Chemistry Study on Hot Corino Serpen South CARMA-7

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Abstract

This thesis reports molecule line identification results on a recently discovered hot corino source, CARMA-7 in Serpen South region from its ALMA observation data. Complex organic molecules such as $(CH_3)_2CO$ (Acetone), CH_3OH (Methanol) and H_2NCH_2CN (Aminoacetonitrile) are detected. By analyzing contour plots of the source, it can be (tentatively) concluded that CARMA-7 is not only rich in chemistry but also undergoing rapid motions including bipolar outflow jets and a possible rotating accretion disk.

Keywords: hot corino, astrochemistry, ALMA

1. Introduction

This thesis studies the chemistry of a recently discovered hot corino-like protostar, CARMA-7 in the Serpen South region. CARMA-7 is one of the very few hot corinoes discovered so far and has a high degree of chemical richness and motion traces of possible bipolar molecular outflow jets. This thesis report will attempt to list, plot and discuss molecular line identification results and motion signatures of CARMA-7 from a set of 6 spectral windows of ALMA observation data in 2015.

2. Observation

The ALMA observation on CARMA-7 is divided into 6 spectral windows, each with a different rest frequency (GHz) and frequency range but same VLSR of 8.0 km/s. The observation data cubes are divided into multiple channels: spectral window 0, 1, 2, 4 and 5 have 960 channels whereas spectral window 3 has 1920 channels. All raw data cubes have a 360 × 360 dimension, resulting in a total of 129600 pixels per slice.

Spectral window	Rest frequency (GHz)
SPW0	337.061
SPW1	336.6619
SPW2	335.913
SPW3	345.5527
SPW4	347.2043
SPW5	346.8721

Figure 1 All 6 spectral windows and their rest frequencies

3. Methods

To accurately identify all molecules from all 6 spectral windows, a variety of continuum substraction and line identification tools were attempted. These tools include STATCONT, ADMIT (ALMA Data Mining Toolkit, integrated with CASA) and XCLASS. Raw fits data cubes were first cropped (to eliminate impacts of the cube's original circular shape on calculation of background noise rms and improve focus on center area) and continummed substrated (with noise level set to 1) with STATCONT to produce line cubes that were ready as input file for ADMIT's ContinuumSub and LineIdentification tasks.

To understand the physical structure and motions of CARMA-7, contour plots based on background rms (10 levels from 2× background rms to 20× background noise rms) were drawn for channels that shows traces of explicit strcuture / identifiable motions in each spectral window. Background noise were calculated from pixel blocks of a specified size from all four corners (upper left, lower left, upper right, lower right) for each channel plotted.

4. Results

Detected lines and their distribution

Figure x to figure x shows some "promising" molecule lines (with an identifiable line height and overall profile) from spectral window 0 to 5. In these observations, CARMA-7 was found to be chemically rich, with some spectral windows dominated by one molecule (spectral window x, x and x) with high intensity peak / rms ratio and broad lines with sometimes complex shapes. The most noteworthy detections are $(CH_3)_2CO$ (Acetone), CH_3OH (Methanol) and $(CH_2OH)_2$ (Ethylene glycol), which are found in 5 out of all 6 spectral windows. In addition, some more complicated organic compounds with higher molar mass such as CH_3CHO (Acetaldehyde), H_2NCH_2CN (Aminoacetonitrile), CH_3CH_2OH (Ethanol) and CH_3OCHO (Methyl formate) are also deteced with multiple occurrence in at least 4 out of 6 spectral windows. Interestingly, the complexity / molar mass of molecules detected does not seem to have a correlation with their commonness across all 6 spectral windows. Nevertheless, the exact spatial distribution of each molecule are still subjected to future study.

Molecule	Occurrence
$(CH_3)_2CO$	SPW0, SPW1, SPW2, SPW3, SPW4
CH_3OH	SPW0, SPW1, SPW2, SPW3, SPW4
$(CH_2OH)_2$	SPW0, SPW2, SPW3, SPW4, SPW5
CH_3CHO	SPW0, SPW2, SPW4, SPW5
H_2NCH_2CN	SPW0, SPW1, SPW2, SPW3
CH_3CH_2OH	SPW0, SPW2, SPW3, SPW5
CH_3OCHO	SPW1, SPW2, SPW3, SPW5
$H^{13}CCCH$	SPW0, SPW2, SPW3
CH_2CHCN	SPW0, SPW4
CH_2OHCHO	SPW0, SPW2
CH_3NH_2	SPW0, SPW2
HC_3N	SPW1, SPW3
CH_3CH_2CN	SPW2, SPW3
H_2CCHOH	SPW2, SPW3
$H_2C^{18}O$	SPW2, SPW3
$HCOOD$	SPW3, SPW4
HCO	SPW3, SPW5
$H_2CCCHCN$	SPW4, SPW5

Figure 2 Selected identified lines that occur in multiple spectral windows

It was also found that CARMA-7 shares a notable amount of molecules with other discovered hot corino sources including B335, HH212, L483, Ser-emb1 and SVS13-A. It was found out that Monohydric alcohols such as CH_3CHO (Acetaldehyde), CH_3OH (Methanol), some carbon nitriles such as CH_3NH_2 and silicon compound (SiO) are shared the most between CARMA-7 and other hot corino sources. In addition, CARMA-7 seems to have a higher richness of unique carbon nitriles and other nitrile compounds such as H_2NCH_2CN (Aminoacetonitrile) and CH_3CH_2CN (Propionitrile), all of which were identified in multiple spectral windows.

Molecule	Occurrence
CH_3CHO	B335, HH212, L483, SPW0, SPW2, SPW4, SPW5, SVS13-A
CH_3OH	Ser-emb1, SPW0, SPW2, SPW3, SPW4, SVS13-A
CH_3CH_2OH	SPW0, SPW1, SPW2, SPW3, SPW5, SVS13-A
NH_2CHO	B335, L483, SPW2, SPW3, SVS13-A
CH_3OCHO	Ser-emb1, SPW1, SPW2, SPW3, SPW5
CH_3NH_2	SPW0, SPW2, SPW3, SVS13-A13
SiO	L483 , Ser-emb1, SPW4

Figure 3 Selected lines that occurs in both CARMA-7 and other hot corino sources

However, it is also worth noting that these abovementioned common molecules are almost never the dominant lines with high peak intensity and width (or a well-defined line profile) in their spectral windows. For instance, spectral window 0, 1 has a dominant line of $C^{17}O$ and HCN respectively whereas spectral window 3, 4 has a dominant line of CO (absorption?) and SiO, none of which are shared with molecules detected in other hot corino sources. This may help pinpoint some unique molecules that are only observable from CARMA-7.

Motion of the source

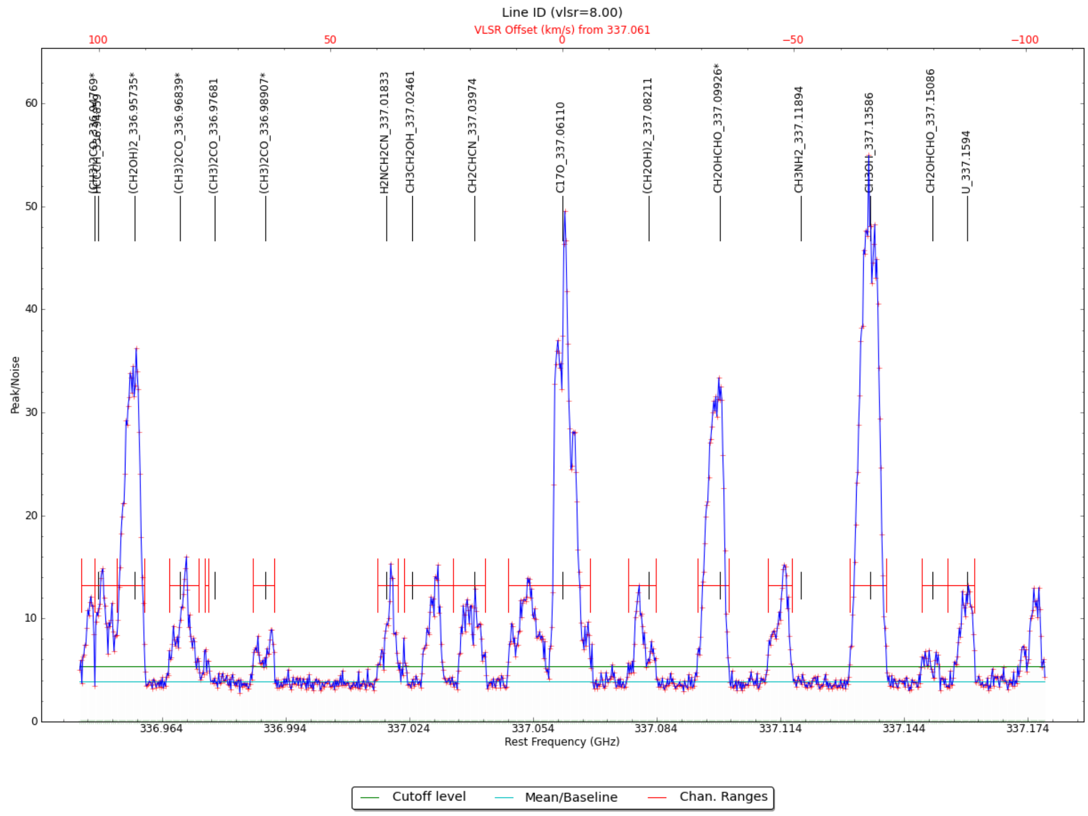
In certain spectral windows such as spectral window 3 and spectral window 2, bipolar outflow jets are clearly visible and in progress with each channel but nevertheless are condensed only to a small channel range (figure x). In other spectral windows, the source does appear to be in some type of less well-defined motion that involves rotation around its (visual) center as in these spectral windows, the line-dense regions seem to be revolving around center of the plot. Such pattern is clearly visible in contour plots of spectral window 0 and spectral window 5, as shown in figure x and figure x.

