Onsala Proposal

Cheng 0108.F-9319

A Deuteration Survey Across Galactic environments

Semester: may2021 **Science Cat.: ISM and star formation**

Abstract

N2H+ and its deuterated form N2D+ are known to be good tracers of cold, dense conditions within molecular cloud clumps and cores, and thus are important probes of the physical and chemical conditions of the earliest stages of star formation. Our team has carried out extensive theoretical and observational work to understand the behaviour of N2H+ and N2D+ and how their abundance ratio, D_frac, traces the evolution of the star formation process. Here we propose to extend our observational studies to a sample of ten protoclusters that span a wide range of Galactic environmental conditions, to investigate the differences in deuteration distribution for regions in different stages & environments. By comparison with astrochemical models, this will allow estimation of relative and absolute ages of the different regions in the protocluster and thus constrain theoretical models of star cluster formation. This is a partly a resubmission of an approved program (0107.F-9307) in last cycle, which helps build a 3-cloud sample, and partly an expansion of the project to 7 additional clouds that span a wider range of environments.

Applicants

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Yu Cheng	University of Virginia (astronomy department)	ycheng.astro@gmail.com	United States	Pi	Yes
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Prof. Paola Caselli	MPE	caselli@mpe.mpg.de	Germany		
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Mr. Chi Yan Law	Chalmers University of Technology (Space, Earth and Environment)	chiyan.law@chalmers.se	Sweden		
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Ashley Barnes	The Argelander-Institut für Astronomie (AIfA), University in Bonn	ashleybarnes.astro@gmail.com	Germany		

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Is this a long term proposal: No

Overall scheduling requirements

We require weather with pmv<2mm for observation of N2H+(3-2) at around 279.512GHz.

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	SEPIA345 (277-371 GHz)	2h (2h)	278GHz, 290GHz	1-2 mm	14.5-20.5	We require a LO frequency of 284GHz, and correspondingly the two 8GHz sidebands will has center frequency of 276GHz, 292GHz, respectively. The configuration covers N2H+(3-2) at 279.51176GHz, and also DCO+(4-3) at 288.143858GHz, DCN(4-3) at 289.644907GHz, as well as a few lines from H2CO near 291GHz.
B	APEX	SEPIA345 (277-371 GHz)	3h (3h)	278GHz, 290GHz	1-2 mm	15.5-21.5	We require a LO frequency of 284GHz, and correspondingly the two 8GHz sidebands will has center frequency of 276GHz, 292GHz, respectively. The configuration covers N2H+(3-2) at 279.51176GHz, and also DCO+(4-3) at 288.143858GHz, DCN(4-3) at 289.644907GHz, as well as a few lines from H2CO near 291GHz.
C	APEX	SEPIA345 (277-371 GHz)	4h (4h)	278GHz, 290GHz	1-2 mm	15-21	We require a LO frequency of 284GHz, and correspondingly the two 8GHz sidebands will has center frequency of 276GHz, 292GHz, respectively. The configuration covers N2H+(3-2) at 279.51176GHz, and also DCO+(4-3) at 288.143858GHz, DCN(4-3) at 289.644907GHz, as well as a few lines from H2CO near 291GHz.

Observing runs are continued on the last page

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
G34.77	18:56:45.00	+01:23:00.0	J2000	42.0	76	A	
G28.37	18:51:00.00	-04:03:00.0	J2000	80.0	51	B	
G34.43	18:53:18.70	+01:27:04.3	J2000	58.0	40	D	
G35.39	18:57:08.00	+02:10:30.0	J2000	45.0	60	C	
G0.25	17:46:09.60	-28:42:42.5	J2000	40.0	17	H	
W49	19:10:12.88	+09:06:06.2	J2000	16.0	17	E	
G345.50	17:04:02.90	-40:44:23.5	J2000	-18.0	39	F	
W51	19:23:41.60	+14:30:40.8	J2000	60.0	17	G	

Scientific Rationale

Deuterated molecules are important probes of the physical and chemical conditions in star-forming regions. In molecular clouds that are cold ($T < 20$ K) and dense ($n_{\rm H} > 10^5$ cm^{-3}), i.e., prior to star formation, CO and its isotopologues mostly freeze out onto dust grains. On the other hand, N-bearing species, such as NH_3 and N_2H^+, appear to remain in the gas phase (e.g., Caselli et al. 1999). The high levels of CO freeze-out lead to high abundances of H_2D^+, which then results in deuterated forms of the N-bearing molecules becoming enhanced. The deuteration fraction (hereafter $D_{\rm frac}$), defined as the column density ratio of one species containing deuterium to its counterpart containing hydrogen, can rise to be orders of magnitude larger than the mean interstellar value of [D]/[H] $\sim 10^{-5}$ (Oliveira et al. 2003).

