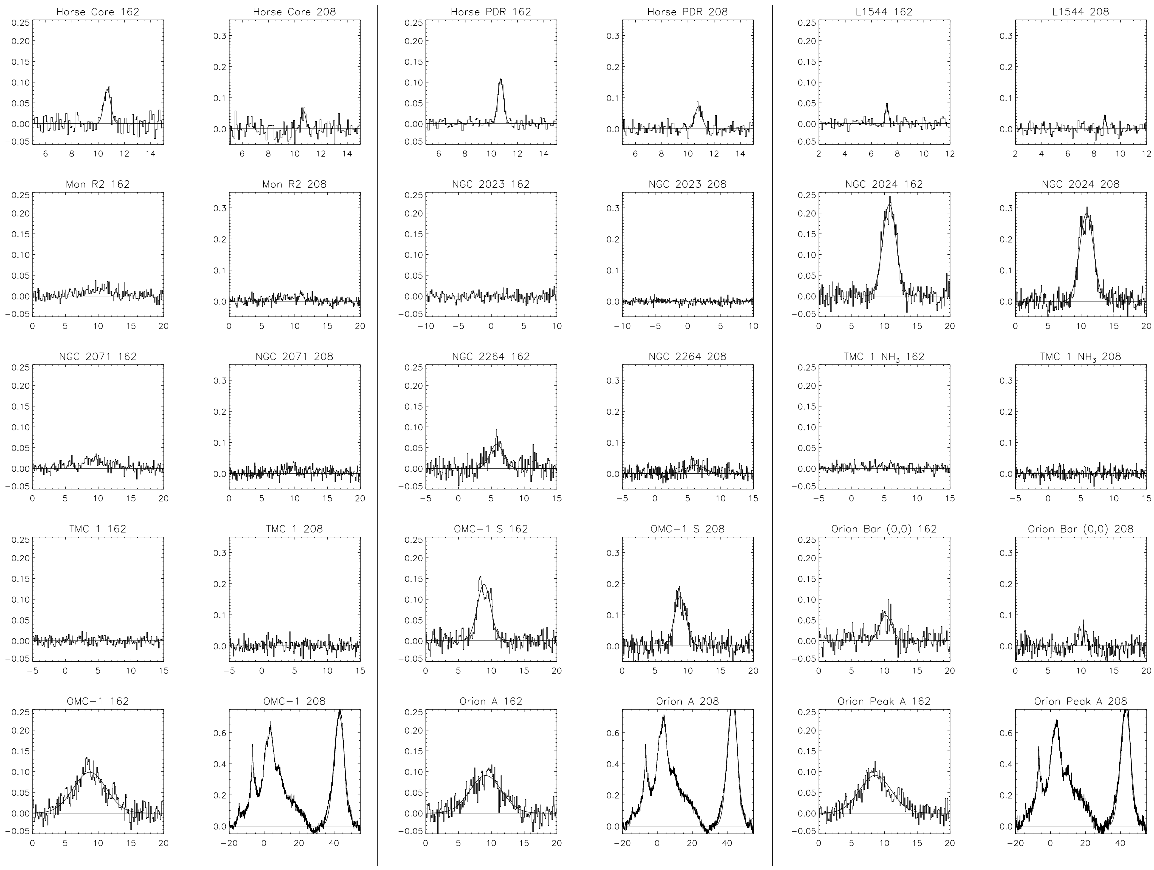

Figure 2: Sources observed by APEX during 2024. The right panel for each source shows the higher frequency component of the Λ-doublet at 162 GHz, while the left one similarly shows the high frequency components at 208 GHz.