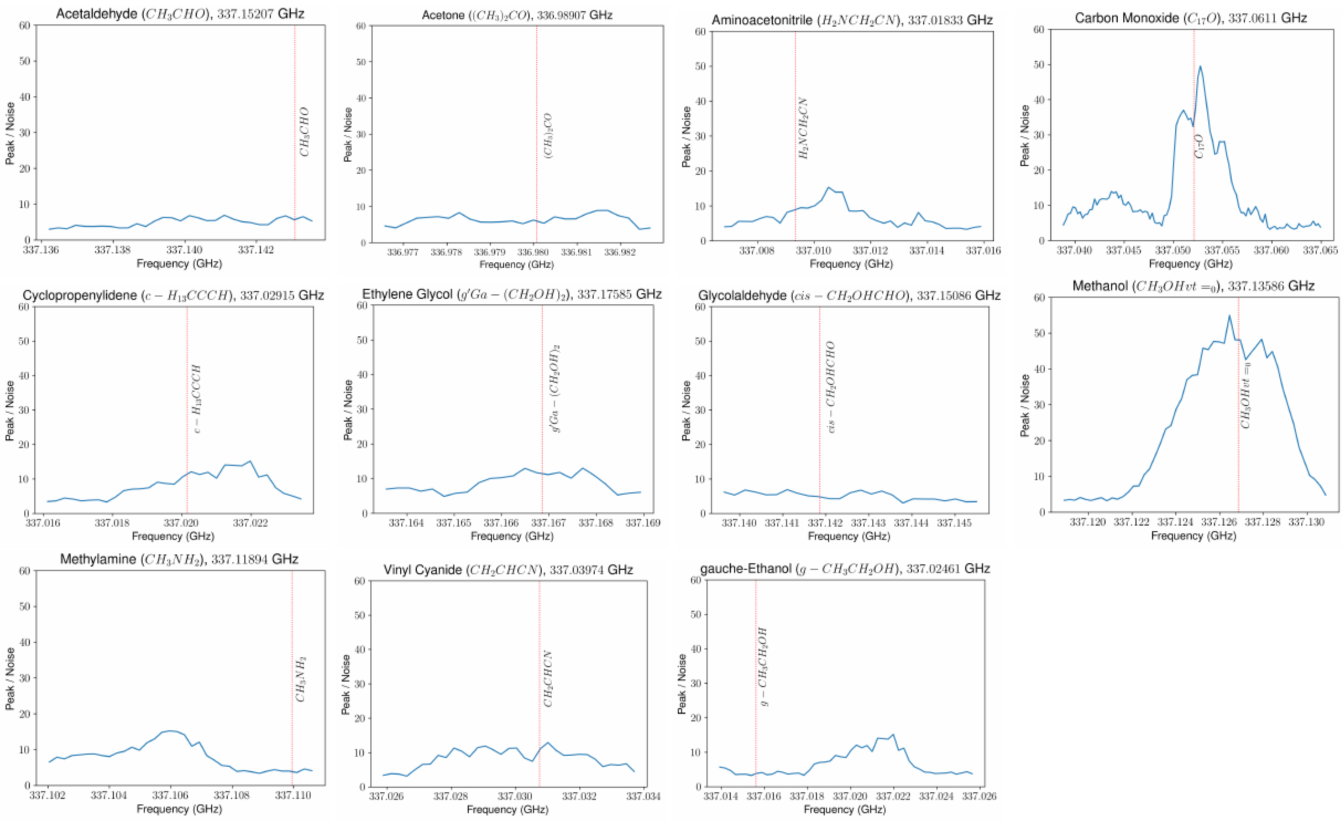
It is notable that in all 3 spectral windows (2, 3 and 4) where bipolar outflow jets are observed, these jets are only visible for a rather small frequency range (all less than 20% of the spectral window's frequency range).

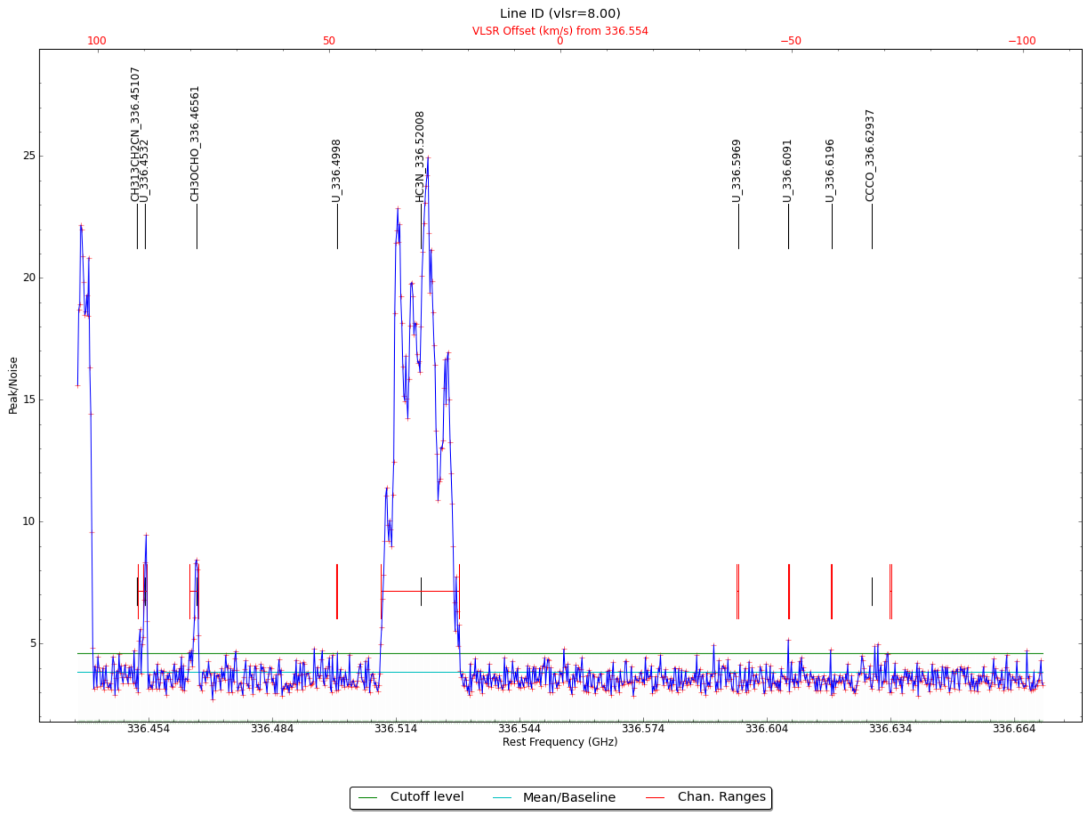
Difficulties arise when trying to match molecular lines to channel ranges where signs of motions can be traced. Interestingly, the molecular line plot (peak vs. background rms) does not seem to correspond the slice plot well. This makes analysing source motion difficult since the molecular line shape, which typically reveals information about the source cannot be used to aid understanding of the exact motion. However, some prominent / dominant lines may still suggest relevant information on source motion, as they appear to be in particularly irregular shapes (example lines, figure x and x)

5. Conclusion

6. Appendix: plots and tables



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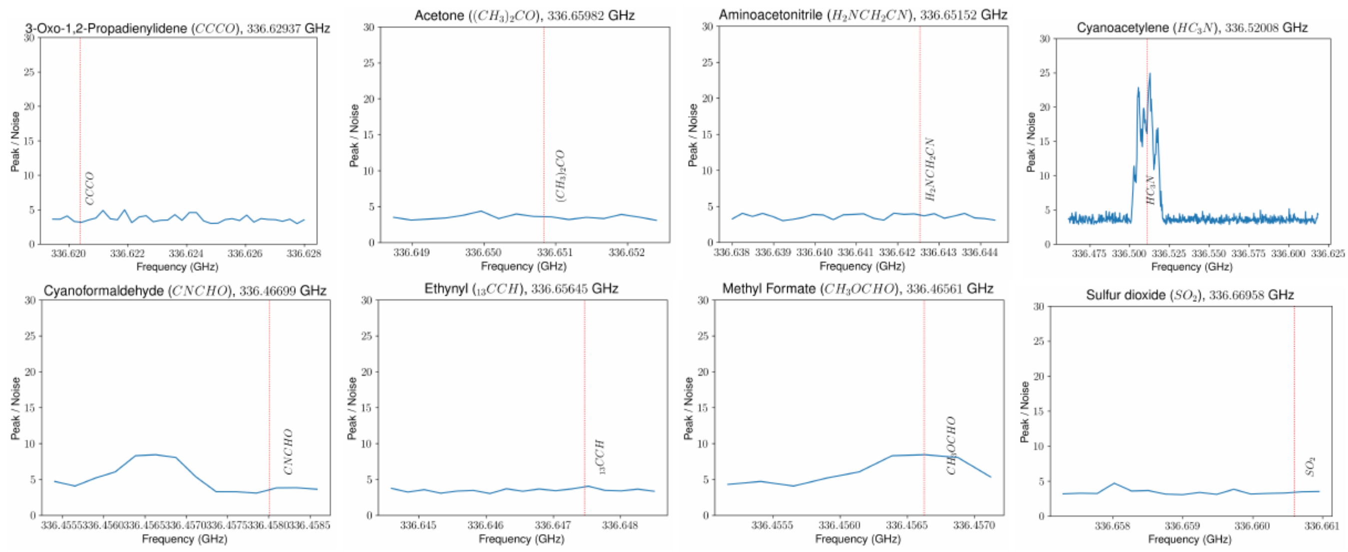
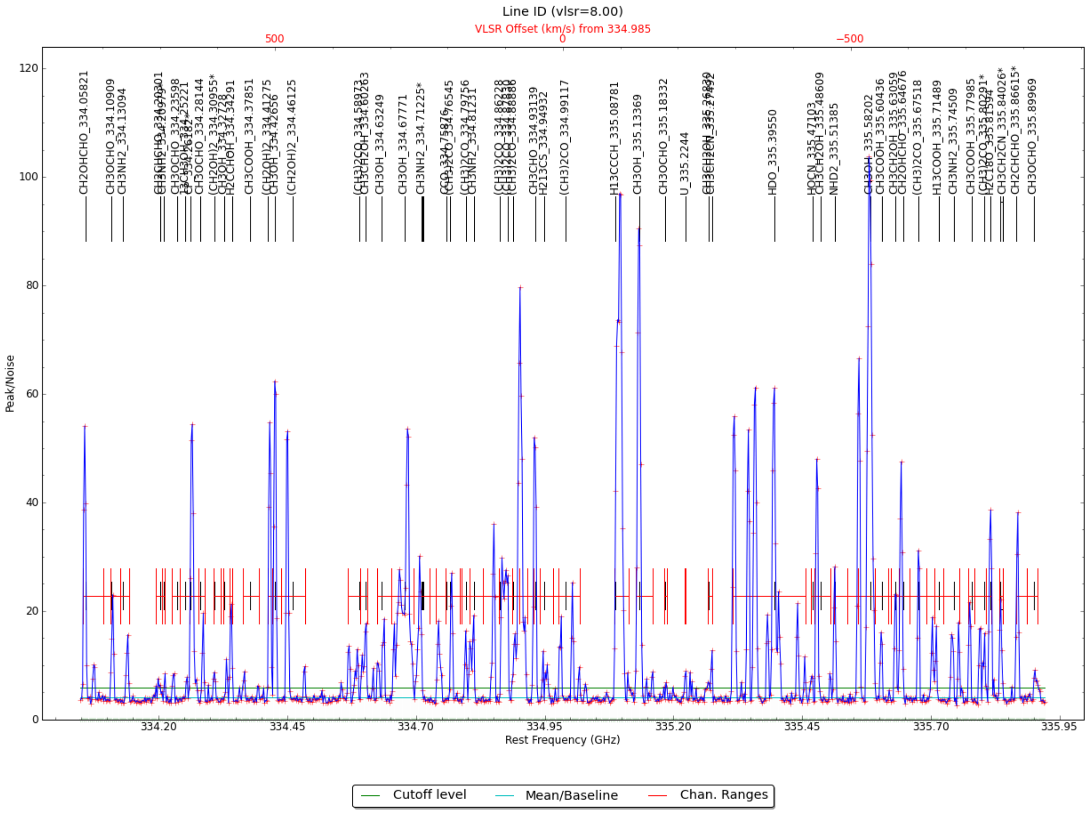
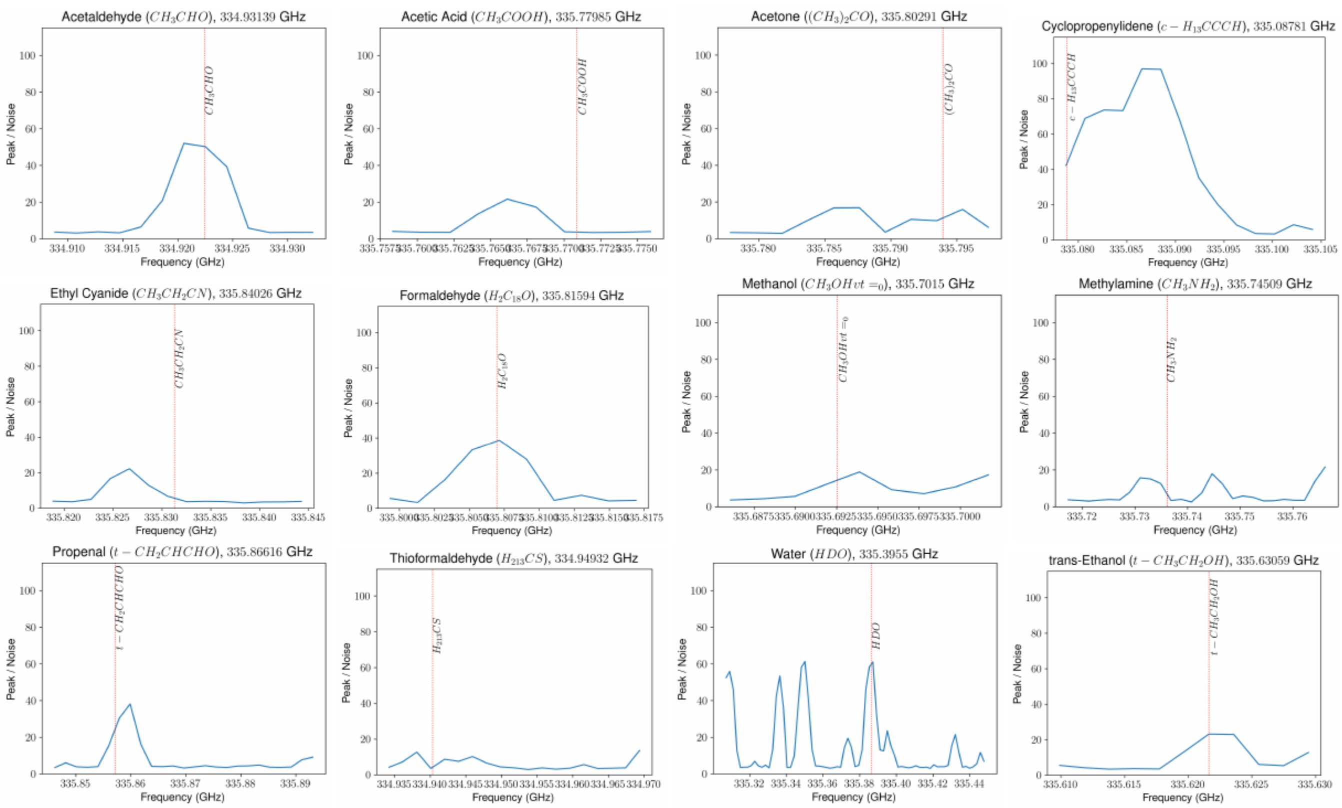
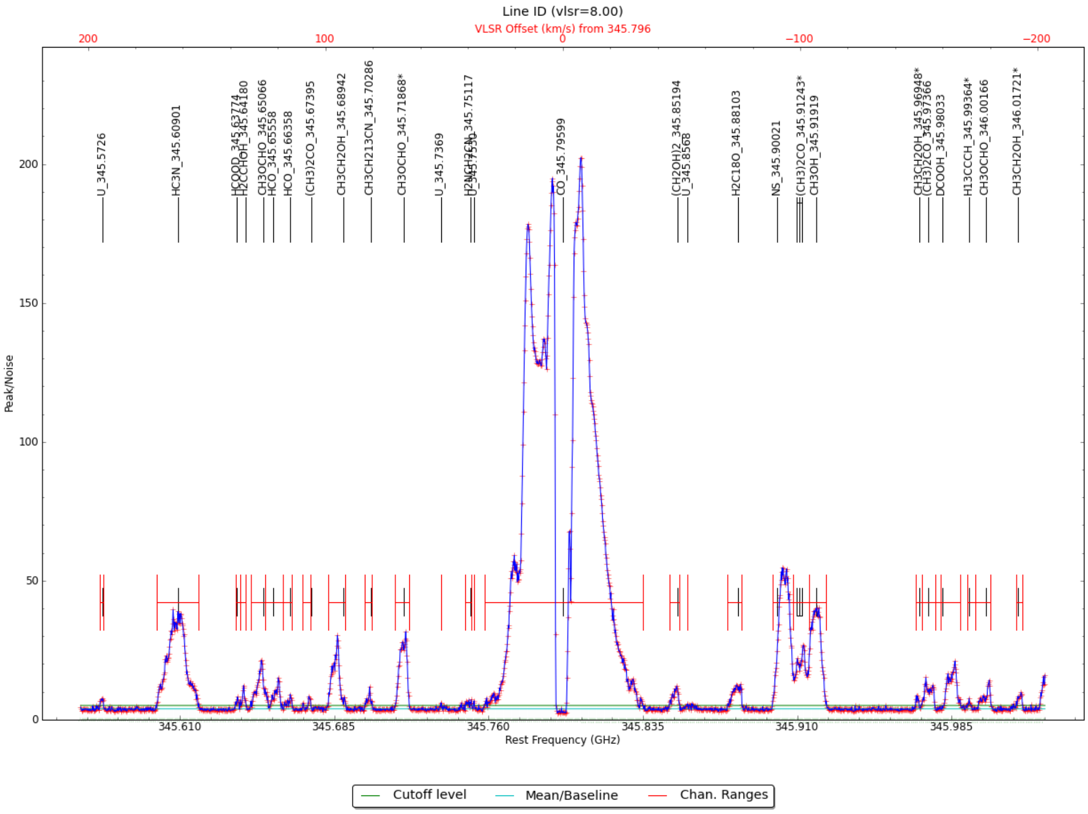
VLSR Offset (km/s) from 336.554
Peak/Noise
Rest Frequency (GHz)
CH313CH2CN_336.45107
U_336.4532
CH3OCHO_336.46561
U_336.4998
HC3N_336.52008
U_336.5969
U_336.6091
U_336.6196
CCCO_336.62937
Cutoff level
Mean/Baseline
Chan. Ranges

