

The Complex Organic Molecules of Embedded Protostars at Perseus

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1. INTRODUCTION

Planet formation may start during the embedded phase of star formation. In the scenario where planets form from the embedded disks, resulting in substructures, the chemistry of embedded disks may play a significant role for the chemical composition of the forming planets. In the recent years, observations discover the emission of carbon-chain molecules and complex organic molecules (COMs) toward the center of several embedded protostars, indicating that embedded protostars have developed a complex chemistry at the disk-forming region. If the forming planets inherit the chemistry of embedded disks, the abundance of complex organic molecules may implicate future developments of organics on the planets.

Heavier or more complex molecules, such as cyclic-C₃H₂, SO, and complex organic molecules (COMs), are in the gas phase at the inner protostellar envelope ($T \gtrsim 100$ K), exclusively tracing the properties of the inner envelope where a disk may be forming (Aikawa 2013; Sakai et al. 2014). The kinematics of a rotating infalling envelope has been analyzed with the observations of heavier or more complex molecules, such as CH₃OH and CH₂DOH for HH 212 (Lee et al. 2017), CS for IRAS 04365+2535 (Sakai et al. 2016) and L483 (Oya et al. 2017), cyclic-C₃H₂ for L1527 (Sakai et al. 2014), OCS for IRAS 16293–2422 A (Oya et al. 2016), and methanol and HCOOH for B335 (Imai et al. 2019).

In the review by Herbst & van Dishoeck (2009), complex molecules are defined as carbon-bearing molecules that contain six atoms or more. Saturated complex molecules are rich in hydrogen atoms, often called complex organic molecules (COMs), while the unsaturated complex molecules are lack of hydrogen atoms, mostly in the form of long carbon-chain molecules. While recent observations show several embedded protostars with rich spectra of complex molecules, the occurrence of complex molecules at embedded protostars and its relation-

ship to the star formation process remain poorly understood. Several protostars are rich in COMs but show little emission of long carbon-chain molecules, such as IRAS 16293–2422 (Jørgensen et al. 2016), NGC 1333 IRAS 4A (Bottinelli et al. 2004), B335 (Imai et al. 2016, 2019), and BHR 71 (Yang et al. 2020 accepted); some protostars are rich in long carbon-chain molecules but not in COMs, such as L1527 (Sakai et al. 2010) and IRAS 15398–3359 (Sakai et al. 2009). While the bimodal chemical appearance hints a bimodal evolutionary path, the chemical evolution at the embedded protostars remain ill-constrained as a few protostars show the emission of both COMs and long carbon-chain molecules at different scales, such as L483 (Oya et al. 2017).

The Perseus ALMA Chemistry Survey (PEACHES) aims to provide the statistics on the occurrence of complex molecules at embedded protostars. This program unbiasedly observes 51 embedded protostars with ALMA around 260 GHz, covering the emission of simple molecules such as CS and H¹³CN as well as the emission of complex molecules including CH₃OH and CH₃OCHO.

2. OBSERVATIONS

3. RESULTS

The ALMA image cubes are post-processed to extract 1D spectra for identifying the emission of complex molecules and more in-depth analyses. Because the complex molecules only sublime at the temperature greater than ~ 100 K, we focus on the spectra toward the continuum sources. Four steps of post-processing reduces the image cubes to 1D spectra, which are summarized below.

- Continuum fitting: We use the CASA task `imfit` to iteratively fit for continuum sources down to 5σ of the residual image within the central 70% of the primary beam size ($20''$). For Set3-ID09, the fitting uses a threshold of 4σ and extends the mask to the entire primary beam as a continuum source is detected toward the edge of the primary beam where the noise is elevated.