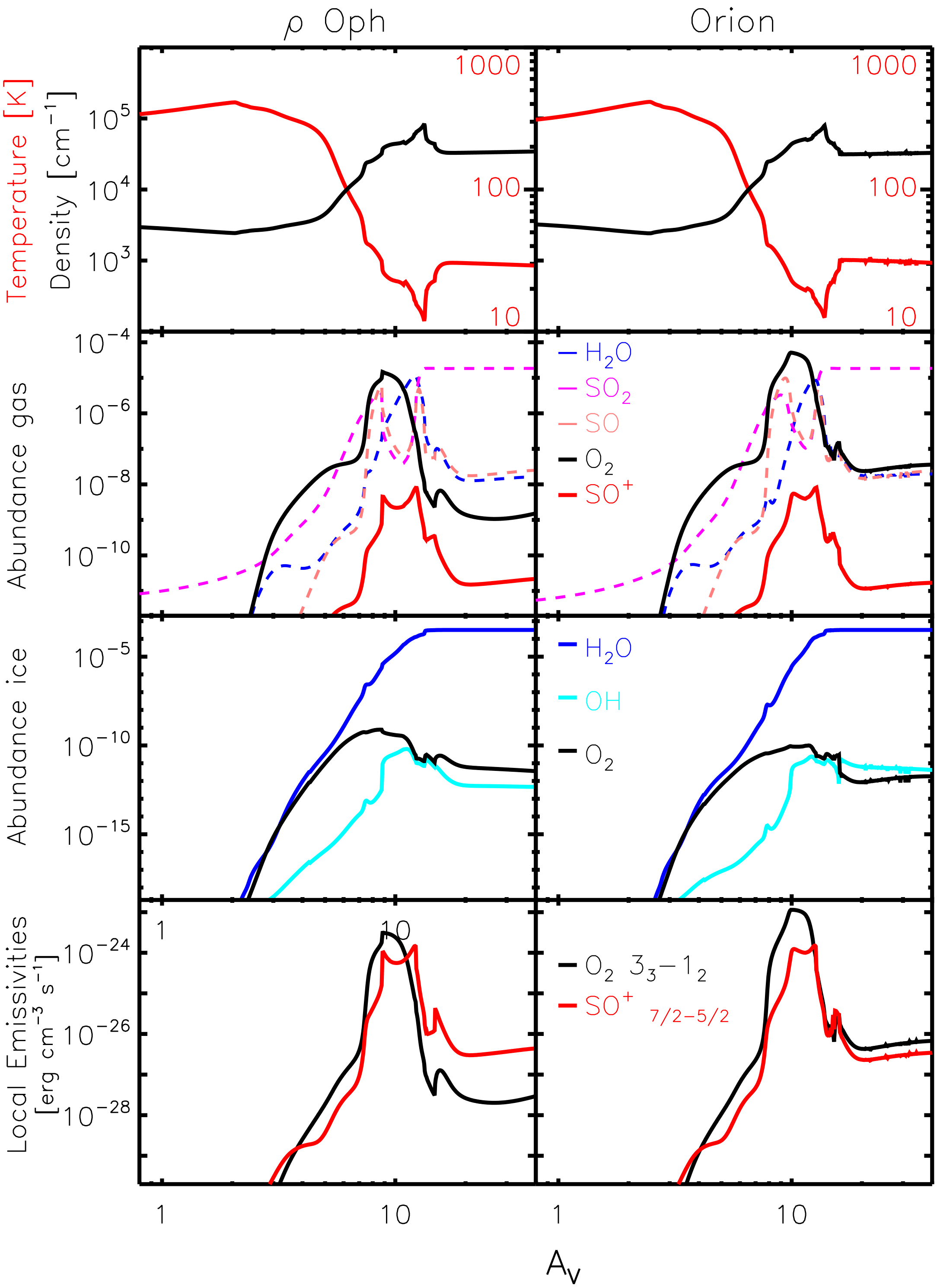

Figure 3: The PDR models of ρ Oph A ($G_0 = 8000$) and Ori A ($G_0 = 10000$) using our updated and enhanced Meudon code (Larsson et al. 2025). **Left panel:** Radial profiles of density, temperature and molecular abundances for ρ Oph A as functions of the visual extinction A_V in magnitudes into the PDR. **Right panel:** Similar for H_2 Peak 1 in Orion.

