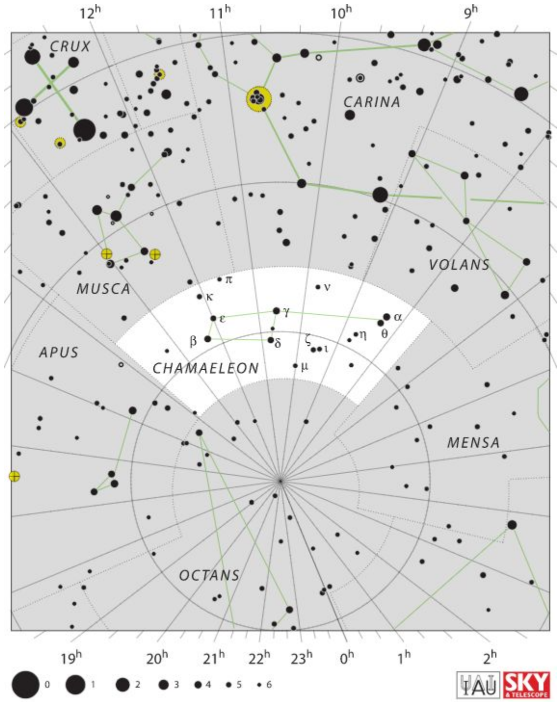
Examine **HCO+ absorption spectra** toward continuum sources located behind **the Chamaeleon molecular cloud** in the Milky Way to study the physical conditions of the **"Dark Neutral Medium (DNM)"** that is not traced by CO(1-0) emission

(reference: Liszt et al. 2018, A&A, 617,54)

2020 Alma Summer School
Group 1 (lead by Min-Young Lee)
Shinna Kim, Jaekyun Park, Suyeon Son

Chamaeleon Complex

Distance : ~ 160 pc



IAU and Sky & Telescope magazine (Roger Sinnott & Rick Fienberg), 5 June 2011, Wikipedia

The Chamaeleon I complex (VLT UT1 + FORS1)

ESO PR Photo 17c/99 (6 March 1999)