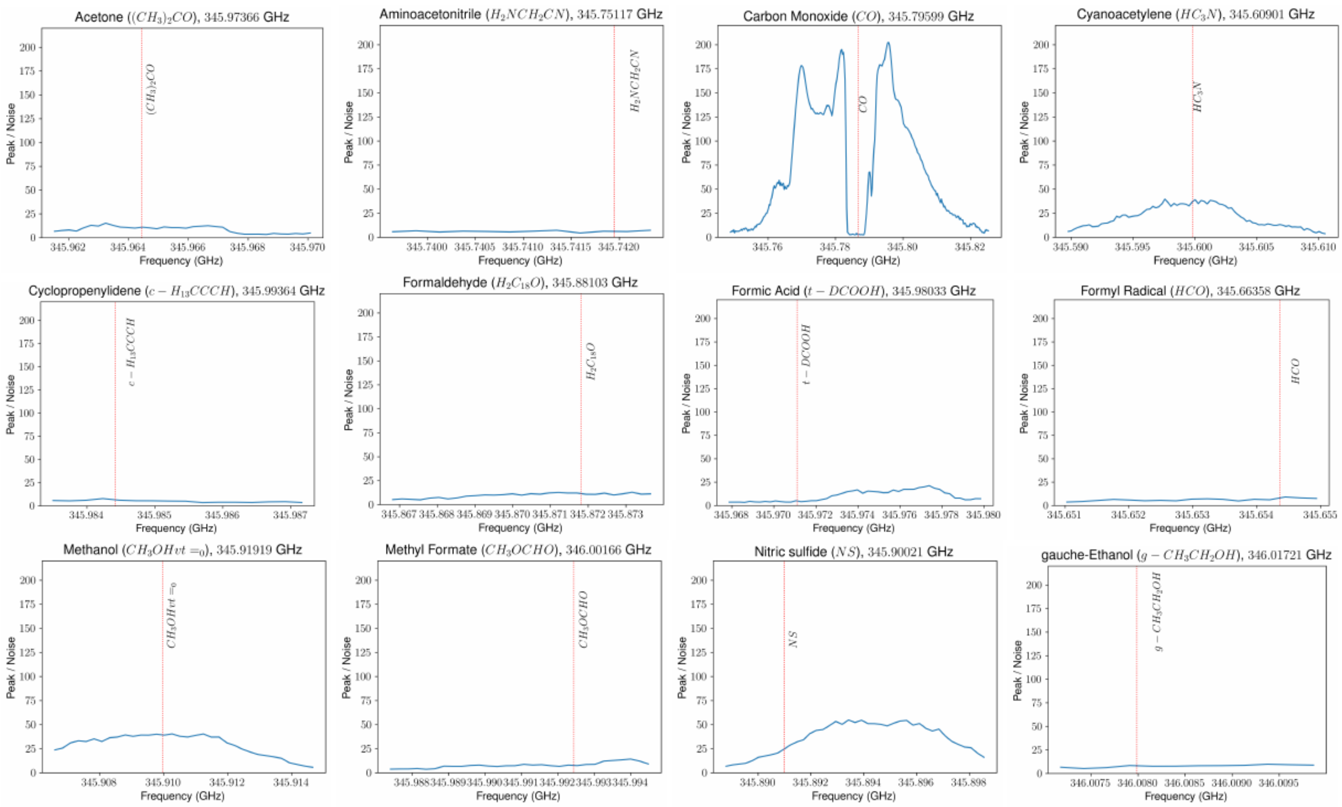

3-Oxo-1,2-Propadienylidene ($CCCO$), 336.62937 GHz
Acetone ($(CH_3)_2CO$), 336.65982 GHz
Aminoacetonitrile (H_2NCH_2CN), 336.65152 GHz
Cyanoacetylene (HC_3N), 336.52008 GHz
Cyanoformaldehyde ($CNCHO$), 336.46699 GHz
Ethynyl ($_{13}CCH$), 336.65645 GHz
Methyl Formate (CH_3OCHO), 336.46561 GHz
Sulfur dioxide (SO_2), 336.66958 GHz
Peak / Noise
Frequency (GHz)



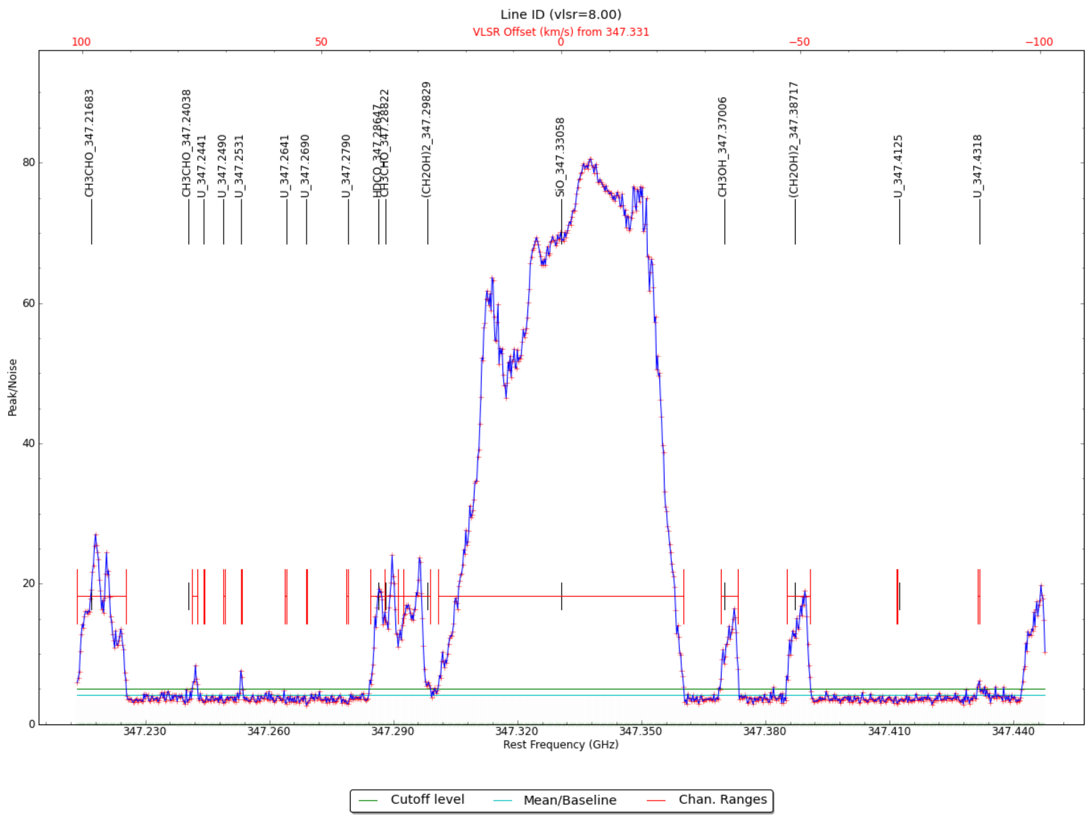




Line ID (vlsr=8.00)
VLSR Offset (km/s) from 345.796
Peak/Noise
Rest Frequency (GHz)
Cutoff level
Mean/Baseline
Chan. Ranges