Table 1: **Source List for APEX 12m**

No.	Source Name	RA_{2000} (h m s)	Dec_{2000} (° ′ ″)	Mol/Frq (GHz)	Tel/Beam (″)	v_{LSR} ($km\,s^{-1}$)	FWHM ($km\,s^{-1}$)	$\int T_{mb}\,dv$ ($K\,km\,s^{-1}$)	T_{kin} (K)	N(Mol) (cm^{-2})	X(Mol)	Ref.
1	L 134N	15 54 06.5	−02 52 19	O_2/487	SWAS/4.′2 [a]	10.2		<0.0077	10			Gol 00
2	L134N NH_3	15 54 08.52	−02 52 48	O_2/118	ODIN/9′	10.2	0.6	<0.024	10	≤1.1 E+15	≤1.7 E-7	Pag 03
3	ρ Oph A (1)	16 26 23.4	−24 23 02	O_2/487	SWAS/4.′2 [a]	3.5		<0.0080	30			Gol 00
4	ρ Oph A (2)	16 26 26.4	−24 23 24	O_2/118	ODIN/9′	3.5	1.5	0.02	30	1 E+15	5 E-8	Lar 07
5	ρ Oph A O1	16 26 25.7	−24 23 24	O_2/487	HIFI/44	3.0	1.6	0.019	≥ 50	5.5 E+15		Lis 12
6	ρ Oph D	16 28 28.9	−24 19 19	O_2/487	HIFI/44	3.5	0.2		7	<1.2 E+16	<1.1 E-7	Wir 16
7	IRAS16293	16 32 22.8	−24 28 35	O_2/118	ODIN/9′	2.7	0.94	<0.017	30	≤2.5 E+15	≤1.2 E-7	Pag 03
8	NGC63341	17 20 53.38	−35 47 1.5	O_2/118	ODIN/9′	3-5	4.0	<0.017	50	≤5.0 E+15	≤7.1 E-8	Pag 03
9	Sgr B2	17 47 19.7	−28 23 07	O_2/487	SWAS/4.′2 [a]	64		<0.011	30			Gol 00
10	Sgr B2(M)	17 47 19.73	−28 24 02.3	SO^+/255	SEST/22	62		15.4+8.2	39			Num 98
11	W33	18 14 15.1	−17 55 25	O_2/487	SWAS/4.′2 [a]	32.7-38.4		<0.013	23			Gol 00
12	L 429	18 17 05.1	−08 13 40	O_2/487	HIFI/44	6.7	0.4		7	<1.1 E+16	<9.2 E-8	Wir 16
13	M17 SW	18 20 22.1	−16 12 37	O_2/487	SWAS/4.′2 [a]	20		<0.0073	40			Gol 00
14	M17SW	18 20 23.11	−16 12 47.2	O_2/118	ODIN/9′	20	4.3	<0.024	50	≤5.0 E+15	≤7.1 E-8	Pag 03
15	S68FIRS1	18 29 50.3	+01 15 18.6	O_2/118	ODIN/9′	8.5	1.4	<0.016	25	≤5.2 E+15	≤9.7 E-8	Pag 03
16	G34.3 + 0.2	18 53 18.34	+01 14 58.4	O_2/118	ODIN/9′	6.0		<0.024	30	≤1.1 E+15	≤5.2 E-8	Pag 03
17	W49	19 10 13.5	+09 06 29	O_2/487	SWAS/4.′2 [a]	20-70		<0.0081	25			Gol 00
18	W51	19 23 43.0	+14 30 38	O_2/487	SWAS/4.′2 [a]	60		<0.0073	30		(5-7) E-7	Gol 00
19	L 694-2	19 41 04.5	+10 57 02	O_2/487	HIFI/44	9.6	0.3		7	<51.8 E+16	<1.6 E-7	Wir 16

No PhD Students involved

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: Yes

0101.F-9300, 0103.F-9308, 0113.F-9302, result in this proposal

No additional remarks

Observing run info :

Run: A backup strategy: When PWV>2, half of the 32h total budget is available for observations of lower frequency SO+ lines with the SEPIA180 receiver. The set-up should then be the same as in the 097.F-9305 OTF program with the spectral coverage in the LSB: 161.3-165.3 GHz and in the USB: 173.3-177.3 GHz.