Thus, deuterated species are better suited to probe the physical conditions of star formation at its earliest stages and N_2D^+ is probably the best tracer of pre-stellar cores. Furthermore, $D_{\rm frac}^{\rm N_2H^+}$ has been found to be a good evolutionary indicator for both low- and high-mass star formation (Friesen et al. 2010; Fontani et al. 2011). For better theoretical understanding, we have developed astrochemical models and simulations (Goodson et al. 2016; Hsu et al. 2021) to follow the evolution of $D_{\rm frac}^{\rm N_2H^+}$ of molecular clouds, including for collapsing clumps and cores. The Ph.D. thesis of Chia-Jung Hsu at Chalmers is focused on this astrochemical modeling and the outputs of the chemodynamical simulations will be directly compared to the results of the proposed observations. Measurement of $D_{\rm frac}$ allows estimation of cloud age and dynamical history. For example, relatively low values of $D_{\rm frac}$ indicate a relatively young region, while higher values are found in more evolved regions.

Previous Results and Proposed Observations

Observationally, most previous works only use single pointings to measure $D_{\rm frac}$ towards clumps (e.g., Fontani et al. 2011). An estimation of relative and absolute astrochemical ages of different regions of molecular clouds is only possible with a complete deuteration mapping on the cloud scale, which can then be compared with star formation activity. Members of our team made a first deuteration map of N_2H^+ for an infrared dark cloud (IRDC), i.e., G035.39-00.33, with IRAM 30m observations of N_2H^+(1-0) and N_2D^+(2-1) (Barnes, Kong, Tan et al. 2016). G286.21+0.17(G286.21), a massive protocluster at d=2.5 kpc, is another target extensively studied by our group using HST, VLT, ALMA and APEX (e.g., Andersen et al. 2017; Cheng et al. 2018, 2020). We mapped the central 5'×5' region of G286 in N_2D^+(3-2) with ALMA (Fig. 1a) and in N_2H^+(3-2) data with APEX/FLASH+ (PI: Cheng) (Fig. 1b). This enables us to make a $D_{\rm frac}$ map of the protocluster (Fig. 1c) (Cheng et al., in prep.). It is clear that G286 exhibits enhanced deuteration in its outer regions, while having a relatively low N_2D^+/N_2H^+ ratio in the center (Fig. 1c), where conditions are expected to be warmer, indicating that the star formation may take place in the center region first.

Despite the efforts that have been made, it is largely unexplored how the deuteration distributions differ in different evolutionary stages & environments, which requires a larger sample of sources to be studied. Here we propose to extend our deuteration survey to cover a sample of ten protoclusters with APEX (Fig.2 & Table 1). The protocluster sample has been chosen to explore as wide a range as possible of Milky Way environmental conditions of metallicity, pressure, temperature, B-field strength, cosmic ray ionization rate, and levels of external & local feedback. Several of the sample appear as Infrared Dark Clouds (IRDCs), which are early stage sources, while several others are intense "starburst" protoclusters. Some features of each source are (see Table 1 for reference): 1. G0.253+0.016 ("G0.25"), a massive IRDC near the Galactic Center, a region of high metallicity (Z$\sim$2×Solar), pressure, temperature and CR ionization (>10×local rate); 2. G286.21, a later-stage protocluster in Carina, representative of local Solar-circle conditions, with on-going star formation, including HII region feedback; 3. Sh2–284 ("S284"), outer Galaxy source with lowest known metallicity ($\sim$0.3×Solar) of any Galactic star-forming region;

4. G28.37+0.07 ("G28.37"), one of the most massive IRDCs known and thus representative of an early, low local feedback stage of massive cluster formation; 5. G35.39-0.33 ("G35.39"), a filamentary IRDC with wide-spread SiO(2-1) perhaps indicative of large scale shocks from GMC collisions; 6. G34.43+0.24 ("G34.43") a massive IRDC, which is in an early phase of high-mass star formation, including local HII region feedback; 7. G34.77-0.24 ("G34.77") an IRDC, which is undergoing interaction with a supernova remnant; 8. G345.50+0.35 ("G345.50") a protocluster with one of the highest known mass surface densities of $\sim$10 g cm$-$2, implying high pressures (P), and also showing high levels of fragmentation; 9. W51 Main, region with highest density of star formation within 8 kpc; 10. W49, the most luminous protocluster in the Galaxy.