Dark Neutral Medium

- H_2 total column density

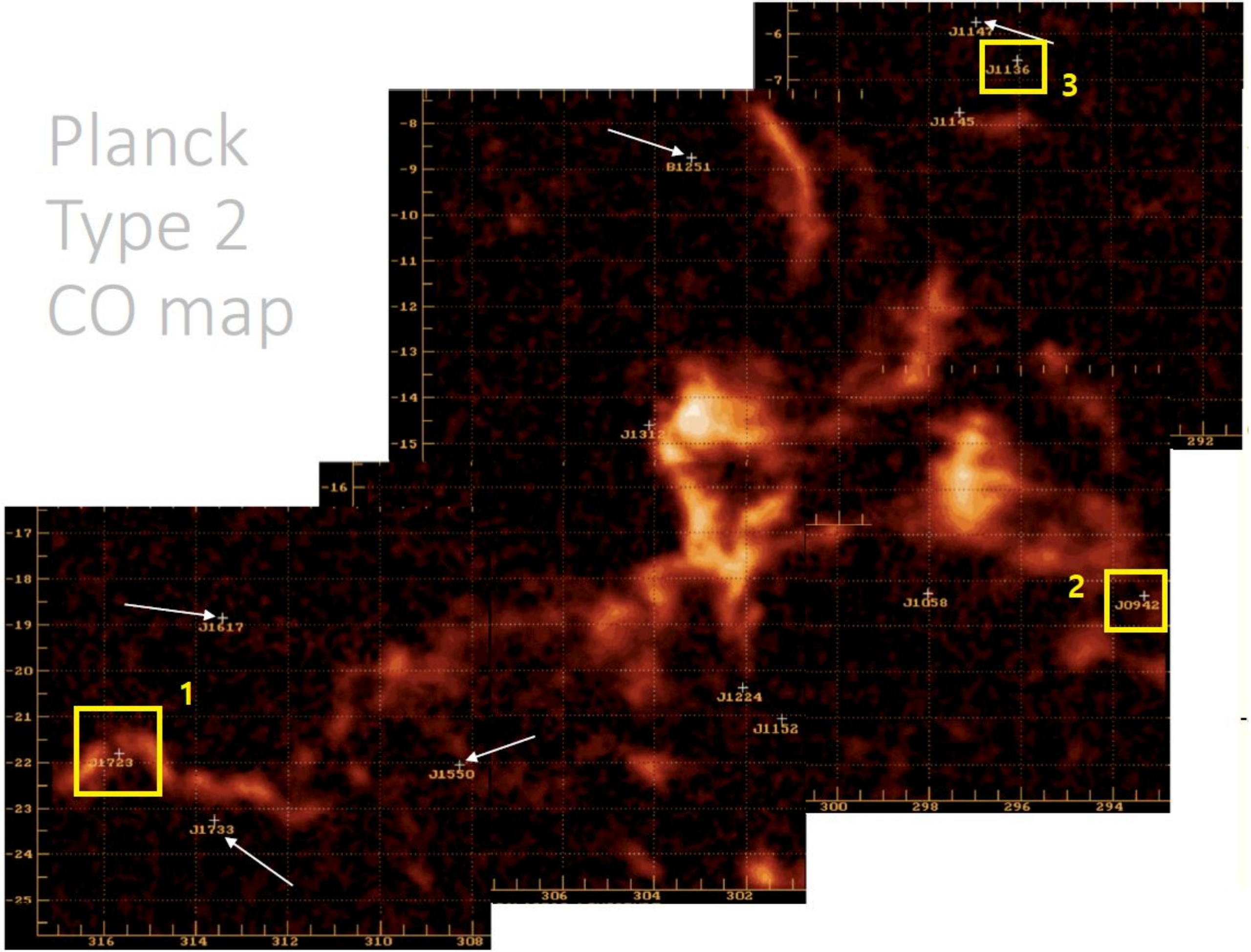
- H tracers - HI & CO

- Not detected gas → DNM (Dark Neutral Medium)
- optically thick H atom
- CO-dark hydrogen molecule

HCO+ absorption spectrum

- Absorption spectrum → calculate H_2 column density
- HCO^+ (J = 1 - 0) line toward the 13 continuum sources
- 13 AGNs in the outskirts of Chamaeleon

Planck Type 2 CO map



Radiative Transfer Equation

$$I^{ON} = I_{bg}e^{-\tau} + I_g\,(1 - e^{-\tau})$$

$$I^{OFF} = I_g\,(1 - e^{-\tau})$$

$$I^{ON} - I^{OFF} = I_{bg}e^{-\tau}$$

- Interferometer → only compact source is observable

$$I^{ON} = I_{bg}e^{-\tau}$$

- ALMA is suitable for observing abs spectrum in continuum source

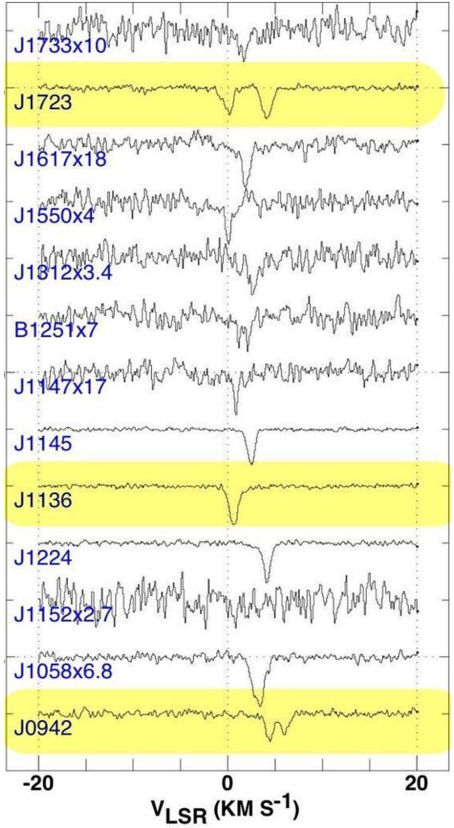
AGN as a continuum source

- Sensitivity
  - depends on continuum source intensity

$$-ln\left(\frac{I^{ON}}{I_{bg}}\right) = \Delta\tau$$

- Angular resolution (of interferometric absorption line)
  - size of the background source (= milliarcsecs in radio)
  - smaller than beam size → ‘pencil-beam measurement’