Table 1. PEACHES Sample

Source	R.A. (J2000)	Decl. (J2000)	v_{lsr}	Beam	Cont. Size	T_{cont}	Ref. (v_{lsr})
	(hh:mm:ss)	(dd:mm:ss)	(km s $^{-1}$)	($''$)	($''$)	(K)	
Per-emb-22-B	03:25:22.35	30:45:13.11	4.3	0 $''$.64 \times 0 $''$.39	0 $''$.95 \times 0 $''$.51	0.92	S19
Per-emb-22-A	03:25:22.41	30:45:13.26	4.3	0 $''$.64 \times 0 $''$.39	0 $''$.86 \times 0 $''$.65	1.71	S19
L1448NW	03:25:35.67	30:45:34.16	4.2	0 $''$.64 \times 0 $''$.39	0 $''$.83 \times 0 $''$.47	3.15	H18
Per-emb-33B/C	03:25:36.32	30:45:15.19	5.3	0 $''$.64 \times 0 $''$.39	0 $''$.75 \times 0 $''$.48	5.55	S19
Per-emb-33-A	03:25:36.38	30:45:14.72	5.3	0 $''$.64 \times 0 $''$.39	0 $''$.73 \times 0 $''$.45	10.33	S19
L1448 IRS3A	03:25:36.50	30:45:21.90	4.6	0 $''$.64 \times 0 $''$.39	0 $''$.85 \times 0 $''$.59	3.21	H18
Per-emb-26	03:25:38.88	30:44:05.28	5.4	0 $''$.64 \times 0 $''$.39	0 $''$.69 \times 0 $''$.45	8.03	S19
Per-emb-42	03:25:39.14	30:43:57.90	5.8	0 $''$.64 \times 0 $''$.39	0 $''$.64 \times 0 $''$.39	0.66	S19
Per-emb-25	03:26:37.51	30:15:27.81	5.5	0 $''$.64 \times 0 $''$.39	0 $''$.69 \times 0 $''$.41	5.27	S18
Per-emb-17	03:27:39.11	30:13:02.96	6.0	0 $''$.64 \times 0 $''$.40	0 $''$.79 \times 0 $''$.48	2.00	S19
Per-emb-20	03:27:43.28	30:12:28.88	5.3	0 $''$.64 \times 0 $''$.40	1 $''$.29 \times 0 $''$.78	0.14	S19
L1455 IRS2	03:27:47.69	30:12:04.33	5.1	0 $''$.64 \times 0 $''$.40	0 $''$.60 \times 0 $''$.38	0.13	H18
Per-emb-35-A	03:28:37.10	31:13:30.77	7.4	0 $''$.66 \times 0 $''$.42	0 $''$.75 \times 0 $''$.51	0.93	Y20
Per-emb-35-B	03:28:37.22	31:13:31.74	7.3	0 $''$.66 \times 0 $''$.42	0 $''$.78 \times 0 $''$.53	0.75	Y20
Per-emb-27	03:28:55.57	31:14:36.97	6.5	0 $''$.66 \times 0 $''$.42	0 $''$.93 \times 0 $''$.66	5.79	Y20
EDJ2009-172	03:28:56.65	31:18:35.43	...	0 $''$.66 \times 0 $''$.42	0 $''$.69 \times 0 $''$.44	0.62	...
Per-emb-36	03:28:57.37	31:14:15.77	6.9	0 $''$.66 \times 0 $''$.42	0 $''$.73 \times 0 $''$.46	5.56	S19
Per-emb-54	03:29:01.55	31:20:20.49	7.9	0 $''$.66 \times 0 $''$.42	0 $''$.69 \times 0 $''$.40	0.07	S19
SVS13B	03:29:03.08	31:15:51.73	8.5	0 $''$.66 \times 0 $''$.42	0 $''$.87 \times 0 $''$.68	6.64	S19
SVS13A2	03:29:03.39	31:16:01.58	8.4	0 $''$.66 \times 0 $''$.42	0 $''$.86 \times 0 $''$.53	0.61	S18
Per-emb-44	03:29:03.76	31:16:03.70	8.7	0 $''$.66 \times 0 $''$.42	0 $''$.98 \times 0 $''$.79	6.84	S19
Per-emb-15	03:29:04.06	31:14:46.23	6.8	0 $''$.66 \times 0 $''$.42	0 $''$.89 \times 0 $''$.70	0.17	S19
Per-emb-50	03:29:07.77	31:21:57.11	9.3	0 $''$.66 \times 0 $''$.42	0 $''$.73 \times 0 $''$.44	4.13	Y20
Per-emb-12-B	03:29:10.44	31:13:32.08	6.9	0 $''$.66 \times 0 $''$.42	1 $''$.33 \times 0 $''$.81	10.04	S19
Per-emb-12-A	03:29:10.54	31:13:30.93	6.9	0 $''$.66 \times 0 $''$.42	1 $''$.11 \times 0 $''$.98	21.85	S19
Per-emb-21	03:29:10.67	31:18:20.16	8.6	0 $''$.66 \times 0 $''$.42	0 $''$.74 \times 0 $''$.48	2.05	Y20
Per-emb-18	03:29:11.27	31:18:31.09	8.1	0 $''$.66 \times 0 $''$.42	0 $''$.84 \times 0 $''$.73	3.42	S19
Per-emb-13	03:29:12.02	31:13:07.99	7.1	0 $''$.66 \times 0 $''$.42	1 $''$.07 \times 0 $''$.83	14.76	S19
IRAS4B'	03:29:12.85	31:13:06.87	7.1	0 $''$.66 \times 0 $''$.42	0 $''$.83 \times 0 $''$.74	7.13	S19
Per-emb-14	03:29:13.55	31:13:58.12	7.9	0 $''$.66 \times 0 $''$.42	0 $''$.79 \times 0 $''$.50	3.05	S19
EDJ2009-235	03:29:18.26	31:23:19.73	7.7	0 $''$.67 \times 0 $''$.42	0 $''$.66 \times 0 $''$.44	0.26	Y20
EDJ2009-237	03:29:18.74	31:23:25.24	...	0 $''$.67 \times 0 $''$.42	0 $''$.67 \times 0 $''$.42	0.12	...
Per-emb-37	03:29:18.97	31:23:14.28	7.5	0 $''$.67 \times 0 $''$.42	0 $''$.82 \times 0 $''$.57	0.56	Y20
Per-emb-60	03:29:20.05	31:24:07.35	...	0 $''$.67 \times 0 $''$.42	0 $''$.73 \times 0 $''$.47	0.08	...
Per-emb-5	03:31:20.94	30:45:30.24	7.3	0 $''$.45 \times 0 $''$.30	0 $''$.56 \times 0 $''$.41	15.29	S19
Per-emb-2	03:32:17.92	30:49:47.81	7.0	0 $''$.45 \times 0 $''$.30	1 $''$.35 \times 0 $''$.97	7.41	S19
Per-emb-10	03:33:16.43	31:06:52.01	6.4	0 $''$.46 \times 0 $''$.30	0 $''$.49 \times 0 $''$.32	1.82	S19
Per-emb-40	03:33:16.67	31:07:54.87	7.4	0 $''$.46 \times 0 $''$.30	0 $''$.47 \times 0 $''$.32	1.44	S19
Per-emb-29	03:33:17.88	31:09:31.74	6.1	0 $''$.46 \times 0 $''$.30	0 $''$.56 \times 0 $''$.39	8.41	Y20
B1-bN	03:33:21.21	31:07:43.63	6.6	0 $''$.46 \times 0 $''$.30	0 $''$.56 \times 0 $''$.47	7.67	C16
B1-bS	03:33:21.36	31:07:26.34	6.6	0 $''$.46 \times 0 $''$.30	0 $''$.63 \times 0 $''$.53	14.79	C16
Per-emb-16	03:43:50.97	32:03:24.12	8.8	0 $''$.50 \times 0 $''$.32	0 $''$.61 \times 0 $''$.52	0.35	S19
Per-emb-28	03:43:51.01	32:03:08.02	8.6	0 $''$.50 \times 0 $''$.32	0 $''$.56 \times 0 $''$.32	1.52	S19
Per-emb-1	03:43:56.81	32:00:50.16	9.4	0 $''$.49 \times 0 $''$.32	0 $''$.68 \times 0 $''$.48	4.57	S19
Per-emb-11-B	03:43:56.88	32:03:03.08	9.0	0 $''$.50 \times 0 $''$.33	0 $''$.92 \times 0 $''$.69	0.40	S19
Per-emb-11-A	03:43:57.07	32:03:04.76	9.0	0 $''$.50 \times 0 $''$.33	0 $''$.61 \times 0 $''$.48	10.47	S19
Per-emb-11-C	03:43:57.70	32:03:09.82	9.0	0 $''$.50 \times 0 $''$.33	1 $''$.10 \times 0 $''$.86	0.34	S19
Per-emb-55	03:44:43.30	32:01:31.22	12.0	0 $''$.50 \times 0 $''$.32	0 $''$.49 \times 0 $''$.33	0.32	S19
Per-emb-8	03:44:43.98	32:01:35.19	11.0	0 $''$.50 \times 0 $''$.32	0 $''$.49 \times 0 $''$.36	8.51	S19
Per-emb-53	03:47:41.59	32:51:43.62	10.2	0 $''$.51 \times 0 $''$.33	0 $''$.58 \times 0 $''$.42	1.55	Y20

References—C16=Carney et al. (2016); H18=Higuchi et al. (2018); S18=Stephens et al. (2018); S19=Stephens et al. (2019); Y20=this study.