Since N_2H^+ generally has a more extended distribution than N_2D^+, our strategy is to first map N_2H^+ with APEX, which will then guide follow up studies to observe N_2D^+. Two sources in this sample (G286.21, S284) have been observed in pilot studies so we aim to map in N_2H^+(3-2) the remaining eight sources in this cycle (and one of these, G28.37, was already approved in the previous cycle and may be withdrawn if completed). Already the N_2H^+(3-2) emission will provide important information. First the abundance of the species can be estimated (with total H_2 column estimated from the *Herschel* dust emission map). The kinematics of the detected N_2H^+(3-2) structures will be analysed, e.g., number of discrete components, velocity gradients and velocity dispersion. An estimation of gravitational boundedness of the structures will also be made, given the total mass measured from the *Herschel* dust map. Ancillary lines will be observed simultaneously: DCO^+, DCN, CH_3OH and H_2CO, which will probe the abundances of these species (thus further testing our astrochemical models), as well as being potential probes of different excitation conditions, e.g., shocks via CH_3OH emission.

Facilities Requested

We request APEX observations with the heterodyne receiver SEPIA345 (band 7: 272-376 GHz). APEX is one of the best millimeter telescopes for N_2H^+(3-2) observation (at a rest frequency of 279.511760GHz). SEPIA345 along with the spectrometer covers an IF range of 8 GHz per sideband, and this allows us to observe N_2H^+(3-2) at 279.5GHz, DCO^+(4-3) at 288.1GHz, DCN(4-3) at 289.6GHz, $CH_3OH(9_1\text{-}8_0)$ at 278.3 GHz, as well as a few transitions from H_2CO around 291GHz with a velocity resolution of 0.065 km/s.

Observing Requirements and Plan

Our previous N_2H^+(3-2) observation for G286.21 and S284 has a sensitivity of 0.065 K per 0.16 km/s channel. Here we request the same brightness temperature sensitivity, which gives similar signal to noise ratio for other regions assuming a similar N_2H^+(3-2) intensity. The corresponding telescope time for each target is estimated from the online estimator, assuming 2 mm pmv and an elevation of 45°, which is listed in Table 1. This results in a total time request of 19.9 hr. Each region will be mapped 7-8 times, and we will scan in different directions to avoid striping. For three targets (G28.37, G35.39, G34.77) we have divided the region into two strips to better cover the regions with intense star formation.

Scheduling Requirements

Our targets have R.A. ranging from 17 h to 19 h, so we require a LST range of 13h-23h for observation. These observations would contribute to Mr. Chia-Jung Hsu and Mr. Chi Yan Law's Ph.D. thesis at Chalmers Univ. (advisor J. Tan), expected to be completed by 2022 and 2023, respectively.