Acetone ($(CH_3)_2CO$), 345.97366 GHz
Aminoacetonitrile (H_2NCH_2CN), 345.75117 GHz
Carbon Monoxide (CO), 345.79599 GHz
Cyanoacetylene (HC_3N), 345.60901 GHz
Cyclopropenylidene ($c-H_{13}CCCH$), 345.99364 GHz
Formaldehyde ($H_2C_{18}O$), 345.88103 GHz
Formic Acid ($t-DCOOH$), 345.98033 GHz
Formyl Radical (HCO), 345.66358 GHz
Methanol ($CH_3OHvt=_0$), 345.91919 GHz
Methyl Formate (CH_3OCHO), 346.00166 GHz
Nitric sulfide (NS), 345.90021 GHz
gauche-Ethanol ($g-CH_3CH_2OH$), 346.01721 GHz
Peak / Noise
Frequency (GHz)



Line ID (vlsr=8.00)
VLSR Offset (km/s) from 347.331
Peak/Noise
Rest Frequency (GHz)
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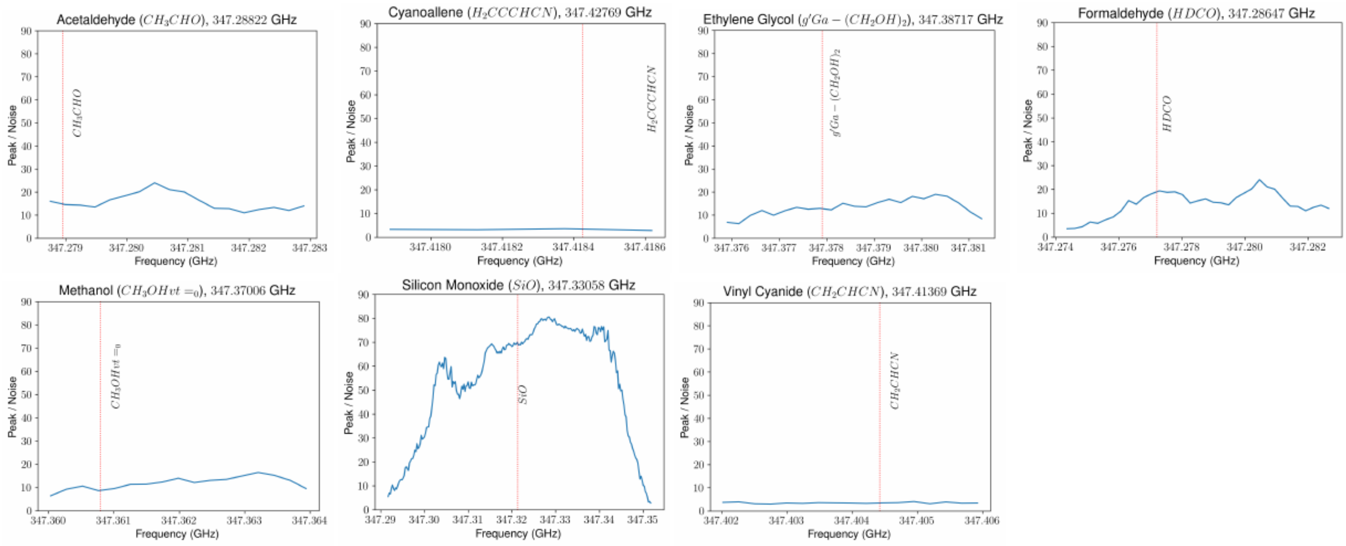
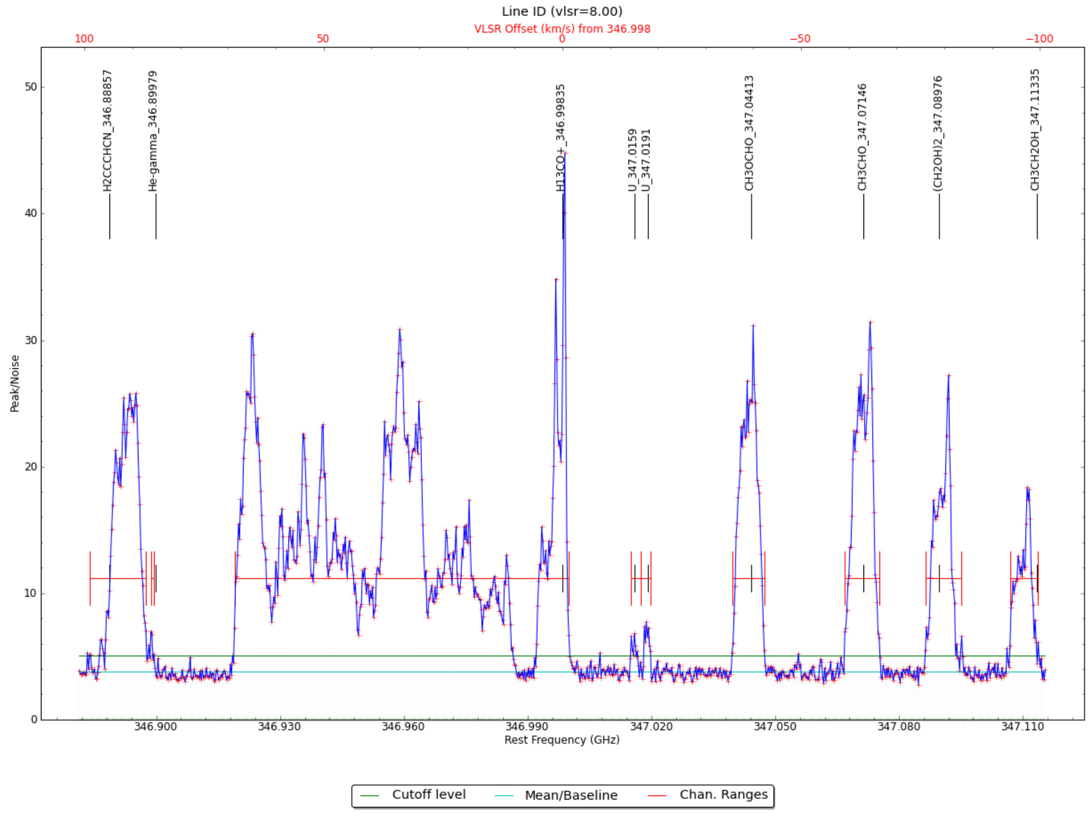
CH3CHO_347.24038
U_347.2441
U_347.2490
U_347.2531
U_347.2641
U_347.2690
U_347.2790
HDCO_347.28647
CH3CHO_347.28822
(CH2OH)2_347.29829
SiO_347.33058
CH3OH_347.37006
(CH2OH)2_347.38717
U_347.4125
U_347.4318
Cutoff level
Mean/Baseline
Chan. Ranges



Acetaldehyde (CH_3CHO), 347.28822 GHz
Cyanoallene ($H_2CCCHCN$), 347.42769 GHz
Ethylene Glycol ($g'Ga-(CH_2OH)_2$), 347.38717 GHz
Formaldehyde ($HDCO$), 347.28647 GHz
Methanol ($CH_3OHvt=_0$), 347.37006 GHz
Silicon Monoxide (SiO), 347.33058 GHz
Vinyl Cyanide (CH_2CHCN), 347.41369 GHz
Peak / Noise
Frequency (GHz)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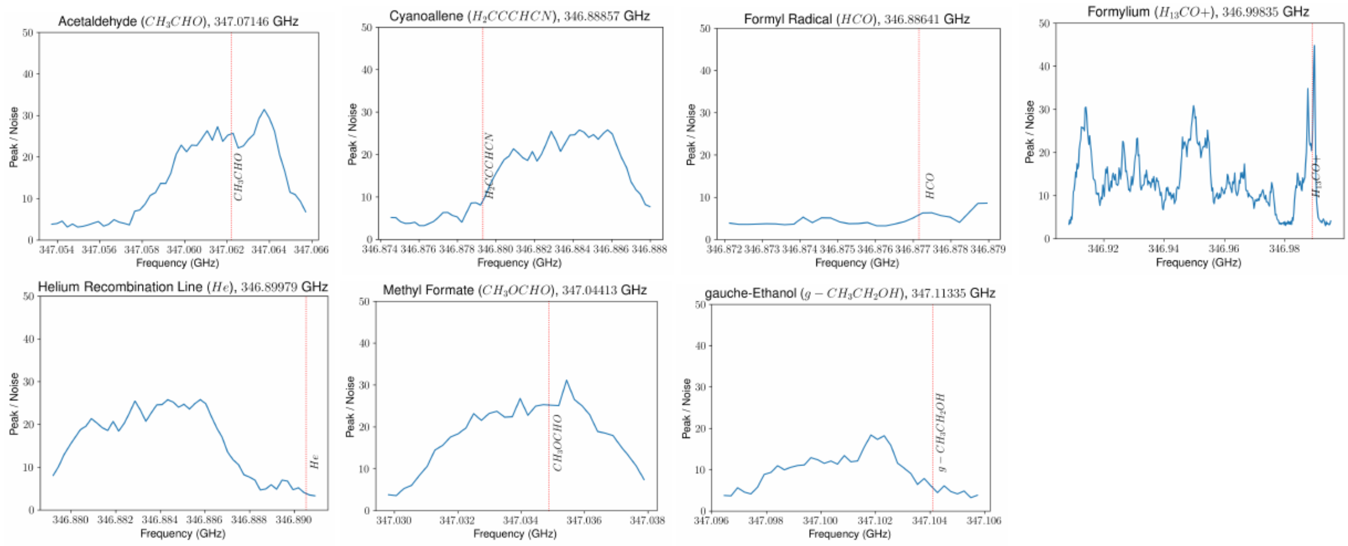
VLSR Offset (km/s) from 346.998
H2CCCHCN_346.88857
He-gamma_346.89979
H13CO+_346.99835
U_347.0159
U_347.0191
CH3OCHO_347.04413
CH3CHO_347.07146
(CH2OH)2_347.08976
CH3CH2OH_347.11335
Peak/Noise
Rest Frequency (GHz)
Cutoff level
Mean/Baseline
Chan. Ranges


Acetaldehyde (CH_3CHO), 347.07146 GHz
Cyanoallene ($H_2CCCHCN$), 346.88857 GHz
Formyl Radical (HCO), 346.88641 GHz
Formylium ($H_{13}CO+$), 346.99835 GHz
Helium Recombination Line (He), 346.89979 GHz
Methyl Formate (CH_3OCHO), 347.04413 GHz
gauche-Ethanol ($g-CH_3CH_2OH$), 347.11335 GHz
Peak / Noise
Frequency (GHz)