Table 2. PEACHES Sample

PEACHES ID	Source	R.A. (J2000)	Decl. (J2000)	v_{lsr}	Beam	Cont. Size	T_{cont}	Ref. (v_{lsr})
		(hh:mm:ss)	(dd:mm:ss)	(km s ⁻¹)	($''$)	($''$)	(K)	
Set1.ID00	L1448NW	03:25:35.67	30:45:34.16	4.2	0 $''$ 64×0 $''$ 39	0 $''$ 83×0 $''$ 47	3.15	H18
Set1.ID01.3	Per-emb-33-A	03:25:36.38	30:45:14.72	5.3	0 $''$ 64×0 $''$ 39	0 $''$ 73×0 $''$ 45	10.33	S19
Set1.ID01.4	Per-emb-33B/C	03:25:36.32	30:45:15.19	5.3	0 $''$ 64×0 $''$ 39	0 $''$ 75×0 $''$ 48	5.55	S19
Set1.ID01.2	L1448 IRS3A	03:25:36.50	30:45:21.90	4.6	0 $''$ 64×0 $''$ 39	0 $''$ 85×0 $''$ 59	3.21	H18
Set1.ID02	Per-emb-26	03:25:38.88	30:44:05.28	5.4	0 $''$ 64×0 $''$ 39	0 $''$ 69×0 $''$ 45	8.03	S19
Set1.ID02.2	Per-emb-42	03:25:39.14	30:43:57.90	5.8	0 $''$ 64×0 $''$ 39	0 $''$ 64×0 $''$ 39	0.66	S19
Set1.ID03	Per-emb-22-A	03:25:22.41	30:45:13.26	4.3	0 $''$ 64×0 $''$ 39	0 $''$ 86×0 $''$ 65	1.71	S19
Set1.ID03.2	Per-emb-22-B	03:25:22.35	30:45:13.11	4.3	0 $''$ 64×0 $''$ 39	0 $''$ 95×0 $''$ 51	0.92	S19
Set1.ID05	Per-emb-25	03:26:37.51	30:15:27.81	5.5	0 $''$ 64×0 $''$ 39	0 $''$ 69×0 $''$ 41	5.27	S18
Set1.ID06	Per-emb-17	03:27:39.11	30:13:02.96	6.0	0 $''$ 64×0 $''$ 40	0 $''$ 79×0 $''$ 48	2.00	S19
Set1.ID07	Per-emb-20	03:27:43.28	30:12:28.88	5.3	0 $''$ 64×0 $''$ 40	1 $''$ 29×0 $''$ 78	0.14	S19
Set1.ID08	L1455 IRS2	03:27:47.69	30:12:04.33	5.1	0 $''$ 64×0 $''$ 40	0 $''$ 60×0 $''$ 38	0.13	H18
Set2.ID00	Per-emb-44	03:29:03.76	31:16:03.70	8.7	0 $''$ 66×0 $''$ 42	0 $''$ 98×0 $''$ 79	6.84	S19
Set2.ID00.2	SVS13A2	03:29:03.39	31:16:01.58	8.4	0 $''$ 66×0 $''$ 42	0 $''$ 86×0 $''$ 53	0.61	S18
Set2.ID01	Per-emb-12-A	03:29:10.54	31:13:30.93	6.9	0 $''$ 66×0 $''$ 42	1 $''$ 11×0 $''$ 98	21.85	S19
Set2.ID01.2	Per-emb-12-B	03:29:10.44	31:13:32.08	6.9	0 $''$ 66×0 $''$ 42	1 $''$ 33×0 $''$ 81	10.04	S19
Set2.ID02	Per-emb-13	03:29:12.02	31:13:07.99	7.1	0 $''$ 66×0 $''$ 42	1 $''$ 07×0 $''$ 83	14.76	S19
Set2.ID02.2	IRAS4B [†]	03:29:12.85	31:13:06.87	7.1	0 $''$ 66×0 $''$ 42	0 $''$ 83×0 $''$ 74	7.13	S19
Set2.ID03	Per-emb-27	03:28:55.57	31:14:36.97	6.5	0 $''$ 66×0 $''$ 42	0 $''$ 93×0 $''$ 66	5.79	Y20
Set2.ID04	Per-emb-54	03:29:01.55	31:20:20.49	7.9	0 $''$ 66×0 $''$ 42	0 $''$ 69×0 $''$ 40	0.07	S19
Set2.ID05	Per-emb-21	03:29:10.67	31:18:20.16	8.6	0 $''$ 66×0 $''$ 42	0 $''$ 74×0 $''$ 48	2.05	Y20
Set2.ID06	Per-emb-14	03:29:13.55	31:13:58.12	7.9	0 $''$ 66×0 $''$ 42	0 $''$ 79×0 $''$ 50	3.05	S19
Set2.ID07	Per-emb-35-A	03:28:37.10	31:13:30.77	7.4	0 $''$ 66×0 $''$ 42	0 $''$ 75×0 $''$ 51	0.93	Y20
Set2.ID07.2	Per-emb-35-B	03:28:37.22	31:13:31.74	7.3	0 $''$ 66×0 $''$ 42	0 $''$ 78×0 $''$ 53	0.75	Y20
Set2.ID08	SVS13B	03:29:03.08	31:15:51.73	8.5	0 $''$ 66×0 $''$ 42	0 $''$ 87×0 $''$ 68	6.64	S19
Set2.ID09	Per-emb-15	03:29:04.06	31:14:46.23	6.8	0 $''$ 66×0 $''$ 42	0 $''$ 89×0 $''$ 70	0.17	S19
Set2.ID11	Per-emb-50	03:29:07.77	31:21:57.11	9.3	0 $''$ 66×0 $''$ 42	0 $''$ 73×0 $''$ 44	4.13	Y20
Set2.ID12	Per-emb-18	03:29:11.27	31:18:31.09	8.1	0 $''$ 66×0 $''$ 42	0 $''$ 84×0 $''$ 73	3.42	S19
Set2.ID13	Per-emb-37	03:29:18.97	31:23:14.28	7.5	0 $''$ 67×0 $''$ 42	0 $''$ 82×0 $''$ 57	0.56	Y20
Set2.ID13.2	EDJ2009-235	03:29:18.26	31:23:19.73	7.7	0 $''$ 67×0 $''$ 42	0 $''$ 66×0 $''$ 44	0.26	Y20
Set2.ID13.3	EDJ2009-237	03:29:18.74	31:23:25.24	...	0 $''$ 67×0 $''$ 42	0 $''$ 67×0 $''$ 42	0.12	...
Set2.ID14	Per-emb-60	03:29:20.05	31:24:07.35	...	0 $''$ 67×0 $''$ 42	0 $''$ 73×0 $''$ 47	0.08	...
Set2.ID15	EDJ2009-172	03:28:56.65	31:18:35.43	...	0 $''$ 66×0 $''$ 42	0 $''$ 69×0 $''$ 44	0.62	...
Set2.ID16	Per-emb-36	03:28:57.37	31:14:15.77	6.9	0 $''$ 66×0 $''$ 42	0 $''$ 73×0 $''$ 46	5.56	S19
Set3.ID00	B1-bS	03:33:21.36	31:07:26.34	6.6	0 $''$ 46×0 $''$ 30	0 $''$ 63×0 $''$ 53	14.79	C16
Set3.ID00.2	B1-bN	03:33:21.21	31:07:43.63	6.6	0 $''$ 46×0 $''$ 30	0 $''$ 56×0 $''$ 47	7.67	C16
Set3.ID01	Per-emb-29	03:33:17.88	31:09:31.74	6.1	0 $''$ 46×0 $''$ 30	0 $''$ 56×0 $''$ 39	8.41	Y20
Set3.ID02	Per-emb-10	03:33:16.43	31:06:52.01	6.4	0 $''$ 46×0 $''$ 30	0 $''$ 49×0 $''$ 32	1.82	S19
Set3.ID03	Per-emb-40	03:33:16.67	31:07:54.87	7.4	0 $''$ 46×0 $''$ 30	0 $''$ 47×0 $''$ 32	1.44	S19
Set3.ID04	Per-emb-2	03:32:17.92	30:49:47.81	7.0	0 $''$ 45×0 $''$ 30	1 $''$ 35×0 $''$ 97	7.41	S19
Set3.ID05	Per-emb-5	03:31:20.94	30:45:30.24	7.3	0 $''$ 45×0 $''$ 30	0 $''$ 56×0 $''$ 41	15.29	S19
Set3.ID06	Per-emb-1	03:43:56.81	32:00:50.16	9.4	0 $''$ 49×0 $''$ 32	0 $''$ 68×0 $''$ 48	4.57	S19
Set3.ID07	Per-emb-11-A	03:43:57.07	32:03:04.76	9.0	0 $''$ 50×0 $''$ 33	0 $''$ 61×0 $''$ 48	10.47	S19
Set3.ID07.2	Per-emb-11-B	03:43:56.88	32:03:03.08	9.0	0 $''$ 50×0 $''$ 33	0 $''$ 92×0 $''$ 69	0.40	S19
Set3.ID07.3	Per-emb-11-C	03:43:57.70	32:03:09.82	9.0	0 $''$ 50×0 $''$ 33	1 $''$ 10×0 $''$ 86	0.34	S19
Set3.ID08	Per-emb-8	03:44:43.98	32:01:35.19	11.0	0 $''$ 50×0 $''$ 32	0 $''$ 49×0 $''$ 36	8.51	S19
Set3.ID08.2	Per-emb-55	03:44:43.30	32:01:31.22	12.0	0 $''$ 50×0 $''$ 32	0 $''$ 49×0 $''$ 33	0.32	S19
Set3.ID09	Per-emb-16	03:43:50.97	32:03:24.12	8.8	0 $''$ 50×0 $''$ 32	0 $''$ 61×0 $''$ 52	0.35	S19
Set3.ID09.2	Per-emb-28	03:43:51.01	32:03:08.02	8.6	0 $''$ 50×0 $''$ 32	0 $''$ 56×0 $''$ 32	1.52	S19
Set3.ID10	Per-emb-53	03:47:41.59	32:51:43.62	10.2	0 $''$ 51×0 $''$ 33	0 $''$ 58×0 $''$ 42	1.55	Y20