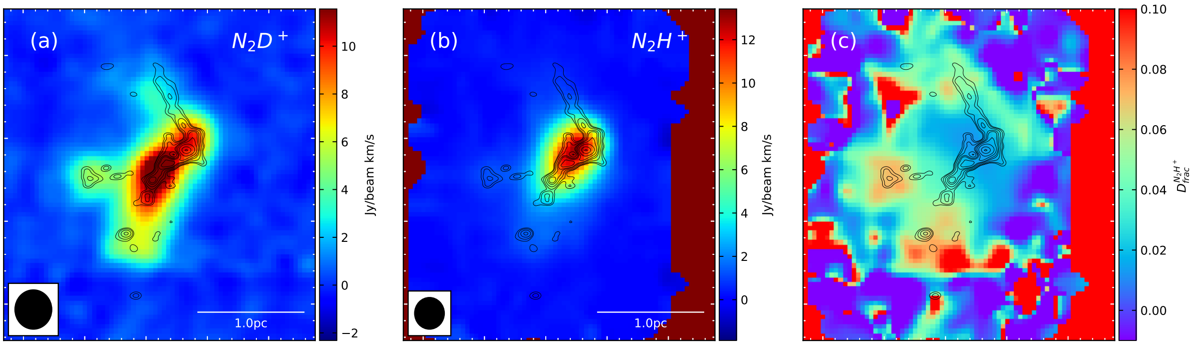

Figure 1: ALMA and APEX observations of the pilot region G286.21. *(a)* Integrated intensity map of N_2D^+(3-2) shown in color scale. The image is made with ALMA total power data with a resolution of 28". The beam size is shown in the lower left corner. The intensity is integrated from -22 to -18km/s. The black contours illustrate the ALMA 1.3 mm continuum image (using 7-m array data with a resolution of $\sim$6"). *(b)* Same as *(a)* but for N_2H^+(3-2) observed with APEX/FLASH+. The beam of 24" is shown in lower left corner. *(c)* $D_{\rm frac}^{\rm N_2H^+}$ map derived from N_2D^+(3-2) and N_2H^+(3-2) integrated in the same velocity range. We smoothed and regrided the N_2H^+ image to match the N_2D^+ observation. Note, high values of $D_{\rm frac}^{\rm N_2H^+}$ are seen in the outer regions of the protocluster, indicating a higher amount of pre-stellar core material is present here compared to the centre.

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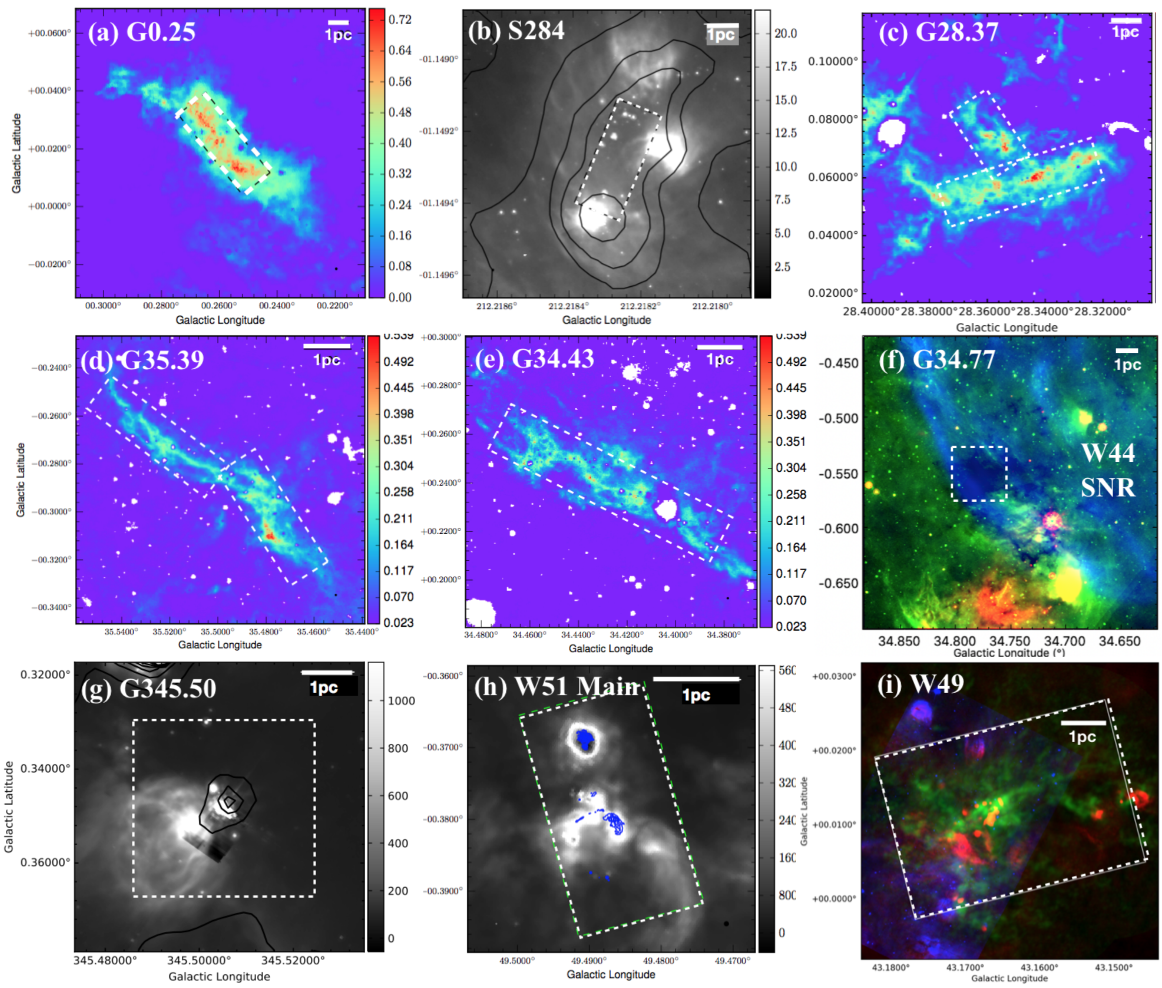