Data Information



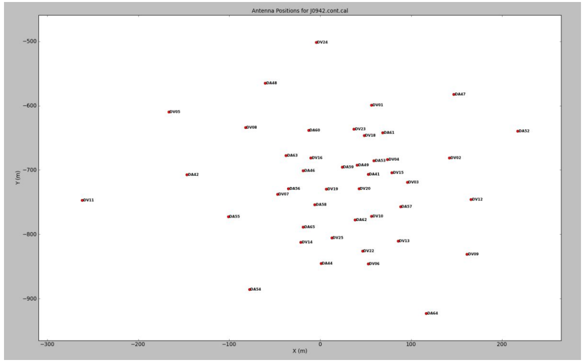
H. Liszt et al. 2018

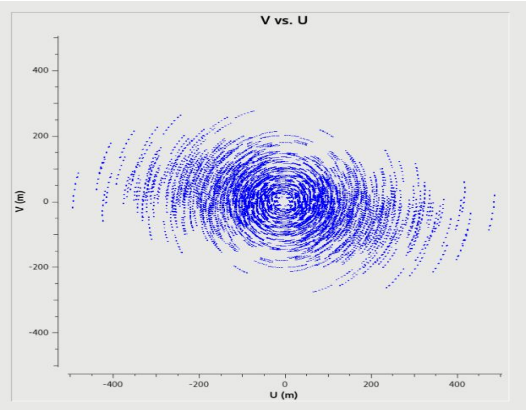
1.JXXXX.**Cont**.cal → *AGN continuum*

2. JXXXX.**HCO+**.cal.contsub → *HCO+ absorption line*

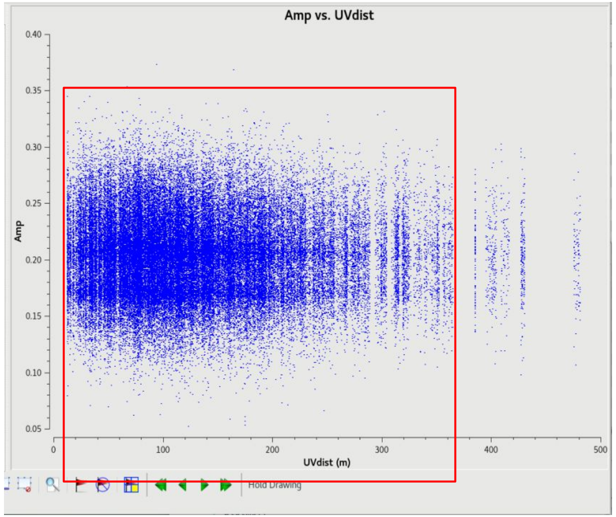
```
   Observer: hliszt     Project: uid://A001/X5ac/X778
Observation: ALMA
Computing scan and subscan properties...
Data records: 94600       Total elapsed time = 2977.1 seconds
   Observed from   01-Jan-2017/16:15:53.7   to   01-Jan-2017/17:05:30.8 (UTC)

   ObservationID = 0         ArrayID = 0
  Date        Timerange (UTC)          Scan  FldId FieldName             nRows     SpwIds   Average Interval(s)    ScanIntent
  01-Jan-2017/16:15:53.7 - 16:17:24.4     9      0 J1723-7713-350           14190  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              16:24:03.2 - 16:25:33.9    14      0 J1723-7713-350           14190  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              16:32:39.4 - 16:34:10.1    19      0 J1723-7713-350           14190  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              16:42:00.1 - 16:43:30.8    25      0 J1723-7713-350           14190  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              16:50:38.3 - 16:52:09.0    30      0 J1723-7713-350           14190  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              16:59:40.8 - 17:01:11.6    36      0 J1723-7713-350           14190  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              17:04:30.3 - 17:05:30.8    40      0 J1723-7713-350            9460  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
           (nRows = Total number of rows per scan)
Fields: 1
  ID   Code Name                RA               Decl           Epoch   SrcId      nRows
  0    none J1723-7713-350      17:23:50.845000 -77.13.50.54000 ICRS    0          94600
Spectral Windows:  (1 unique spectral windows and 1 unique polarization setups)
  SpwID  Name                                  #Chans   Frame   Ch0(MHz)  ChanWid(kHz)  TotBW(kHz) CtrFreq(MHz) BBC Num  Corrs
  0      X1370812824#ALMA_RB_03#BB_4#SW-02#FULL_RES   1920   TOPO   89217.359       -30.518     58593.8  89188.0770        4  XX  YY
Sources: 1
  ID   Name                SpwId RestFreq(MHz)  SysVel(km/s)
  0    J1723-7713-350      0     89188.526      0
```