References—C16=Carney et al. (2016); H18=Higuchi et al. (2018); S18=Stephens et al. (2018); S19=Stephens et al. (2019); Y20=this study.

- **Extracting spectra:** We use the CASA task `specflux` to extract the mean flux density within the ellipse which has the same major and minor axes as well as the position angle as the fitted continuum sources.
- **Baseline calibration:** The continuum has been removed before the imaging process; however, the extracted spectra sometimes still show imperfect baselines. The spectra show significant differences from one to another such as rich emission lines, lack of emission, and broad emission features. Thus, we manually select the frequency ranges for baseline calibration for each spectral window and each field.
- **Velocity correction:** Finally, the frequency of the extracted spectra are corrected according to the source velocities. We collect the source velocities from the literature as well as from the strong emission lines in our spectra. Table 1 lists the adopted source velocities and the corresponding references.

Figure 1 shows the images of the continuum along with the fitted shapes, while the properties of the continuum sources are listed in Table 1. Our observations detect 50 continuum sources. The continuum emission appears as compact circular or elliptical shape with no sub-structure. Some sources show extended continuum emission resembling the shape of outflow cavities.

3.1. Line Identifications and Modeling

Line identification starts with manual identification and verification for a few sources with rich spectra, including Per-emb-12B and B1-bS. We use SPLATALOGUE¹ to identify the molecular species and use XCLASS (Möller et al. 2017) to verify the identification. The XCLASS package is a LTE radiative transfer code that uses the molecular data from the Cologne Database of Molecular Spectroscopy (CDMS; Müller et al. 2001, 2005; Endres et al. 2016) and the Jet Propulsion Laboratory (JPL; Pickett et al. 1998). An identification needs to satisfy the following criteria.

- The spectra agree with the predicted strengths of the model.
- The spectral lines are not all blended with other emission, such as other molecules and the SiO emission tracing the outflows. The emission of a few species, such as HDCO & ¹³CH₃OH, CH₃CHO

& CH₂DOH, ³⁴SO & C₂H₅OH, and CH₃OCH₃ & CH₂DCN, are partially blended (blending occurs at a few lines but other lines remain isolated). The fittings of those species are performed together to verify their identification.

- Identified molecules need to be already found toward young stellar objects as summarized in McGuire (2018).

Table 3 lists the identified species and transitions. Only identifiable transitions are listed. The XCLASS modeling includes all the transitions in our frequency coverage regardless their Einstein-A values and upper energy levels.

Systematic spectral fitting using XCLASS is then applied to all sources using a list of species, compiled from those identifications. The catalogs used in this study are listed in Appendix A. The fitting function in XCLASS includes several optimization algorithms that can be used in series to reduce biases. We configure the algorithm chain that starts with the genetic algorithm followed by the Levenberg-Marquardt χ^2 minimization. The genetic algorithm searches the best-fitting parameters iteratively with generations that evolve like a natural selection, where the better fitting models get less modification over generations. We setup the genetic algorithm to search for the three best-fitting models after five generations. Then, the Levenberg-Marquardt χ^2 minimization applies to the three best-fitting models for 50 iterations to the best-fitting models. We assume the COMs are all concentrated at the center, simplified as a 2D thin circular disk. There are four parameters for the XCLASS modeling, the size of the emitting molecule (r_{COM}), the excitation temperature (T_{ex}), the column density (N_{COM}), and the line width ($\Delta\nu$). Due to the limited frequency coverage, many species only have a few lines detected, we fix r_{COM} as 0''.5, similar to our beam size, and optimize the model with five excitation temperatures, 100, 150, 200, 250, and 300 K. The range of fitted column densities at different temperatures indicates the uncertainty of the column densities.