Molecule	Name	Transition	Frequency	E_u	Intensity	Velocity	V_{lsr}	Peak / rms
$(CH_3)_2COv =_0$	Acetone	$33_{2,32} - 32_{2,31}AE$	336.94769	284.9779	5.8645	6.7346	8.0	8.2528
$c - HCCCHv =_0$	Cyclopropenylidene	$4_{4,1} - 3_{1,2}$	336.94859	32.2203	7.7754	8.5402	8.0	10.942
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$29_{17,12}v = 0 - 29_{16,13}v = 0$	336.95735	355.5986	22.9795	7.6964	8.0	32.3382
$(CH_3)_2COv =_0$	Acetone	$33_{1,32} - 32_{2,31}EE$	336.96839	284.9042	8.6102	8.9506	8.0	12.1167
$(CH_3)_2COv =_0$	Acetone	$24_{12,13} - 23_{11,12}EE$	336.97681	230.3935	2.1859	6.0204	8.0	3.0761
$(CH_3)_2COv =_0$	Acetone	$33_{1,32} - 32_{2,31}AA$	336.98907	284.8304	3.5648	9.0125	8.0	5.0166
H_2NCH_2CN	Aminoacetonitrile	$37_{5,33} - 36_{5,32}$	337.01833	337.6508	8.1389	8.8251	8.0	11.4536
$g - CH_3CH_2OH$	gauche-Ethanol	$36_{5,32} - 35_{6,29}, vt = 0 - 0$	337.02461	643.1397	8.0259	13.0103	8.0	11.2946
$c - H^{13}CCCH$	Cyclopropenylidene	$21_{11,10} - 21_{11,11}$	337.02915	649.5308	0.0	0.0	8.0	0.0
$CH_2CHCNv =_0$	Vinyl Cyanide	$36_{2,35} - 35_{2,34}$	337.03974	309.7482	6.3892	7.3691	8.0	8.9912
$C_{17}O$	Carbon Monoxide	$J = 3 - 2$	337.0611	32.3538	32.425	0.5295	8.0	45.6304
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$33_{8,25}v = 0 - 32_{8,24}v = 1$	337.08211	309.0677	6.6297	5.9492	8.0	9.3296
$cis - CH_2OHCHOv =_0$	Glycolaldehyde	$29_{13,17} - 28_{13,16}$	337.09926	344.463	20.9463	7.5278	8.0	29.4769
$cis - CH_2OHCHOv =_0$	Glycolaldehyde	$29_{13,16} - 28_{13,15}$	337.09927	344.463	0.0	0.0	8.0	0.0
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$69_{18,52}v = 1 - 69_{17,53}v = 1$	337.10336	1346.196	-0.0118	8.1634	8.0	-2.8258
CH_3NH_2	Methylamine	$2_2E2 - 1 - 1_1E2 - 1$	337.11864	22.2636	0.0	0.0	8.0	0.0
CH_3NH_2	Methylamine	$2_2E2 - 1 - 1_1E2 - 1$	337.11894	22.2636	8.052	3.7404	8.0	11.3313
$CH_3OHvt =_0$	Methanol	$3_{3,0} - 4_{2,2}$	337.13586	61.6392	36.2978	7.6565	8.0	51.0804
$cis - CH_2OHCHOv =_0$	Glycolaldehyde	$15_{7,9} - 14_{6,8}$	337.15086	96.4924	2.1438	7.3493	8.0	3.0169
$CH_3CHOv =_0$	Acetaldehyde	$13_{1,12} - 12_{-1,12}E$	337.15207	88.4514	0.0247	6.2404	8.0	5.9389
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$26_{17,9}v = 1 - 26_{16,10}v = 1$	337.16832	314.6439	0.0147	7.4294	8.0	3.5352
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$24_{17,7}v = 0 - 24_{16,8}v = 0$	337.17585	289.264	0.0	0.0	8.0	0.0

Figure 4 Identified lines from spectral window 0

Molecule	Name	Transition	Frequency	E_u	Intensity	Velocity	V_{lsr}	Peak / rms
$CH_3OHvt =_0$	Methanol	$14_{7,8} - 15_{6,9} + +$	336.43822	488.2179	3.3687	7.3909	8.0	3.1028
$CNCHO$	Cyanoformaldehyde	$35_{6,30} - 36_{5,31}$	336.44841	400.3188	2.7454	7.0118	8.0	2.5287
$CH_3^{13}CH_2CN$	Ethyl Cyanide	$34_{8,26} - 34_{7,27}$	336.45107	323.9327	0.6648	8.7744	8.0	1.7433
$CH_3OCHOv =_0$	Methyl Formate	$35_{13,23} - 35_{12,24}A$	336.45452	484.8088	2.9014	6.3529	8.0	2.6725
$CH_3OCHOv =_0$	Methyl Formate	$35_{13,22} - 35_{12,23}E$	336.46561	484.8108	1.7567	7.9995	8.0	4.6065
$CNCHO$	Cyanoformaldehyde	$35_{6,29} - 36_{5,32}$	336.46699	400.3188	3.3371	6.9874	8.0	3.0738
HC_3N	Cyanoacetylene	$J = 37 - 36$	336.52008	306.905	8.053	13.4069	8.0	21.1174
$CCCO$	3-Oxo-1,2-Propadienylidene	$35 - 34$	336.62937	290.8558	-0.3128	12.6003	8.0	-0.8202
^{13}CCH	Ethynyl	$N = 4 - 3, J = 7/2 - 5/2$	336.63657	40.436	-14.343	9.4492	8.0	-13.211
$(CH_3)_2COv =_0$	Acetone	$23_{13,10} - 22_{14,9}EA$	336.64028	222.2164	-13.5255	10.0258	8.0	-12.458
H_2NCH_2CN	Aminoacetonitrile	$37_{19,18} - 36_{19,17}$	336.65152	748.4583	-13.5255	6.1625	8.0	-12.458
^{13}CCH	Ethynyl	$N = 4 - 3, J = 7/2 - 5/2$	336.65645	40.4354	-15.7359	7.0159	8.0	-14.494
$(CH_3)_2COv =_0$	Acetone	$20_{13,8} - 19_{12,7}AA$	336.65982	171.7552	-16.9879	6.8598	8.0	-15.6472
$SO_2v =_0$	Sulfur dioxide	$16_{7,9} - 17_{6,12}$	336.66958	245.1142	-13.0386	7.5137	8.0	-12.0096

Figure 5 Identified lines in spectral window 1

Molecule	Name	Transition	Frequency	E_u	Intensity	Velocity	V_{lsr}	Peak / rms
$cis-CH_2OHCHOv=_0$	Glycolaldehyde	$7_{6,2}-6_{4,3}$	334.05821	37.4116	45.0294	6.5106	8.0	50.0827
$CH_3OCHOv=_0$	Methyl Formate	$15_{6,10}-14_{5,9}A$	334.10909	94.8964	17.0495	9.9217	8.0	18.9629
CH_3NH_2	Methylamine	$17_2E1+1-17_1E1-1$	334.13094	342.265	10.4351	14.8478	8.0	11.6061
$^{33}SO_2$	Sulfur Dioxide	$36_{11,25}-37_{10,28}, F=69/2-71/2$	334.14626	915.5991	-0.6228	8.9463	8.0	-1.4553
$t-CH_2CHCHO$	Propenal	$9_{3,7}-9_{1,8}$	334.20301	37.7617	3.1656	6.2555	8.0	3.5209
CH_3NH_2	Methylamine	8_5B1-9_4B2	334.20979	174.0493	3.9923	8.9327	8.0	4.4404
$(CH_3)_2COv=_0$	Acetone	$13_{11,3}-12_{8,4}AA$	334.21979	80.4654	-0.4388	7.6194	8.0	-1.0253
$CH_3OCHOv=_0$	Methyl Formate	$29_{5,24}-28_{6,23}A$	334.23598	282.1007	3.9697	1.2063	8.0	4.4152
$^{13}CH_3OHvt=_0$	Methanol	$3_{2,1}-2_{0,2}$	334.25221	35.9468	3.4457	9.4204	8.0	3.8324
CP	Carbon Monophosphide	$N=7-6, J=15/2-13/2, F=8-7$	334.26182	64.2111	45.3174	11.3104	8.0	50.4031
$CH_3OCHOv=_0$	Methyl Formate	$15_{6,9}-14_{5,9}E$	334.28144	94.9147	13.9904	12.98	8.0	15.5604
$g'Ga-(CH_2OH)_2$	Ethylene Glycol	$15_{9,7}v=1-14_{8,7}v=0$	334.30955	99.0907	4.2402	7.0359	8.0	4.7161
$CH_3OHvt=_1$	Methanol	$21_{5,16}-22_{4,19}$	334.32728	964.3871	6.4237	12.1515	8.0	7.1446
$s-H_2CCHOH$	Vinyl Alcohol	$17_{4,13}-16_{4,12}$	334.34291	182.2279	15.4923	6.892	8.0	17.2309
$CH_3COOHv=_0$	Acetic Acid	$30_{*,29}-29_{*,28}v=0$	334.37851	259.444	4.3631	-4.0152	8.0	4.8527
$g'Ga-(CH_2OH)_2$	Ethylene Glycol	$24_{6,19}v=0-23_{5,18}v=0$	334.41275	165.9969	45.6615	10.8101	8.0	50.7858
$CH_3OHvt=_1$	Methanol	$3_{0,3}-2_{1,2}$	334.42656	314.4694	52.4693	7.1835	8.0	58.3575
$g'Ga-(CH_2OH)_2$	Ethylene Glycol	$13_{10,4}v=1-12_{9,4}v=0$	334.46125	94.1713	44.2048	-2.9053	8.0	49.1656
$(CH_3)_2COv=_0$	Acetone	$13_{11,2}-12_{8,4}EE$	334.58973	80.5543	8.5715	-10.7174	8.0	9.5334
$t-CH_3CH_2OH$	trans-Ethanol	$24_{7,17}-24_{6,18}$	334.60263	313.8344	12.3572	5.1576	8.0	13.7439
$CH_3OHvt=_1$	Methanol	$22_{3,20}-22_{2,21}$	334.63249	1001.3148	13.0942	11.6487	8.0	14.5637
$CH_3OHvt=_1$	Methanol	$25_{-3,22}-24_{-2,22}$	334.67771	1073.8453	21.2092	-0.8691	8.0	23.5894
CH_3NH_2	Methylamine	$2_2A2-1_1A1, F=2-1$	334.71119	22.5092	0.0	0.0	8.0	0.0
CH_3NH_2	Methylamine	$2_2A2-1_1A1, F=2-2$	334.71174	22.5092	0.0	0.0	8.0	0.0
CH_3NH_2	Methylamine	2_2A2-1_1A1	334.71225	22.5093	23.4786	3.1788	8.0	26.1134
CH_3NH_2	Methylamine	$2_2A2-1_1A1, F=1-1$	334.7124	22.5093	0.0	0.0	8.0	0.0
CH_3NH_2	Methylamine	$2_2A2-1_1A1, F=3-2$	334.71251	22.5093	0.0	0.0	8.0	0.0
CH_3NH_2	Methylamine	$2_2A2-1_1A1, F=1-0$	334.71377	22.5093	0.0	0.0	8.0	0.0
CCO	Oxoethenylidene	$N=14-13, J=14-14$	334.75876	116.8058	12.7521	-3.4945	8.0	14.1832
$(CH_3)_2COv=_0$	Acetone	$12_{8,4}-11_{5,7}AE$	334.76545	64.565	20.6655	11.5016	8.0	22.9846
$HOCO+$	Protonated Carbon Dioxide	$19_{1,19}-20_{0,20}$	334.78159	231.5354	0.0959	7.2491	8.0	0.2241
$(CH_3)_2COv=_0$	Acetone	$21_{13,9}-20_{12,8}EA$	334.79756	186.8541	11.0979	10.7281	8.0	12.3434
CH_3NH_2	Methylamine	20_3B1-19_4B2	334.81231	482.4697	13.6576	4.5153	8.0	15.1903
$(CH_3)_2COv=_0$	Acetone	$13_{11,2}-12_{8,4}EA$	334.86228	80.6413	28.7854	-3.5054	8.0	32.0158
$(CH_3)_2COv=_0$	Acetone	$12_{8,4}-11_{5,7}EA$	334.8783	64.5704	55.5111	1.3852	8.0	61.7407
$(CH_3)_2COv=_0$	Acetone	$14_{11,4}-13_{8,5}EE$	334.88886	90.3851	67.9959	19.9035	8.0	75.6266