Angular Resolution / Field Of View (FOV)





antenna tracks in uv plane



1.angular resolution θ = 1.22 x λ/D

D = 350m

λ = 3.36mm ← freq. = 89.188GHz

θ ~ 2.4”

cell size = 0.8”

2. FOV = 1.22 x λ/D

D = 12m

FOV ~ 70”

imsize = 1.5 x 0.8” / 70” ~ 131 → [150,150]

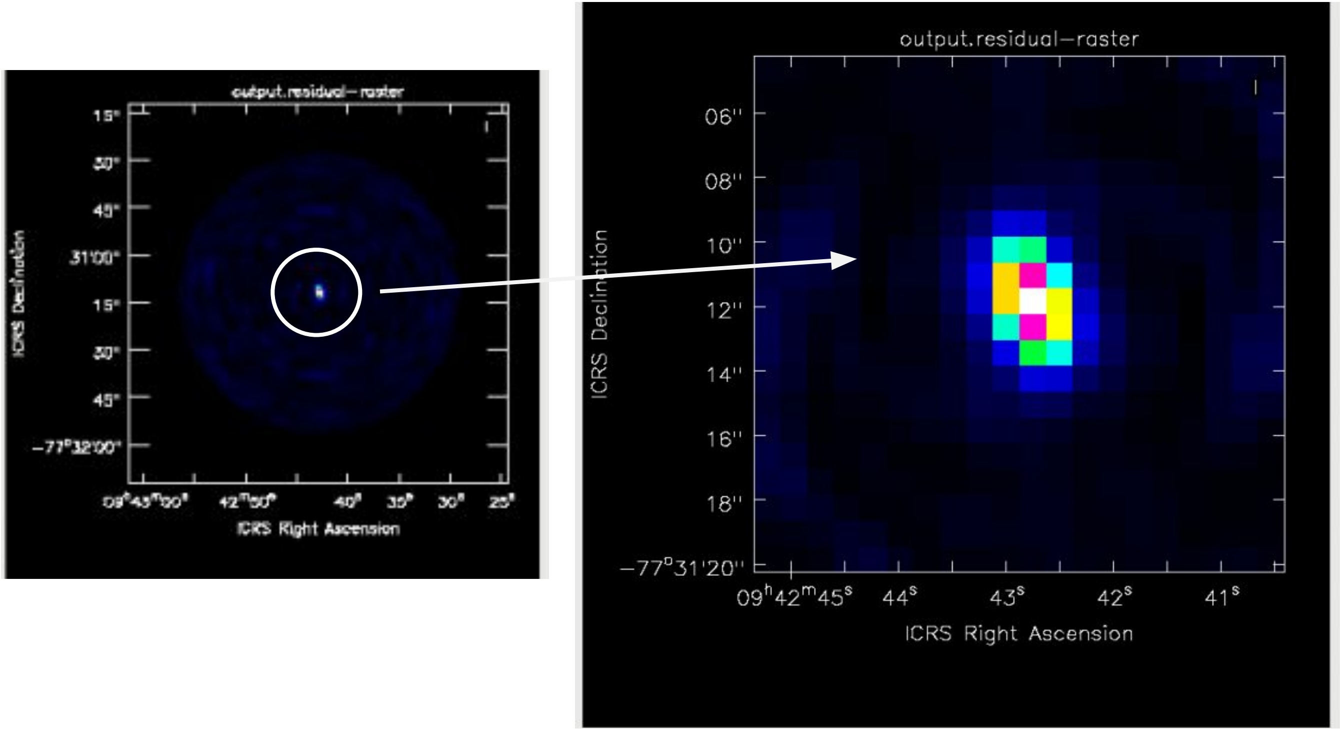
tclean (continuum)