¹ <http://www.splatalogue.net/>

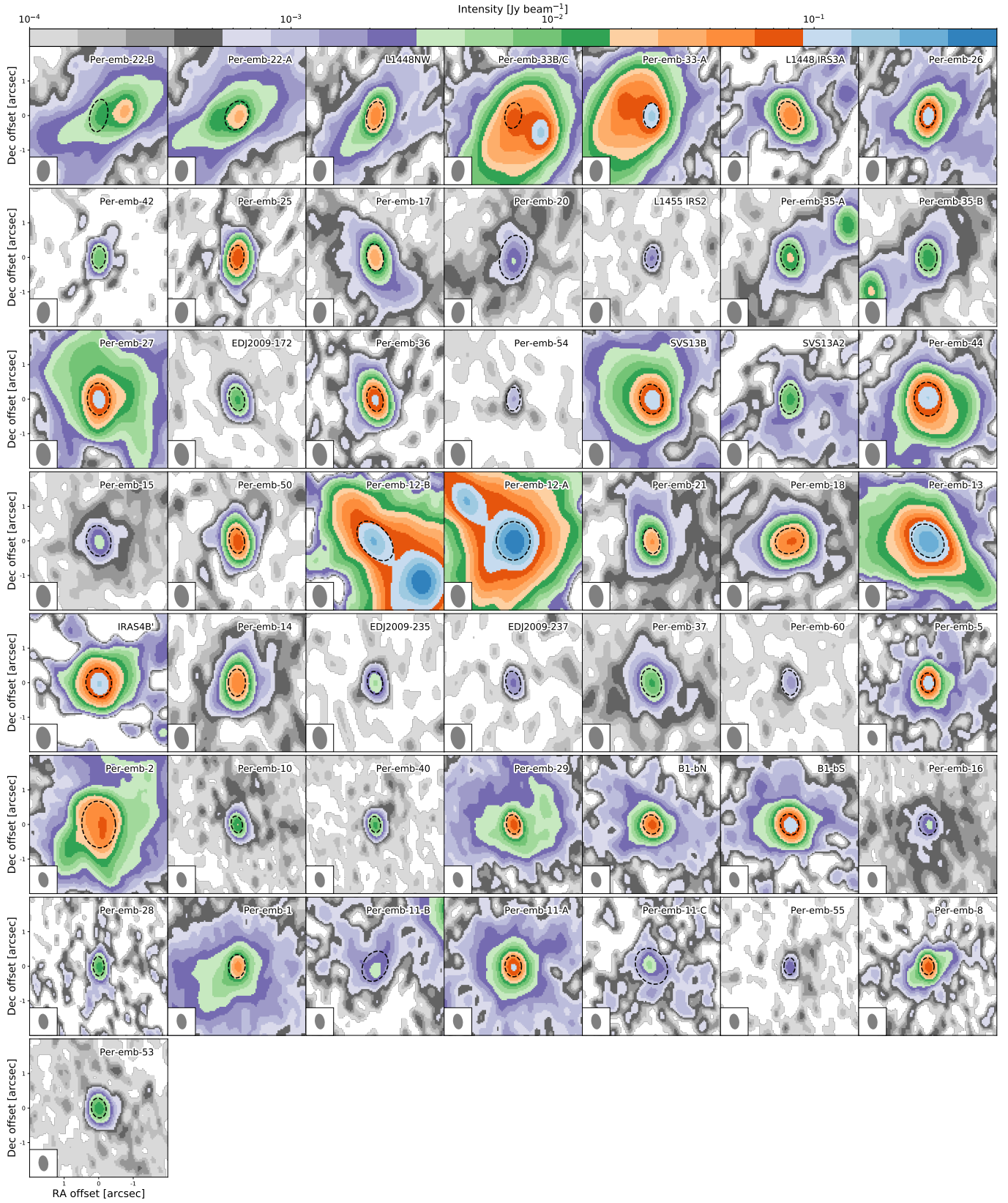


Figure 1. The continuum images of all PEACHES protostars. Non-detections toward L1448 IRS 2E and NGC 1333 SVS 3 are not shown. The dashed ellipses illustrate the size of fitted continuum, which is the region for extracting 1D spectra.