Figure 2: Nine protoclusters spanning Galactic environments (see Fig. 1 for G286.21). Dashed rectangles show target regions: (a) G0.25: Galactic Center IRDC (MIREX map, g cm^{-2}); (b) S284: low metallicity, outer Galaxy (*Spitzer* 8μm+*Herschel* 500μm contours) (APEX obs. already completed); (c) G28.37: massive IRDC (MIREX map) (APEX obs. already approved); (d) G35.39: filamentary IRDC formed by GMC collision (MIREX); (e) G34.43: IRDC with HII region feedback (MIREX) (f) G34.77: IRDC interacting with W44 SNR (radio cont.-blue; 8/24μm-green/red); (g) G345.50: High pressure clump (8μm+500μm contours); (h) W51 Main: massive protocluster (8μm+Ku band contours for ionized gas). (i) W49: most active Galactic star-forming region (1.3cm cont.-red, CO(2-1)-green, 8μm-blue).

Table 1: Protocluster Sample	R.A./ Dec.	d (kpc)	M ($M_\odot$)	Mapping area	t_{obs} (hr)	Ref
1. G0.253+0.016 ("G0.25"): Galactic Center, high Z, ζ	17:46:09.6 -28:42:42.5	8.0	$1\text{x}10^5$	2'x1'	2.0	Kauffmann+13, Rathborne+15
2. G286.21+0.17 ("G286.21"): Carina, Solar-circle	10:38:33 -58:19:22	2.5	$\sim 10^4$	3.3'x2.5'	-	Cheng+18, Cheng+20
3. Sh 2–284 ("S284"): Outer Galaxy, low Z	06:45:00.0 +0:17:56.9	5.0	$\sim 10^4$	4'x2'	-	Puga+09 Negueruela+15
4. G28.37+0.07 ("G28.37"): Massive IRDC	18:42:51 -04:02:54	5.0	$5\text{x}10^4$	4'x1'+2'x1'	3.1	Butler+14, Kong+19
5. G35.39-0.33 ("G35.39"): IRDC, GMC collision	18:57:08 +02:10:30	2.9	$1\text{x}10^4$	3.7'x1'+3.3'x1'	3.7	Jiménez-Serra+10, Barnes+16
6. G34.43+0.24 ("G34.43"): IRDC Filament, HII Region	18:53:18.7 +1:27:04.3	3.7	$5\text{x}10^3$	3'x1.5'	2.3	Shepherd+07
7. G34.77−0.55 ("G34.77"): IRDC, Supernova Remnant	18:56:45 +1:23:00	2.9	$3\text{x}10^3$	2.5'x1.5'+2.5'x1.5'	4.5	Cosentino+19
8. G345.50+0.35 ("G345.50"): High P, Fragmentation	17:04:22.9 -40:44:23.5	2.2	$\sim 10^3$	2'x2'	2.3	Cesaroni+17 O'Neill+21
9. W51 Main ("W51"): Highest density starburst	19:23:41.6 14:30:40.8	5.4	$\sim 10^5$	2'x1'	1.0	Ginsburg+17
10. W49: Most luminous Galactic protocluster	19:10:12.9 09:06:06.3	11.1	$\sim 10^5$	1.5'x1'	1.0	Ginsburg+16

Table 1: Summary of the protocluster sample. The targets shown in green have already been observed in N_2H^+(3-2) with APEX. We aim to observe the remaining eight targets in this cycle (seven, if approved G28.37 observations are completed in 2021).