cell = ‘0.8arcsec’

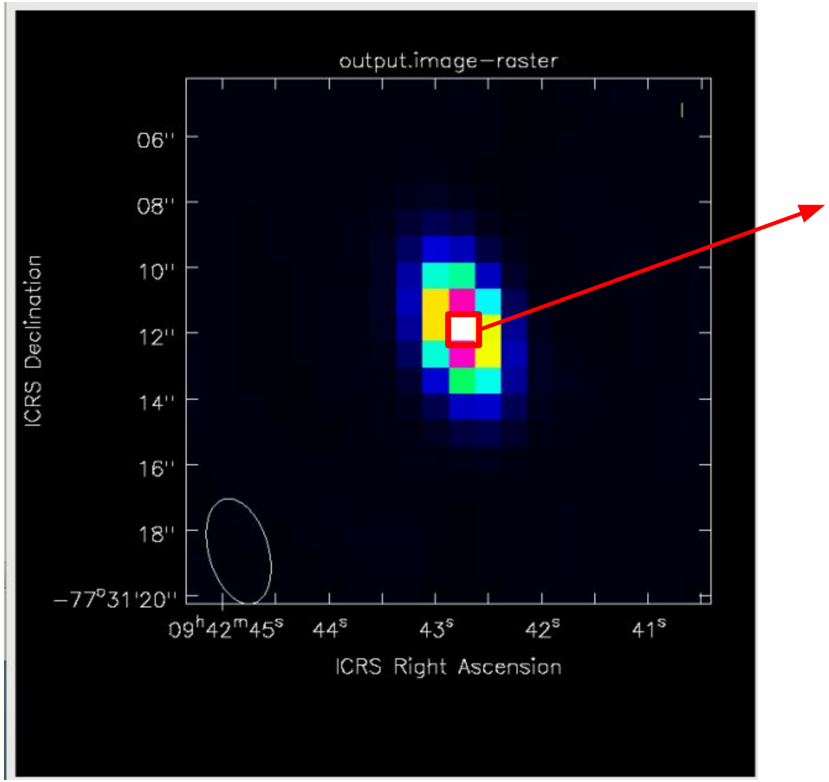
specmode = ‘mfs’

pbcor = False

weighting = ‘natural’



tclean (continuum image)



compact → unresolved source

observed peak brightness = 0.185553 [Jy/beam]
Intensity: 0.203 [Jy] (H. Liszt et al. 2018)

tclean (HCO+ absorption)

cell = ‘0.8arcsec’

specmode = ‘cube’