Table 3. Line Identification

Frequency (MHz)	Transition ^a	log(Einstein-A)	E_u (K)	g_u	Ref.
Ethyne (CCH)					
262065.00 (0.05)	$[3, 5/2, 3] \rightarrow [2, 3/2, 2]^b$	-4.31	25.16	7	CDMS
262067.47 (0.05)	$[3, 5/2, 2] \rightarrow [2, 3/2, 1]^b$	-4.35	25.16	5	CDMS
262078.93 (0.02)	$[3, 5/2, 2] \rightarrow [2, 3/2, 2]^b$	-5.22	25.16	5	CDMS
Cyclopropenylidene (c-C ₃ H ₂)					
244222.15 (0.01)	$[3, 2, 1] \rightarrow [2, 1, 2]$	-4.23	18.17	21	CDMS
246557.77 (0.02)	$[16, 10, 7] \rightarrow [16, 9, 8]$	-3.36	397.83	99	CDMS
260479.75 (0.02)	$[5, 3, 2] \rightarrow [4, 4, 1]$	-3.79	44.72	33	CDMS
Methanol (CH ₃ OH $v_t = 0$)					
243915.79 (0.01)	$[5, 1, 4] \rightarrow [4, 1, 3] A$	-4.22	49.66	44	CDMS
246873.30 (0.02)	$[19, 3, 16] \rightarrow [19, 2, 17] A$	-4.08	490.65	156	CDMS
261805.68 (0.01)	$[2, 1, 1] \rightarrow [1, 0, 1] E$	-4.25	28.01	20	CDMS
Methanol (¹³ CH ₃ OH $v_t = 0$)					
246426.12 (0.22)	$[23, 4, 19] \rightarrow [22, 5, 18]$	-4.58	721.02	47	CDMS
247086.3 (0.5)	$[23, 3, 20] \rightarrow [23, 2, 21] A \rightarrow A+$	-4.07	674.86	47	CDMS
259036.49 (0.17)	$[17, 3, 15] \rightarrow [17, 2, 16] A+ \rightarrow A-$	-4.04	396.48	35	CDMS
Methanol (CH ₂ DOH $v_t = 0$)					
243514.31 (0.01)	$[9, 2, 8] \rightarrow [10, 1, 10] o_1$	-5.17	131.85	19	JPL
246973.11 (0.01)	$[4, 1, 4] \rightarrow [4, 1, 3] e_1$	-4.67	37.69	9	JPL
260543.63 (0.01)	$[3, 2, 1] \rightarrow [3, 1, 2] o_1$	-4.65	48.34	7	JPL
Methanol (CH ₃ ¹⁸ OH $v_t = 0$)					
246256.60 (0.04)	$[11, 2, 10] \rightarrow [10, 3, 7] A$	-4.64	184.27	92	CDMS
Sulfur monoxide (SO ³ Σ)					
258255.83 (0.01)	$[N, J]=[6, 6] \rightarrow [5, 5]$	-3.67	56.50	13	CDMS
261843.72 (0.03)	$[N, J]=[7, 6] \rightarrow [6, 5]$	-3.64	47.55	15	CDMS
Sulfur monoxide (³⁴ SO)					
246663.47 (0.1)	$[N, J]=[5, 6] \rightarrow [4, 5]$	-3.74	49.89	11	CDMS
Sulfur dioxide (SO ₂)					
244254.22 (0.01)	$[14, 0, 14] \rightarrow [13, 1, 13]$	-3.79	93.90	29	CDMS
Hydrogen cyanide (H ¹³ CN)					
259010.26 (0.01)	$[J, F]=[3, 3] \rightarrow [2, 3]$	-4.07	24.86	7	CDMS
259011.55 (0.01)	$[J, F]=[3, 2] \rightarrow [2, 1]$	-3.19	24.86	5	CDMS
259011.80 (0.01)	$[J, F]=[3, 3] \rightarrow [2, 2]$	-3.16	24.86	7	CDMS
259011.86 (0.01)	$[J, F]=[3, 4] \rightarrow [2, 3]$	-3.11	24.86	9	CDMS
259012.34 (0.01)	$[J, F]=[3, 2] \rightarrow [2, 3]$	-5.46	24.86	5	CDMS
259013.89 (0.01)	$[J, F]=[3, 2] \rightarrow [2, 2]$	-3.92	24.86	5	CDMS
Carbon Monosulfide (CS)					
244935.56 (0.01)	$[J]=[5] \rightarrow [4]$	-3.53	35.27	11	CDMS
Formaldehyde (HDCO)					
246924.6 (0.1)	$[4, 1, 4] \rightarrow [3, 1, 3]$	-3.40	37.60	9	CDMS
259034.9 (0.1)	$[4, 2, 2] \rightarrow [3, 2, 1]$	-3.44	62.86	9	CDMS
Methyl formate (CH ₃ OCHO)					
245883.2 (0.1)	$[20, 13, 7] \rightarrow [19, 13, 6] E$	-3.89	235.98	82	JPL
245885.2 (0.1)	$[20, 13, 7] \rightarrow [19, 13, 6] A$	-3.89	235.98	82	JPL
245885.2 (0.1)	$[20, 13, 8] \rightarrow [19, 13, 7] A$	-3.89	235.98	82	JPL
246027.5 (0.1)	$[21, 2, 19] \rightarrow [20, 3, 18] E$	-4.63	139.85	86	JPL
246038.9 (0.1)	$[21, 2, 19] \rightarrow [20, 3, 18] A$	-4.63	139.85	86	JPL
246054.8 (0.1)	$[20, 12, 8] \rightarrow [19, 12, 7] E$	-3.84	219.43	82	JPL
246060.8 (0.1)	$[20, 12, 8/9] \rightarrow [19, 12, 7/8] A$	-3.84	219.43	82	JPL
246076.9 (0.1)	$[20, 12, 9] \rightarrow [19, 12, 8] E$	-3.84	219.41	82	JPL
246285.4 (0.1)	$[20, 11, 9] \rightarrow [19, 11, 8] E$	-3.80	204.21	82	JPL

Table 3 continued

Table 3 (continued)

Frequency (MHz)	Transition ^a	log(Einstein-A)	E_u (K)	g_u	Ref.
246295.1 (0.1)	[20, 11, 10]→[19, 11, 9] A	−3.80	204.21	82	JPL
246295.1 (0.1)	[20, 11, 9]→[19, 11, 8] A	−3.80	204.21	82	JPL
246308.3 (0.1)	[20, 11, 10]→[19, 11, 9] E	−3.80	204.20	82	JPL
246456.1 (0.1)	[10, 5, 6]→[9, 4, 5] E	−5.52	49.09	42	JPL
246600.0 (0.1)	[20, 10, 10]→[19, 10, 9] E	−3.77	190.34	82	JPL
246613.4 (0.1)	[20, 10, 11]→[19, 10, 10] A	−3.77	190.34	82	JPL
246613.4 (0.1)	[20, 10, 10]→[19, 10, 9] A	−3.77	190.34	82	JPL
246623.2 (0.1)	[20, 10, 11]→[19, 10, 10] E	−3.77	190.34	82	JPL
246630.0 (0.1)	[35, 6, 30]→[35, 5, 31] A	−4.77	397.98	142	JPL
246660.5 (0.1)	[10, 5, 6]→[9, 4, 5] A	−4.74	49.08	42	JPL
246675.4 (0.1)	[15, 4, 12]→[14, 3, 11] E	−4.93	81.85	62	JPL
246683.5 (0.1)	[15, 4, 12]→[14, 3, 11] A	−4.93	81.84	62	JPL
246752.9 (0.1)	[10, 5, 5]→[9, 4, 5] E	−4.90	49.10	42	JPL
246891.6 (0.1)	[19, 4, 15]→[18, 4, 14] E	−3.66	126.22	78	JPL
246914.7 (0.1)	[19, 4, 15]→[18, 4, 14] A	−3.66	126.22	78	JPL
246945.7 (0.1)	[10, 5, 6]→[9, 4, 6] E	−4.90	49.09	42	JPL
247040.7 (0.1)	[20, 9, 11]→[19, 9, 10] E	−3.74	177.83	82	JPL
247044.1 (0.1)	[21, 3, 19]→[20, 3, 18] E	−3.66	139.90	86	JPL
247053.5 (0.1)	[21, 3, 19]→[20, 3, 18] A	−3.66	139.89	86	JPL
247057.3 (0.1)	[20, 9, 12]→[19, 9, 11] A	−3.74	177.83	82	JPL
247057.7 (0.1)	[20, 9, 11]→[19, 9, 10] A	−3.74	177.83	82	JPL
247063.7 (0.1)	[20, 9, 12]→[19, 9, 11] E	−3.74	177.83	82	JPL
247124.3 (0.1)	[10, 5, 5]→[9, 4, 6] E	−4.74	49.08	42	JPL
258275.0 (0.1)	[21, 13, 8]→[20, 13, 7] E	−3.79	248.37	86	JPL
258277.4 (0.1)	[21, 13, 8]→[20, 13, 7] A	−3.79	248.37	86	JPL
258277.4 (0.1)	[21, 13, 9]→[20, 13, 8] A	−3.79	248.37	86	JPL
259341.9 (0.1)	[24, 0, 24]→[23, 1, 23] E	−4.37	158.23	98	JPL
259342.0 (0.1)	[24, 1, 24]→[23, 1, 23] E	−3.58	158.23	98	JPL
259342.1 (0.1)	[24, 0, 24]→[23, 0, 23] E	−3.58	158.23	98	JPL
259342.3 (0.1)	[24, 1, 24]→[23, 0, 23] E	−4.37	158.23	98	JPL
259342.7 (0.1)	[24, 0, 24]→[23, 1, 23] A	−4.37	158.22	98	JPL
259342.9 (0.1)	[24, 1, 24]→[23, 1, 23] A	−3.58	158.22	98	JPL
259343.0 (0.1)	[24, 0, 24]→[23, 0, 23] A	−3.58	158.22	98	JPL
259343.2 (0.1)	[24, 1, 24]→[23, 0, 23] A	−4.37	158.22	98	JPL
261822.3 (0.1)	[17, 10, 7]→[17, 9, 8] A	−4.73	156.63	70	JPL
262088.2 (0.1)	[16, 10, 6]→[16, 9, 7] A	−4.76	146.59	66	JPL
262088.2 (0.1)	[16, 10, 7]→[16, 9, 8] A	−4.76	146.59	66	JPL
Methyl formate (CH ₃ OCHO $v = 1$)					
243511.5 (0.1)	[20, 12, 8]→[19, 12, 7] E	−3.85	407.25	82	JPL
245846.9 (0.1)	[21, 3, 19]→[20, 3, 18] E	−3.66	326.30	86	JPL
246106.8 (0.1)	[20, 7, 14]→[19, 7, 13] A	−3.70	343.77	82	JPL
246184.2 (0.1)	[20, 8, 13]→[19, 8, 12] E	−3.72	353.27	82	JPL
246187.0 (0.1)	[21, 2, 19]→[20, 2, 18] A	−3.66	326.62	86	JPL
246233.6 (0.1)	[20, 7, 13]→[19, 7, 12] A	−3.70	343.79	82	JPL
246274.9 (0.1)	[20, 7, 13]→[19, 7, 12] E	−3.70	343.86	82	JPL
246410.95 (0.01)	[10, 5, 5]→[9, 4, 6] A	−4.73	236.70	42	JPL
246422.7 (0.1)	[22, 1, 21]→[21, 2, 20] A	−4.51	330.43	90	JPL
246461.2 (0.1)	[22, 2, 21]→[21, 2, 20] A	−3.65	330.43	90	JPL
246488.4 (0.1)	[22, 1, 21]→[21, 1, 20] A	−3.65	330.43	90	JPL
246562.9 (0.1)	[21, 2, 19]→[20, 2, 18] E	−3.66	326.24	86	JPL
246706.5 (0.1)	[22, 2, 21]→[21, 2, 20] E	−3.65	329.89	90	JPL
246731.7 (0.1)	[22, 1, 21]→[21, 1, 20] E	−3.65	329.89	90	JPL
246985.2 (0.1)	[20, 6, 15]→[19, 6, 14] A	−3.68	335.37	82	JPL
259003.9 (0.1)	[21, 7, 14]→[20, 7, 13] A	−3.63	356.22	86	JPL