Figure 6 Identified lines in spectral window 2 (part i)

Molecule	Name	Transition	Frequency	E_u	Intensity	Velocity	V_{lsr}	Peak / rms
$CH_3CHOv =_0$	Acetaldehyde	$17_{2,15} - 16_{2,14}A++$	334.93139	152.6118	43.1424	6.3067	8.0	47.9839
$H_2^{13}CS$	Thioformaldehyde	$10_{1,9} - 9_{1,8}$	334.94932	101.6033	7.7273	9.4859	8.0	8.5944
$(CH_3)_2COv =_0$	Acetone	$12_{8,4} - 11_{5,7}EE$	334.99117	64.4966	13.4849	-0.0038	8.0	14.9982
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$41_{17,24}v = 0 - 41_{16,25}v = 0$	335.07602	565.0077	0.462	10.367	8.0	1.0795
$c - H_{13}CCCH$	Cyclopropenylidene	$5_{3,2} - 5_{0,5}$	335.08781	43.7198	83.5866	13.1283	8.0	92.9669
$CH_3OHvt =_0$	Methanol	$2_{2,1} - 3_{1,2} --$	335.13369	44.6721	77.7538	7.0251	8.0	86.4796
$CH_3OCHOv =_0$	Methyl Formate	$28_{4,24} - 27_{5,23}A$	335.18332	257.0799	2.4819	9.7965	8.0	2.7604
$g - CH_3CH_2OH$	gauche-Ethanol	$32_{6,27} - 32_{5,27}, vt = 1 - 0$	335.2683	545.844	7.8166	7.151	8.0	8.6938
$CH_3CH_2CNv =_0$	Ethyl Cyanide	$55_{8,48} - 55_{7,49}$	335.27492	733.8889	7.8166	8.2166	8.0	8.6938
HDO	Water	$3_{3,1} - 4_{2,2}$	335.3955	335.2672	46.6299	-58.3771	8.0	51.8628
$HOCN$	Cyanic acid	$16_{2,14} - 15_{2,13}$	335.47103	265.334	3.6165	14.814	8.0	4.0224
$g - CH_3CH_2OH$	gauche-Ethanol	$9_{4,5} - 8_{3,6}, vt = 1 - 1$	335.48609	118.6556	39.5665	1.356	8.0	44.0067
NHD_2	Ammonia	$1_{1,1}0s - 0_{0,0}0s$	335.51385	16.102	47.0375	68.9121	8.0	52.3161
$CH_3OHvt =_0$	Methanol	$7_{1,7} - 6_{1,6} ++$	335.58202	78.9709	56.2576	-11.484	8.0	62.571
$CH_3COOHv =_0$	Acetic Acid	$15_{-15,0} - 14_{-14,0}v = 0$	335.60436	128.6181	10.8442	-12.7636	8.0	12.0612
$t - CH_3CH_2OH$	trans-Ethanol	$23_{7,17} - 23_{6,18}$	335.63059	293.607	17.1709	8.6112	8.0	19.0979
$cis - CH_2OHCHOv =_0$	Glycolaldehyde	$21_{7,14} - 21_{4,17}$	335.64676	158.7973	39.0976	3.8067	8.0	43.4853
$(CH_3)_2COv =_0$	Acetone	$12_{11,1} - 11_{8,4}EE$	335.67518	71.4144	24.4019	8.8142	8.0	27.1404
$cis - CH_2OHCHOv =_0$	Glycolaldehyde	$68_{15,54} - 68_{14,55}$	335.69367	1456.6243	-0.829	8.4429	8.0	-1.9371
H_2NCH_2CN	Aminoacetonitrile	$21_{3,18} - 20_{2,19}$	335.69558	112.127	-0.829	6.7331	8.0	-1.9371
$CH_3OHvt =_0$	Methanol	$25_{8,17} - 26_{7,20} ++$	335.7015	1073.9686	0.0	0.0	8.0	0.0
$t - H_{13}COOH$	Formic Acid	$6_{3,3} - 7_{1,6}$	335.71489	50.4224	13.3501	-0.5284	8.0	14.8482
CH_3NH_2	Methylamine	$14_1E1 - 1 - 13_2E1 - 1$	335.74509	225.3446	12.4894	4.6287	8.0	13.8909
$CH_3COOHv =_0$	Acetic Acid	$13_{11,2} - 12_{9,3} - -v = 0$	335.77985	89.7941	15.7797	3.9964	8.0	17.5506
$(CH_3)_2COv =_0$	Acetone	$32_{2,30} - 31_{3,29}EA$	335.80289	281.4994	0.0	0.0	8.0	0.0
$(CH_3)_2COv =_0$	Acetone	$32_{2,30} - 31_{2,29}AE$	335.80291	281.4994	11.5028	1.213	8.0	12.7937
$H_2C_{18}O$	Formaldehyde	$5_{1,5} - 4_{1,4}$	335.81594	60.2335	31.1124	7.7668	8.0	34.6039
$CH_3CH_2CNv =_0$	Ethyl Cyanide	$10_{4,6} - 10_{1,9}$	335.84026	41.4386	16.3359	3.3581	8.0	18.1692
$t - CH_2CHCHO$	Propenal	$4_{4,1} - 3_{3,0}$	335.86615	37.2113	30.6761	9.7555	8.0	34.1186
$t - CH_2CHCHO$	Propenal	$4_{4,0} - 3_{3,1}$	335.86616	37.2113	0.0	0.0	8.0	0.0
$CH_3OCHOv =_0$	Methyl Formate	$27_{9,19} - 26_{9,17}E$	335.89969	277.8455	4.5668	11.5288	8.0	5.0793

Figure 7 Identified lines in spectral window 2 (part ii)

Molecule	Name	Transition	Frequency	E_u	Intensity	Velocity	V_{lsr}	Peak / rms
HC_3N	Cyanoacetylene	$J = 38 - 37$	345.60901	323.4915	21.2643	9.0408	8.0	35.7027
$t - HCOOD$	Formic Acid	$21_{8,13} - 22_{7,16}$	345.63774	410.7233	2.5643	8.2591	8.0	4.3054
$s - H_2CCHOH$	Vinyl Alcohol	$18_{2,17} - 17_{2,16}$	345.6418	168.4271	4.9808	7.4902	8.0	8.3628
$CH_3OCHOv =_0$	Methyl Formate	$9_{9,1} - 8_{8,1}E$	345.65066	80.3102	10.4041	6.7926	8.0	17.4684
HCO	Formyl Radical	$4_{2,3} - 3_{2,2}, J = 9/2 - 7/2$	345.65558	172.8172	4.2624	6.5482	8.0	7.1566
HCO	Formyl Radical	$4_{2,3} - 3_{2,2}, J = 9/2 - 7/2$	345.66358	172.8071	3.0956	7.6552	8.0	5.1975
$(CH_3)_2COv =_0$	Acetone	$15_{7,8} - 14_{6,9}EE$	345.67395	92.9358	2.6695	7.1301	8.0	4.4821
$g - CH_3CH_2OH$	gauche-Ethanol	$21_{1,21} - 20_{0,20}, vt = 1 - 1$	345.68942	246.219	15.7399	4.9342	8.0	26.4272
$CH_3CH_2^{13}CN$	Ethyl Cyanide	$33_{8,26} - 33_{7,27}$	345.70286	311.1458	4.7335	7.251	8.0	7.9476
$CH_3OCHOv =_0$	Methyl Formate	$9_{9,1} - 8_{8,0}A$	345.71868	80.3192	16.5648	8.1389	8.0	27.8123
H_2NCH_2CN	Aminoacetonitrile	$38_{4,35} - 37_{4,34}$	345.75117	343.2689	1.9722	7.0606	8.0	3.3113
CO	Carbon Monoxide	$3 - 2$	345.79599	33.1917	113.7963	−20.5825	8.0	191.0639
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$22_{1,21}v = 1 - 21_{0,21}v = 0$	345.85194	122.0468	4.9053	7.3147	8.0	8.2359
$H_2C_{18}O$	Formaldehyde	$5_{0,5} - 4_{0,4}$	345.88103	49.8711	5.2881	8.3375	8.0	8.8788
NS	Nitric sulfide	$J = 15/2 - 13/2, \Omega = 1/2$	345.90021	70.7983	30.2713	10.9672	8.0	50.8255
$(CH_3)_2COv =_0$	Acetone	$15_{7,8} - 14_{6,9}AA$	345.91243	92.8831	13.6343	8.2044	8.0	22.892
$CH_3OHvt =_0$	Methanol	$18_{-3,16} - 17_{-4,14}$	345.91919	459.4299	21.6847	8.0579	8.0	36.4085
$CH_3CH_2CNv =_0$	Ethyl Cyanide	$32_{8,25} - 32_{7,26}$	345.94052	298.1705	0.2829	8.1896	8.0	0.7596
$g - CH_3CH_2OH$	gauche-Ethanol	$28_{15,13} - 29_{14,15}, vt = 1 - 0$	345.96948	674.3881	2.8709	7.2094	8.0	4.8203
$(CH_3)_2COv =_0$	Acetone	$24_{12,12} - 23_{13,11}EE$	345.97366	235.2414	6.7394	7.6064	8.0	11.3155
$t - DCOOH$	Formic Acid	$21_{5,17} - 22_{2,20}$	345.98033	301.3129	10.2415	12.8261	8.0	17.1954
$c - H^{13}CCCH$	Cyclopropenylidene	$13_{3,10} - 13_{2,11}$	345.99364	208.5557	2.2908	8.0618	8.0	3.8462
$CH_3OCHOv =_0$	Methyl Formate	$28_{12,17} - 27_{12,16}E$	346.00166	335.4293	2.8637	6.4006	8.0	4.8082
$g - CH_3CH_2OH$	gauche-Ethanol	$20_{11,9} - 19_{11,8}, vt = 1 - 1$	346.01721	384.5567	3.5314	9.2137	8.0	5.9293

Figure 8 Identified lines in spectral window 3

Molecule	Name	Transition	Frequency	E_u	Intensity	Velocity	V_{lsr}	Peak / rms
$CH_3CHOvt =_1$	Acetaldehyde	$18_{5,13} - 17_{5,12}E$	347.21683	420.4368	11.3958	9.7207	8.0	22.936
$CH_3CHOv =_0$	Acetaldehyde	$19_{0,19} - 18_{-1,18}E$	347.24038	171.8864	2.1204	9.5018	8.0	4.2677
$(CH_3)_2COv =_0$	Acetone	$41_{25,16} - 41_{22,19}EA$	347.26121	700.7776	−0.0697	9.714	8.0	−0.1438
$CH_{213}CHCN$	Vinyl Cyanide	$50_{5,45} - 50_{4,46}$	347.27314	631.6862	−0.5368	8.4083	8.0	−1.1077
$HDCO$	Formaldehyde	$4_{2,2} - 5_{0,5}$	347.28647	62.8611	7.5691	11.0417	8.0	15.2342
$CH_3CHOv =_0$	Acetaldehyde	$18_{5,14} - 17_{5,13}A++$	347.28822	214.6964	9.9113	12.3779	8.0	19.9483
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$19_{8,12}v = 1 - 18_{7,11}v = 1$	347.29829	125.2303	9.7218	5.8715	8.0	19.5668
SiO	Silicon Monoxide	$8 - 7$	347.33058	75.017	37.9513	−7.0397	8.0	76.3837
$CH_3OHvt =_0$	Methanol	$4_{2,2} - 4_{-1,4}$	347.37006	45.4594	6.1449	9.6635	8.0	12.3678
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$32_{6,26}v = 1 - 31_{6,25}v = 0$	347.38717	282.6495	7.3878	9.4337	8.0	14.8693
$CH_2CHCNv =_0$	Vinyl Cyanide	$55_{3,53} - 56_{0,56}$	347.41369	719.2458	0.1307	8.6672	8.0	0.2697
$(CH_3)_2COv =_0$	Acetone	$24_{14,10} - 23_{15,9}AA$	347.41743	242.8387	−0.135	7.3357	8.0	−0.2786
$t - HCOOD$	Formic Acid	$21_{1,20} - 21_{1,21}$	347.42058	247.3015	−0.161	5.6621	8.0	−0.3321
$H_2CCCHCN$	Cyanoallene	$81_{4,77} - 80_{5,76}$	347.42769	849.0271	−0.0005	8.172	8.0	−0.1791