pbcor = False

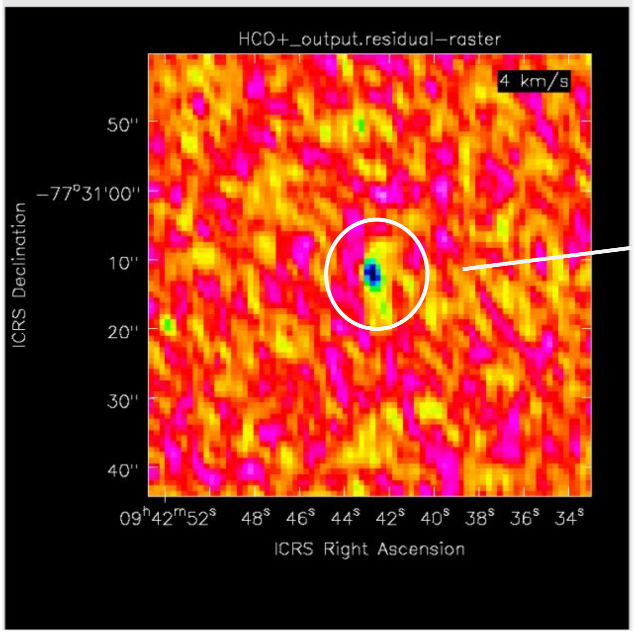
weighting = ‘natural’

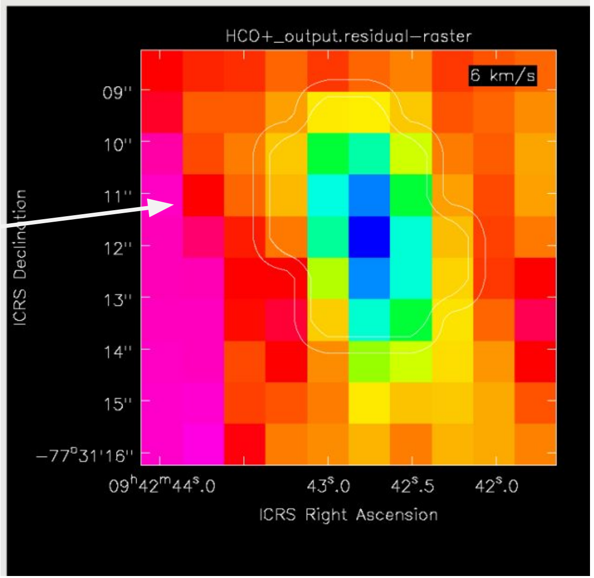
width = ‘0.2km/s’

start = ‘-20km/s’

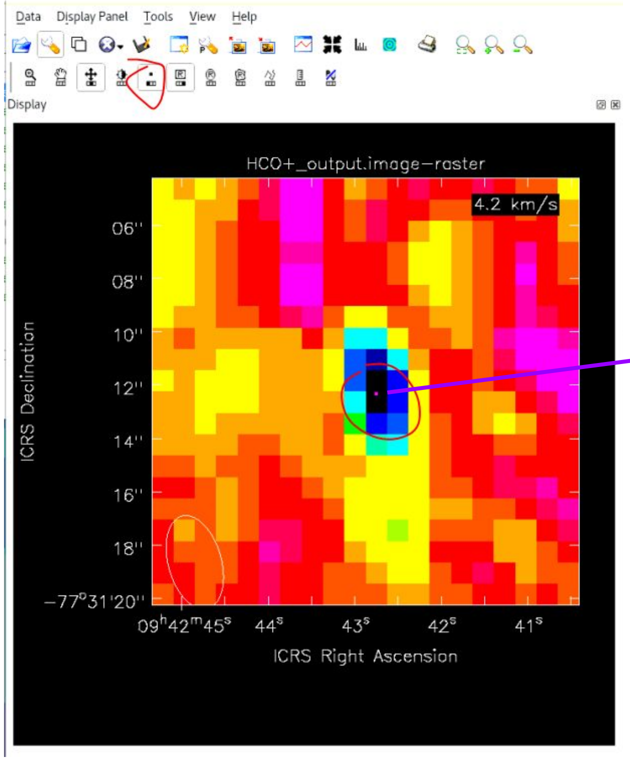
nchan = ‘200’