Table 3 continued

Table 3 (*continued*)

Frequency (MHz)	Transition ^a	log(Einstein-A)	E_u (K)	g_u	Ref.
259025.8 (0.1)	[21, 7, 14]→[20, 7, 13] E	-3.63	356.29	86	JPL
260479.6 (0.1)	[44, 9, 36]→[44, 8, 37] A	-4.59	828.74	178	JPL
Dimethyl ether (CH ₃ OCH ₃)					
246499.29 (0.01)	[37, 6, 31]→[37, 5, 12] AA	-4.01	693.72	750	CDMS
246505.09 (0.01)	[37, 6, 31]→[37, 5, 12] AE	-4.01	693.72	450	CDMS
246505.09 (0.01)	[37, 6, 31]→[37, 5, 12] EA	-4.01	693.72	300	CDMS
246697.43 (0.01)	[27, 4, 23]→[26, 5, 21] AA	-4.70	367.61	330	CDMS
246697.87 (0.01)	[27, 4, 23]→[26, 5, 21] EE	-4.70	367.61	880	CDMS
246698.31 (0.01)	[27, 4, 23]→[26, 5, 21] AE	-4.70	367.61	110	CDMS
246698.31 (0.01)	[27, 4, 23]→[26, 5, 21] EA	-4.70	367.61	220	CDMS
259305.22 (0.01)	[33, 3, 31]→[34, 6, 28] AA	-6.61	563.02	670	CDMS
259308.39 (0.01)	[33, 3, 31]→[34, 6, 28] AE	-6.61	563.02	402	CDMS
259308.39 (0.01)	[33, 3, 31]→[34, 6, 28] EA	-6.61	563.02	268	CDMS
259309.47 (0.01)	[17, 5, 12]→[17, 4, 13] AE	-4.06	174.54	210	CDMS
259309.76 (0.01)	[17, 5, 12]→[17, 4, 13] EA	-4.06	174.54	140	CDMS
259311.95 (0.01)	[17, 5, 12]→[17, 4, 13] EE	-4.06	174.54	560	CDMS
259314.28 (0.01)	[17, 5, 12]→[17, 4, 13] AA	-4.06	174.54	350	CDMS
Acetone (CH ₃ COCH ₃)					
244218.91 (0.01)	[20, 5, 15]→[19, 6, 14] AE	-3.32	139.69	82	JPL
244218.91 (0.01)	[20, 6, 15]→[19, 5, 14] AE	-3.32	139.69	250	JPL
244218.92 (0.01)	[20, 5, 15]→[19, 6, 14] EA	-3.32	139.69	160	JPL
244218.92 (0.01)	[20, 6, 15]→[19, 5, 14] EA	-3.32	139.69	160	JPL
246400.99 (0.05)	[34, 7, 28]→[34, 5, 29] EE	-4.17	364.98	1100	JPL
246400.99 (0.05)	[34, 6, 28]→[34, 5, 29] EE	-4.03	364.98	1100	JPL
246400.99 (0.05)	[34, 7, 28]→[34, 6, 29] EE	-4.03	364.98	1100	JPL
246400.99 (0.05)	[34, 6, 28]→[34, 6, 29] EE	-4.17	364.98	1100	JPL
246404.27 (0.01)	[22, 3, 19]→[21, 4, 18] AE	-3.23	149.62	90	JPL
246404.27 (0.01)	[22, 4, 19]→[21, 3, 18] AE	-3.23	149.62	270	JPL
246404.29 (0.01)	[22, 3, 19]→[21, 4, 18] EA	-3.23	149.62	180	JPL
246404.29 (0.01)	[22, 4, 19]→[21, 3, 18] EA	-3.23	149.62	180	JPL
246450.40 (0.01)	[22, 4, 19]→[21, 3, 18] EE	-3.23	149.57	720	JPL
246450.40 (0.01)	[22, 3, 19]→[21, 3, 18] EE	-5.09	149.57	720	JPL
246450.40 (0.01)	[22, 3, 19]→[21, 4, 18] EE	-3.24	149.57	720	JPL
246450.40 (0.01)	[22, 4, 19]→[21, 4, 18] EE	-4.92	149.57	720	JPL
246496.17 (0.46)	[25, 14, 12]→[24, 15, 9] AE	-5.01	257.11	100	JPL
246496.47 (0.02)	[22, 3, 19]→[21, 4, 18] AA	-3.23	149.51	270	JPL
246496.47 (0.02)	[22, 4, 19]→[21, 3, 18] AA	-3.23	149.51	450	JPL
246714.12 (0.05)	[9, 8, 1]→[8, 5, 4] EA	-5.84	40.59	76	JPL
246714.94 (0.05)	[32, 4, 28]→[32, 4, 29] EA	-3.97	305.61	260	JPL
246714.94 (0.05)	[32, 5, 28]→[32, 3, 29] EA	-3.97	305.61	260	JPL
246715.04 (0.05)	[32, 5, 28]→[32, 4, 29] AE	-3.97	305.61	390	JPL
246715.04 (0.05)	[32, 4, 28]→[32, 3, 29] EA	-3.97	305.61	130	JPL
246719.92 (0.04)	[33, 6, 28]→[33, 4, 29] EE	-5.62	344.85	1100	JPL
246719.92 (0.04)	[33, 5, 28]→[33, 4, 29] EE	-3.87	344.85	1100	JPL
246719.92 (0.04)	[33, 6, 28]→[33, 5, 29] EE	-3.87	344.85	1100	JPL
246719.92 (0.04)	[33, 5, 28]→[33, 5, 29] EE	-5.61	344.85	1100	JPL
261818.11 (0.01)	[20, 7, 13]→[19, 8, 12] EA	-3.31	151.17	160	JPL
261818.17 (0.01)	[20, 7, 13]→[19, 8, 12] AE	-3.31	151.17	82	JPL
261819.09 (0.01)	[20, 8, 13]→[19, 7, 12] EA	-3.31	151.17	160	JPL
261819.17 (0.01)	[20, 8, 13]→[19, 7, 12] AE	-3.31	151.17	250	JPL
Methyl cyanide (CH ₃ CN)					
257507.56 (0.01)	[<i>N</i> , <i>K</i>]=[14, 2]→[13, 2]	-3.00	121.28	58	JPL
257522.43 (0.01)	[<i>N</i> , <i>K</i>]=[14, 1]→[13, 1]	-2.99	99.84	58	JPL
257527.38 (0.01)	[<i>N</i> , <i>K</i>]=[14, 0]→[13, 0]	-2.99	92.70	58	JPL