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Students involved

Student	Level	Applicant	Supervisor	Applicant	Expected completion date	Data required
Chia-Jung Hsu	Doctor	Yes	Prof Jonathan Tan	Yes	2022/08	Yes
Yu Cheng	Doctor	Yes	Prof Jonathan Tan	Yes	2021/06	Yes
Mr. Chi Yan Law	Doctor	Yes	Prof Jonathan Tan	Yes	2023/08	Yes

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: Yes

0103.F-9307 (PI: Cheng), 6hr, Deuteration mapping of a massive protocluster(G286)
0105.F-9314(PI: Cheng),7hr, The onset of star formation in a low metallicity protocluster
0107.F-9307(PI:cheng),Deuteration in a massive Infrared Dark Cloud,3.1hr, time allocated but not observed by the time of this submission

Additional remarks

ESO=ycheng

Observing run info :

Run: A backup strategy: N2H+(3-2) at ~280GHz could still be observed with slightly poor weather e.g., pmv up to 3mm, and we could still have some scientific results with slight loss of S/N.
Run: B backup strategy: N2H+(3-2) at ~280GHz could still be observed with slightly poor weather e.g., pmv up to 3mm, and we could still have some scientific results with slight loss of S/N.
Run: C backup strategy: N2H+(3-2) at ~280GHz could still be observed with slightly poor weather e.g., pmv up to 3mm, and we could still have some scientific results with slight loss of S/N.
Run: D backup strategy: N2H+(3-2) at ~280GHz could still be observed with slightly poor weather e.g., pmv up to 3mm, and we could still have some scientific results with slight loss of S/N.
Run: E backup strategy: N2H+(3-2) at ~280GHz could still be observed with slightly poor weather e.g., pmv up to 3mm, and we could still have some scientific results with slight loss of S/N.
Run: F backup strategy: N2H+(3-2) at ~280GHz could still be observed with slightly poor weather e.g., pmv up to 3mm, and we could still have some scientific results with slight loss of S/N.
Run: G backup strategy: N2H+(3-2) at ~280GHz could still be observed with slightly poor weather e.g., pmv up to 3mm, and we could still have some scientific results with slight loss of S/N.
Run: H backup strategy: N2H+(3-2) at ~280GHz could still be observed with slightly poor weather e.g., pmv up to 3mm, and we could still have some scientific results with slight loss of S/N.

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
D	APEX	SEPIA345 (277-371 GHz)	2h (2h)	278GHz, 290GHz	1-2 mm	14.5-20.5	We require a LO frequency of 284GHz, and correspondingly the two 8GHz sidebands will has center frequency of 276GHz, 292GHz, respectively. The configuration covers N2H+(3-2) at 279.51176GHz, and also DCO+(4-3) at 288.143858GHz, DCN(4-3) at 289.644907GHz, as well as a few lines from H2CO near 291GHz.
E	APEX	SEPIA345 (277-371 GHz)	4h (4h)	278GHz, 290GHz	1-2 mm	15-21	We require a LO frequency of 284GHz, and correspondingly the two 8GHz sidebands will has center frequency of 276GHz, 292GHz, respectively. The configuration covers N2H+(3-2) at 279.51176GHz, and also DCO+(4-3) at 288.143858GHz, DCN(4-3) at 289.644907GHz, as well as a few lines from H2CO near 291GHz.
F	APEX	SEPIA345 (277-371 GHz)	2h (2h)	278GHz, 290GHz	1-2 mm	14.5-20.5	We require a LO frequency of 284GHz, and correspondingly the two 8GHz sidebands will has center frequency of 276GHz, 292GHz, respectively. The configuration covers N2H+(3-2) at 279.51176GHz, and also DCO+(4-3) at 288.143858GHz, DCN(4-3) at 289.644907GHz, as well as a few lines from H2CO near 291GHz.
G	APEX	SEPIA345 (277-371 GHz)	1h (1h)	278GHz, 290GHz	1-2 mm	14.5-20.5	We require a LO frequency of 284GHz, and correspondingly the two 8GHz sidebands will has center frequency of 276GHz, 292GHz, respectively. The configuration covers N2H+(3-2) at 279.51176GHz, and also DCO+(4-3) at 288.143858GHz, DCN(4-3) at 289.644907GHz, as well as a few lines from H2CO near 291GHz.
H	APEX	SEPIA345 (277-371 GHz)	1h (1h)	278GHz, 290GHz	1-2 mm	14.5-20.5	We require a LO frequency of 284GHz, and correspondingly the two 8GHz sidebands will has center frequency of 276GHz, 292GHz, respectively. The configuration covers N2H+(3-2) at 279.51176GHz, and also DCO+(4-3) at 288.143858GHz, DCN(4-3) at 289.644907GHz, as well as a few lines from H2CO near 291GHz.