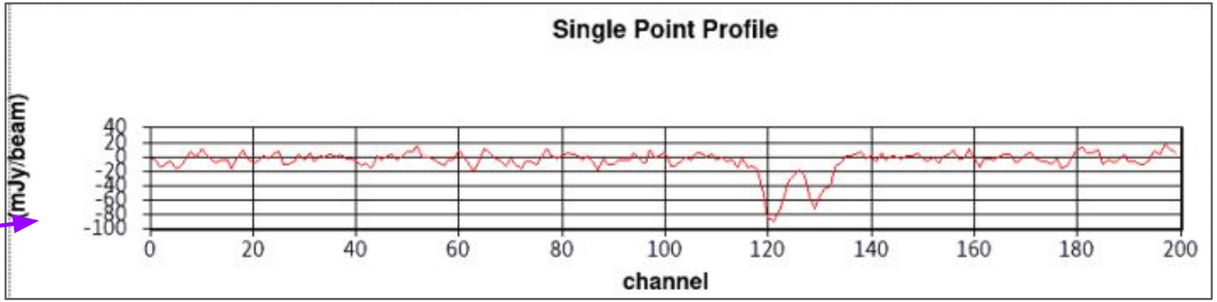
restfrq = ‘89.18852470GHz’





tclean (HCO+ absorption image & spectrum)





H. Liszt et al. 2018

Change Parameters : weighting, pbcor, pixel size

Weighting	pbcor	cell size	peak intensity [Jy / beam]		
			J0942 (논문 : 0.203)	J1136 (논문 : 0.466)	J1723 (논문 : 0.309)
natural	**X**	**0.8”**	0.186	0.431	0.299
uniform	X	0.8”	0.185	0.431	0.277
natural	**O**	0.8”	0.186	0.431	0.299
natural	X	**2.4”**	0.187	0.433	0.324