Table 3 continued

Table 3 (*continued*)

Frequency (MHz)	Transition ^a	log(Einstein-A)	E_u (K)	g_u	Ref.
Acetaldehyde (CH_3CHO $v_t = 0$)					
246330.73 (0.01)	[15, 3, 13]→[15, 2, 14] A	−4.29	131.49	62	JPL
260530.40 (0.01)	[14, 1, 14]→[13, 1, 13] E	−3.20	96.39	58	JPL
260544.02 (0.01)	[14, 1, 14]→[13, 1, 13] A	−3.20	96.32	58	JPL
260547.46 (2.07)	[9, 4, 5]→[9, 3, 7] E, $v_t = 2$	−6.06	456.38	38	JPL
gauche-Ethanol ($g\text{-C}_2\text{H}_5\text{OH}$)					
246414.76 (0.05)	[14, 3, 11]→[13, 3, 10] $v_t = 0 \rightarrow 0$	−3.89	155.72	29	JPL
246524.28 (0.01)	[13, 2, 12]→[12, 1, 12] $v_t = 0 \rightarrow 1$	−4.50	136.95	27	JPL
246658.18 (0.01)	[32, 5, 28]→[32, 4, 29] $v_t = 0 \rightarrow 0$	−6.33	527.94	65	JPL
246662.98 (0.01)	[4, 2, 3]→[3, 1, 3] $v_t = 1 \rightarrow 0$	−4.36	74.77	9	JPL
259322.64 (0.01)	[14, 3, 11]→[13, 2, 11] $v_t = 0 \rightarrow 1$	−4.39	155.72	29	JPL
260457.73 (0.01)	[15, 4, 12]→[14, 4, 11] $v_t = 1 \rightarrow 1$	−3.83	181.10	31	JPL
trans-Ethanol ($\text{C}_2\text{H}_5\text{OH}$)					
246663.62 (0.05)	[24, 1, 23]→[24, 0, 24]	−3.73	252.35	49	JPL
261815.99 (0.05)	[28, 3, 26]→[28, 2, 27]	−3.96	350.98	57	JPL
Glycolaldehyde (<i>cis</i> - CH_2OHCHO)					
246773.09 (0.02)	[30, 2, 28]→[30, 1, 29]	−4.04	252.68	61	CDMS
246778.28 (0.02)	[30, 3, 28]→[30, 2, 29]	−4.04	252.68	61	CDMS
262056.78 (0.01)	[25, 2, 24]→[24, 1, 23]	−3.34	158.25	51	CDMS
261795.48 (0.01)	[25, 11, 14]→[25, 10, 15]	−3.57	254.23	51	CDMS
261798.96 (0.01)	[25, 11, 15]→[25, 10, 16]	−3.57	254.23	51	CDMS
Methyl cyanide (CH_3DCN)					
259315.51 (0.01)	[15, 1, 15]→[14, 1, 14]	−2.82	104.97	31	CDMS
260523.05 (0.01)	[15, 2, 13]→[14, 2, 12]	−2.82	121.60	31	CDMS
Ethyl cyanide ($\text{CH}_3\text{CH}_2\text{CN}$)					
246268.74 (0.01)	[27, 2, 25]→[26, 2, 24]	−2.90	169.80	55	CDMS
246421.92 (0.01)	[28, 2, 27]→[27, 2, 26]	−2.90	177.26	57	CDMS
246548.70 (0.01)	[27, 3, 24]→[26, 3, 23]	−2.90	174.06	55	CDMS
260535.69 (0.05)	[29, 5, 25]→[28, 5, 24]	−2.84	215.06	59	CDMS
Formamide (NH_2CHO)					
243521.04 (0.01)	[12, 1, 12]→[11, 1, 11]	−2.98	79.19	25	CDMS
Formic acid (<i>t</i> - HCOOH)					
262103.48 (0.01)	[12, 0, 12]→[11, 0, 11]	−3.69	82.77	25	CDMS

^a The typical quantum numbers are listed as $[J, K_a, K_c]$ unless specified.

^b The quantum numbers are $[N, J, F]$

4. DETECTION STATISTICS

5. CORRELATIONS OF COMS

6. SPATIAL EXTENT OF COMS

7. DISCUSSION

7.1. Complex Chemistry throughout Star Formation

7.2. 1D Spectra

Y.-L. Yang acknowledges the supports the JSPS Postdoctoral Fellowship from Japan Society for the Promo-

tion of Science. This paper makes use of the following ALMA data: ADS/JAO.ALMA#2016.0.00391.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Facilities: ALMA

Software: astropy, XCLASS, spectral-cube, CASA

APPENDIX

A. CATALOGS FOR MOLECULAR DATA

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