Figure 9 Identified lines in spectral window 4

Molecule	Name	Transition	Frequency	E_u	Intensity	Velocity	V_{lsr}	Peak / rms
HCO	Formyl Radical	$4_{0,4} - 3_{0,3}, J = 7/2 - 5/2$	346.88641	41.6394	0.0362	13.5936	8.0	8.1056
$H_2CCCHCN$	Cyanoallene	$39_{4,36} - 38_{3,35}$	346.88857	211.6287	14.2677	12.8899	8.0	22.0365
He	He Recombination Line	$He_{37}\gamma;$	346.89979	0.0	2.0836	7.0697	8.0	3.2182
$H^{13}CO+$	Formylium	$4 - 3$	346.99835	41.6345	17.3297	-55.2937	8.0	26.7658
$CH_3OCHOv =_0$	Methyl Formate	$47_{14,33} - 47_{13,34}E$	347.04413	799.2405	17.7465	8.0647	8.0	27.4096
$CH_3CHOv =_0$	Acetaldehyde	$20_{2,18} - 20_{-1,20}E$	347.07146	206.5641	15.2135	7.0196	8.0	23.4973
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$29_{6,24}v = 1 - 28_{5,23}v = 1$	347.08976	233.3521	9.3897	7.8703	8.0	14.5024
$g'Ga - (CH_2OH)_2$	Ethylene Glycol	$60_{18,43}v = 1 - 60_{17,44}v = 1$	347.1013	1058.6221	0.0154	7.8127	8.0	3.4385
$g - CH_3CH_2OH$	gauche-Ethanol	$46_{5,42} - 45_{6,39}, vt = 0 - 0$	347.11335	987.1973	9.4604	5.8388	8.0	14.6117

Figure 10 Identified lines in spectral window 5

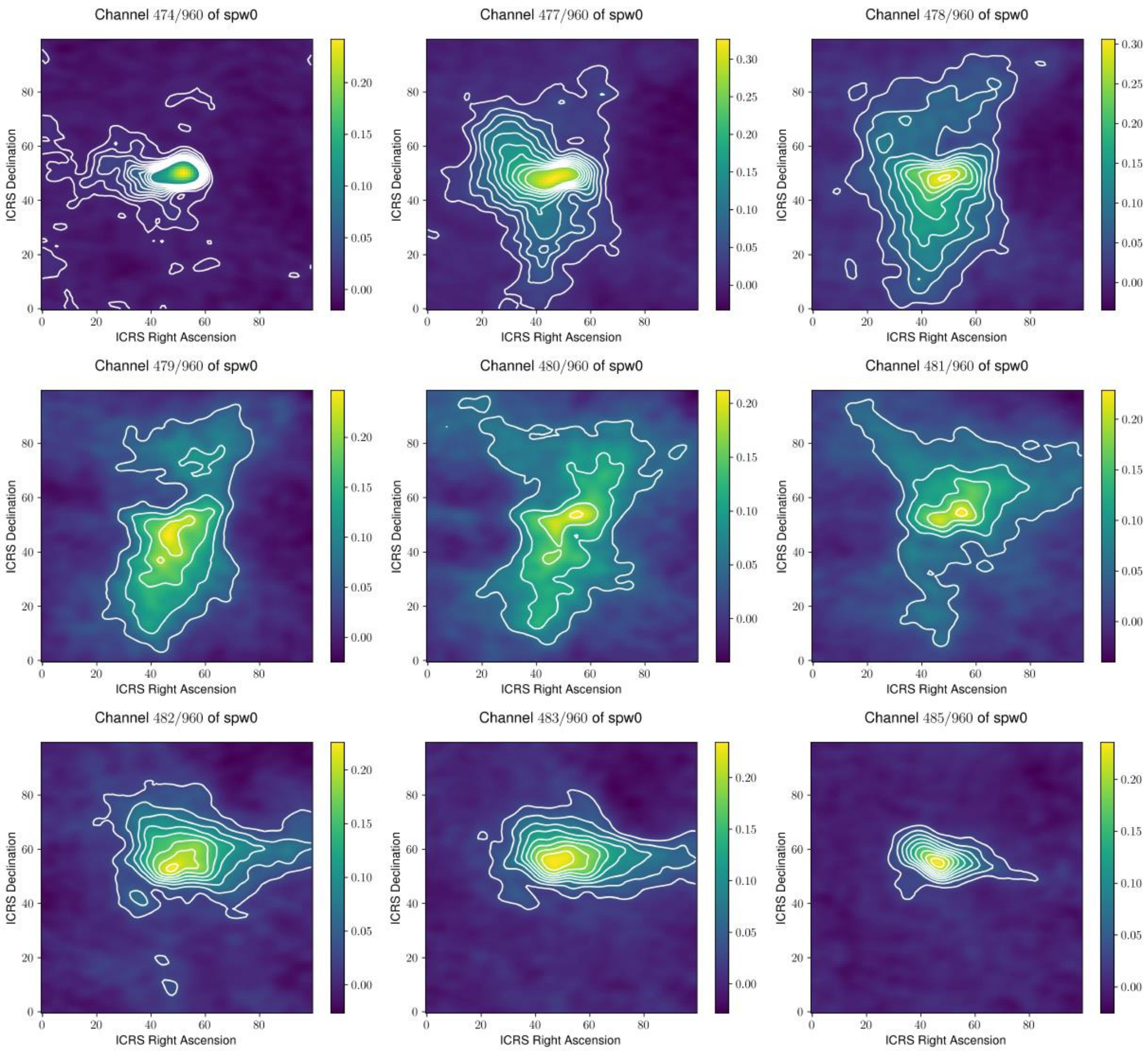


Figure 11 Contour plot of spectral window 0

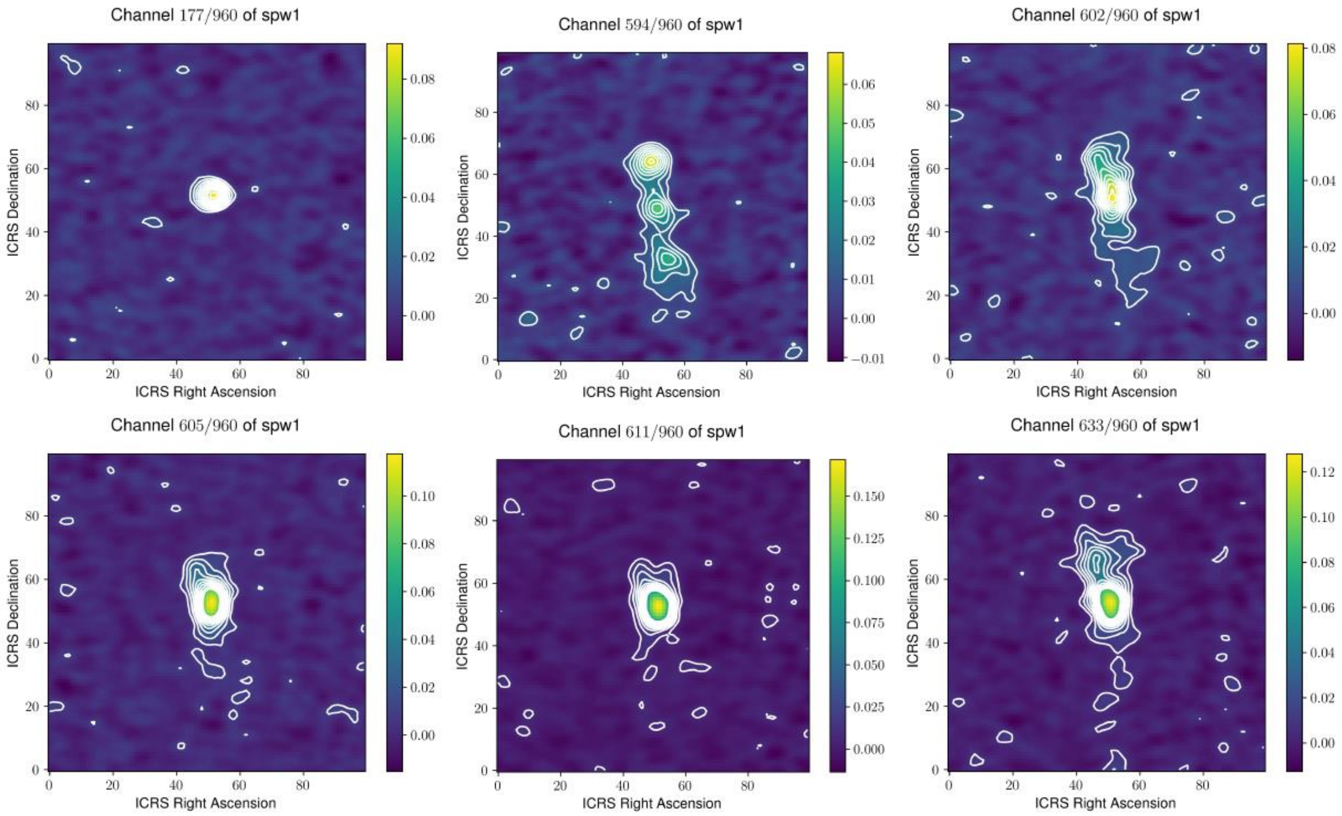


Figure 12 Contour plot of spectral window 1

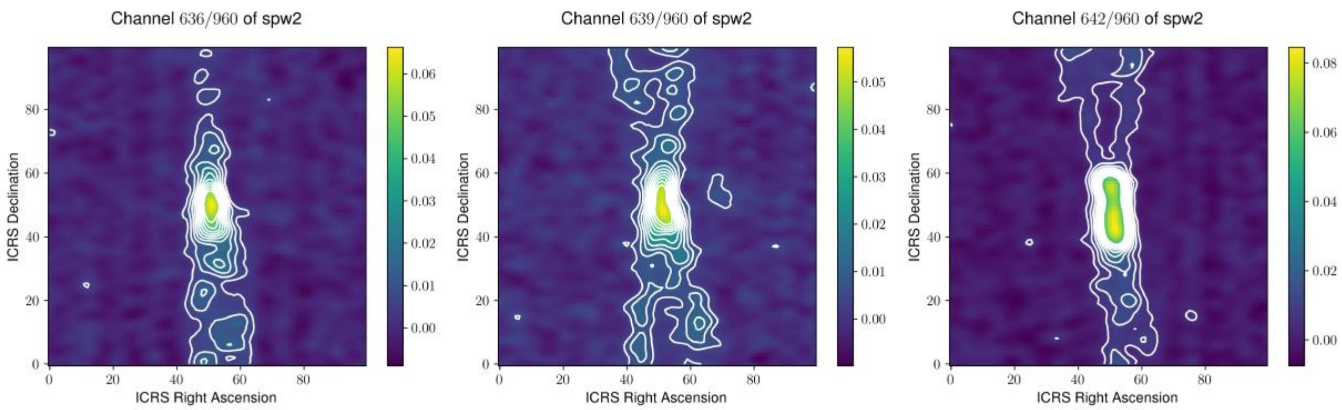


Figure 13 Contour plot of spectral window 2

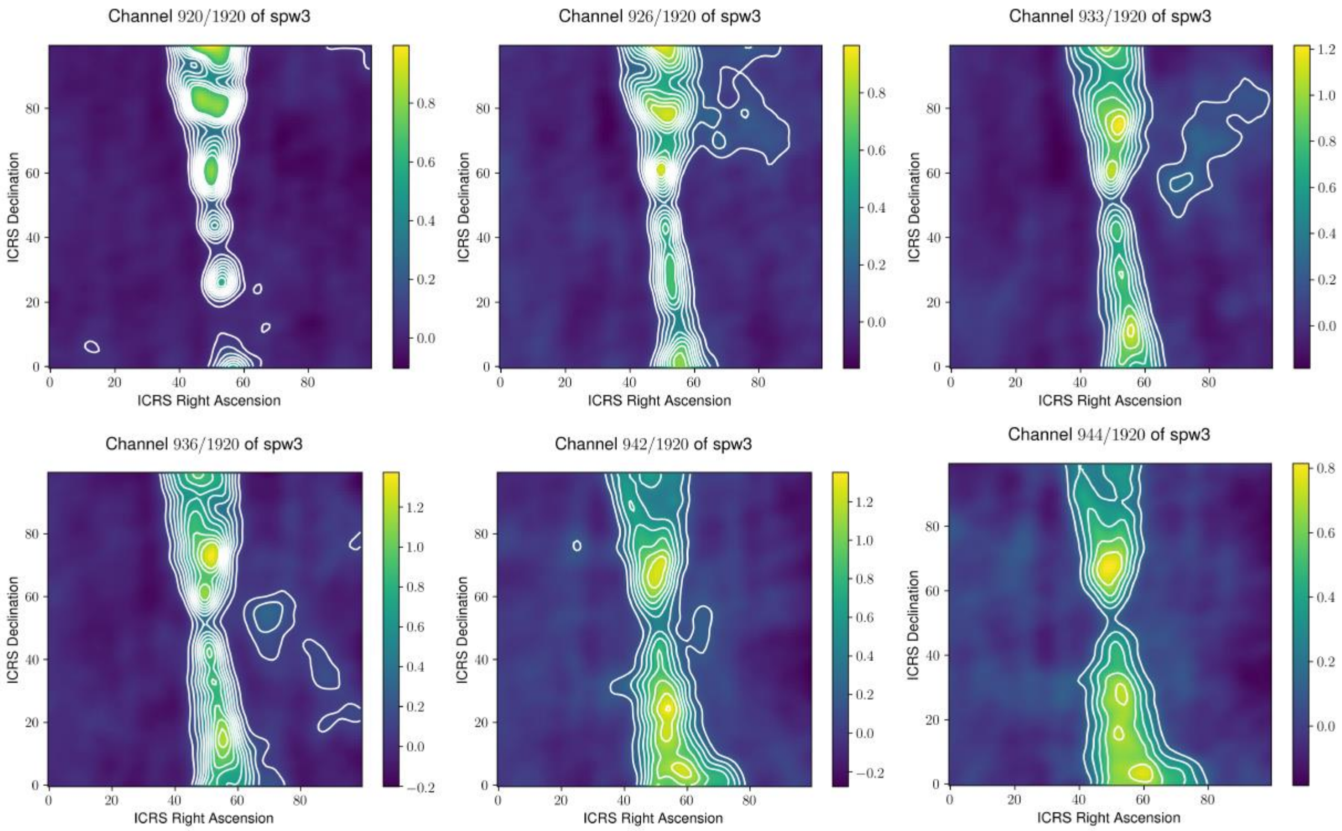


Figure 14 Contour plot of spectral window 3

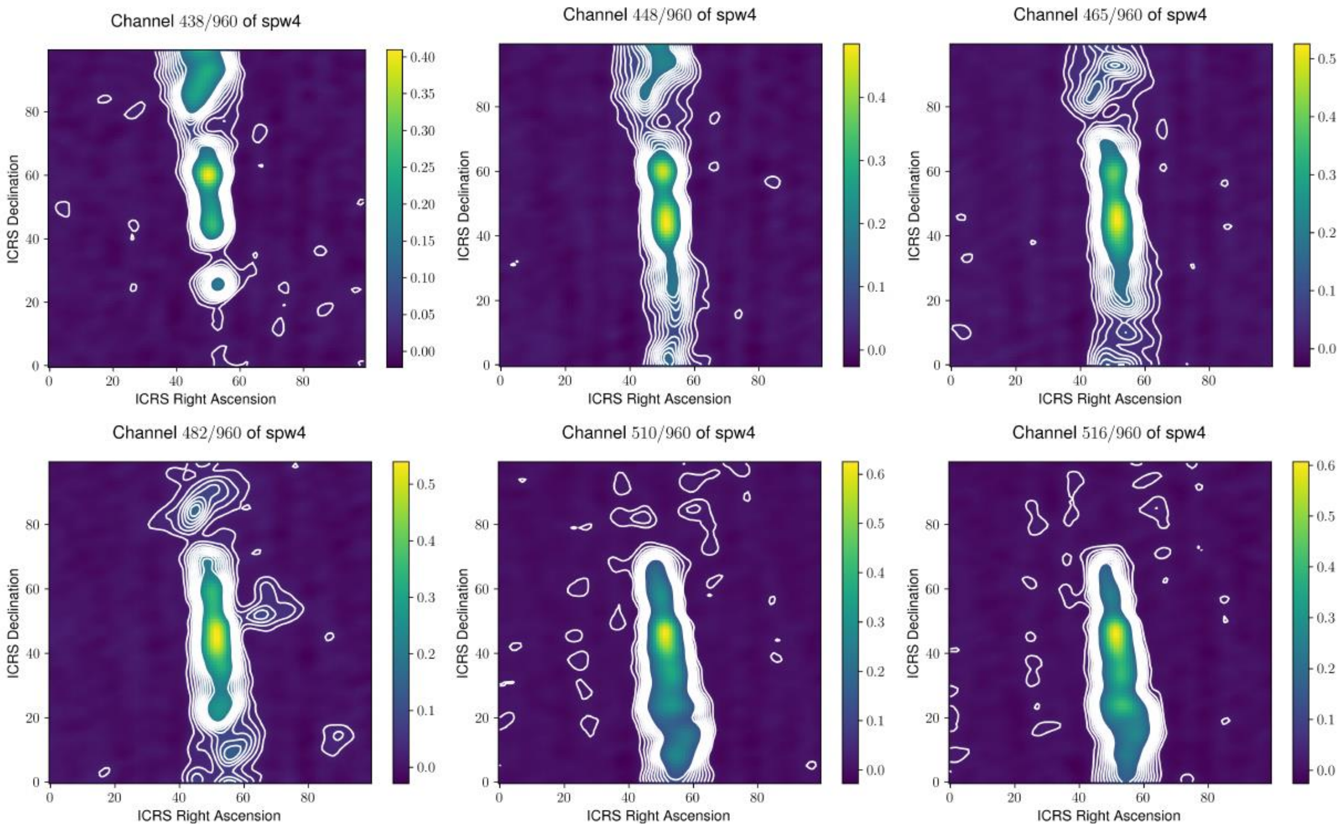


Figure 16 Contour plot of spectral window 4

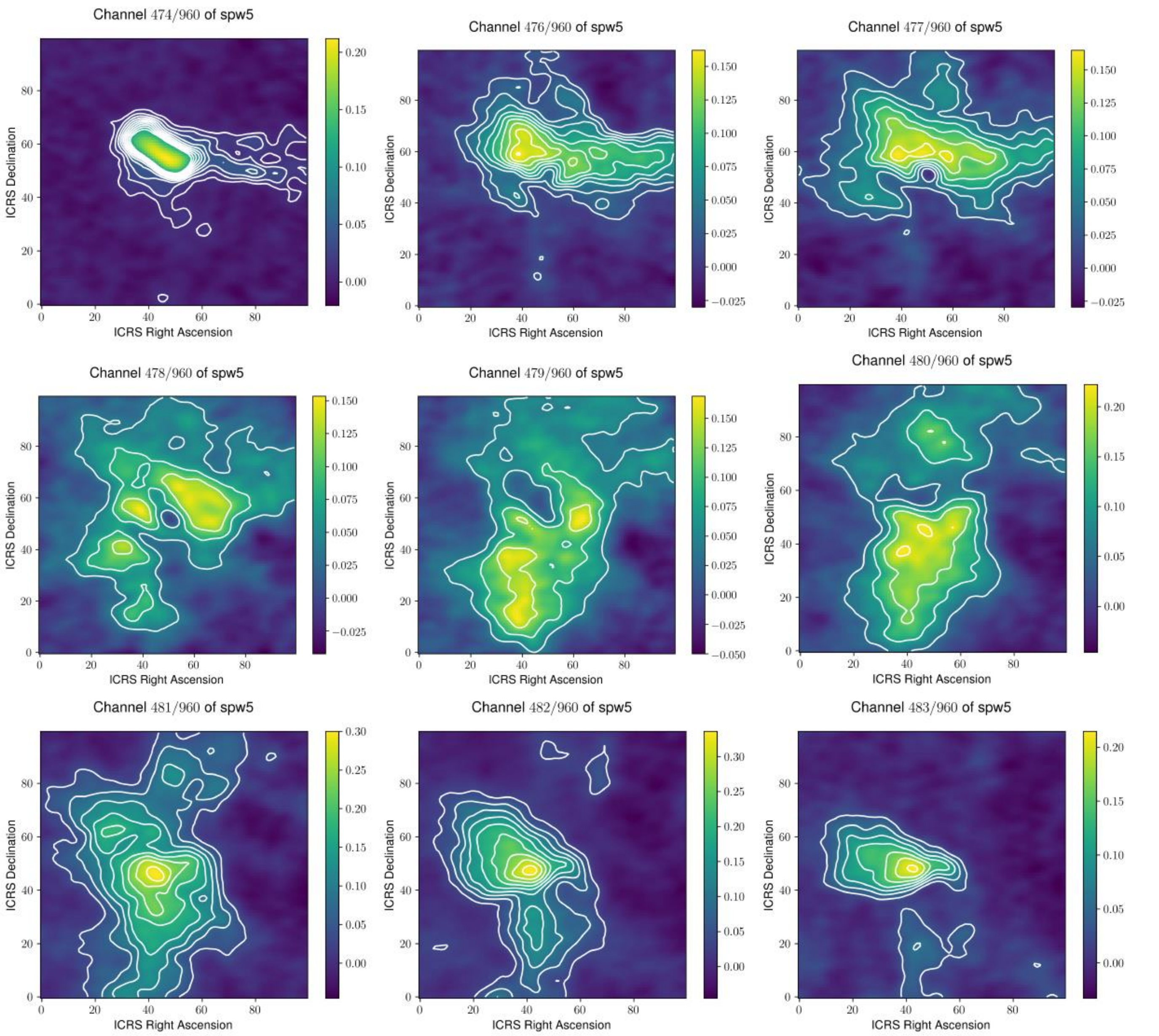


Figure 5 Contour plot of spectral window 5

References

[1] Surname A, Surname B and Surname C 2015 *Journal Name*
[2] Surname A and Surname B 2009 *Journal Name*