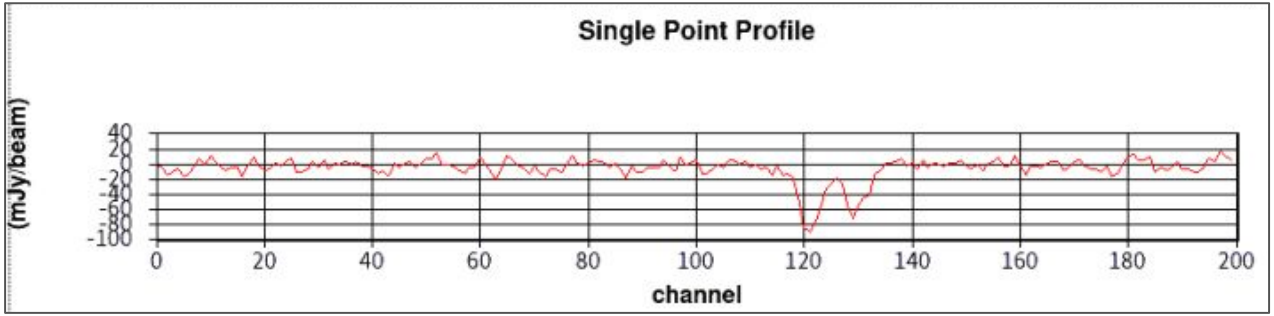
Convert Intensity to Optical Depth

The equation of radiative transfer

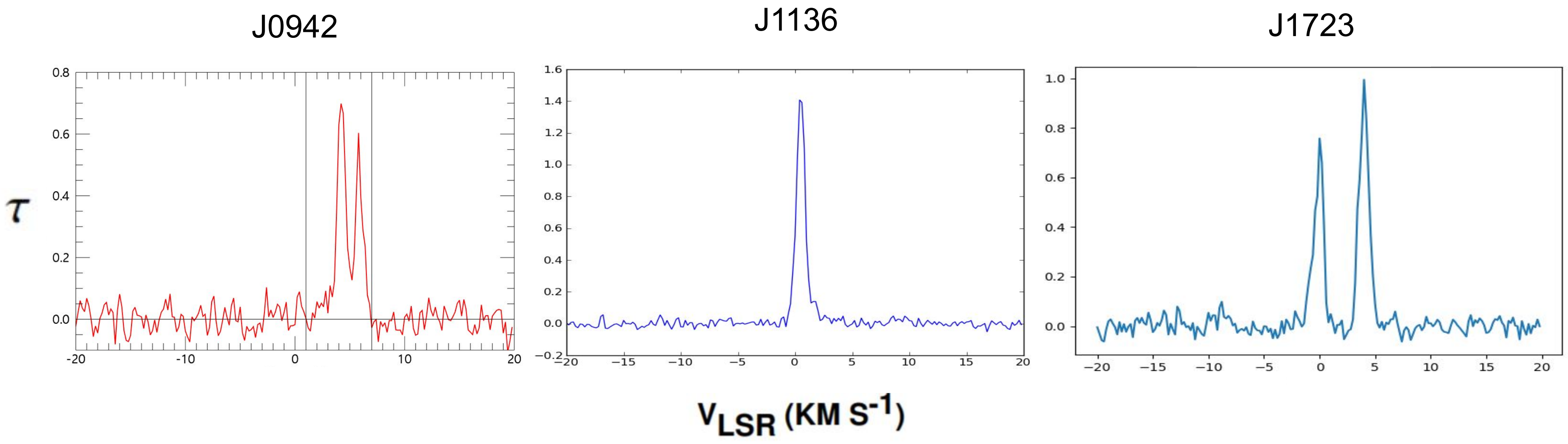
$$I = I_{bg} e^{-\tau}$$

$$I' = I - I_{bg}$$

$$\tau = -ln\left(\frac{I' + I_{bg}}{I_{bg}}\right)$$



Optical Depth (τ)



Convert Optical Depth to H_2 Column Density

$\int \tau \, dv$ = W_{HCO^+}

$$\sigma_W = \sigma_\tau \times (number of channel)^{1/2} \times \Delta v$$

$$N(HCO^+) = 1.10 \times 10^{12}\ cm^{-2} \int \tau \, dv$$

$$N(HCO^+)/N(H_2) = 3 \times 10^{-9}$$

Calculation

	J0942	J1136	J1723
W_{HCO^+} ($km\,s^{-1}$)	1.227	1.524	1.731
$\sigma_{W(HCO^+)}$	0.044	0.184	0.049
$N(HCO^+)$ ($10^{12}\,cm^{-2}$)	1.35	1.68	1.90
$2N(H_2)$ ($10^{20}\,cm^{-2}$)	8.99	11.18	12.70

Table 1. Sightline and spectral line properties.

Source	α(J2000) hh.mmssss	δ(J2000) dd.mmssss	l (°)	b (°)	E_{B-V}[a] (mag)	N(H I)[b] (10^{20} cm^{-2})	$S_{89.2}$ (Jy)	$\sigma_{l/c}$[c]	W_{HCO^+}[d] (km s^{-1})	W_{HCO^+}[d] (km s^{-1})
J0942-7731	09.424275	–77.311158	293.321	–18.329	0.33	9.1	0.203	0.0400	1.142 (0.067)[f]	1.227(0.044)
J1058-8003	10.584331	–80.035416	298.010	–18.288	0.15	6.0	1.189	0.0067	0.201 (0.009)	<0.032
J1136-6827	11.360210	–68.270609	296.070	–6.590	0.47	21.7	0.466	0.0195	1.241 (0.035)	1.524(0.184)
J1145-6954	11.455362	–69.540179	297.316	–7.747	0.38	16.8	0.537	0.0188	0.870 (0.031)	0.150 (0.007)
J1147-6753	11.473340	–67.534176	296.958	–5.767	0.30	23.0	1.552	0.0064	0.054 (0.010)	<0.034
J1152-8344	11.525322	–83.440943	301.238	–21.058	0.28	9.8	0.113	0.0719	0.240 (0.070)	<0.342
J1224-8313	12.245438	–83.131010	302.095	–20.391	0.26	8.7	0.300	0.0249	0.945 (0.044)	0.345 (0.040)
B1251-7138	12.545983	–71.381840	303.213	–8.769	0.28	17.0	0.574	0.0166	0.139 (0.027)	<0.091
J1312-7724	13.123874	–77.241306	304.122	–14.582	0.46	11.0	0.207	0.0390	0.271 (0.036)	<0.202
J1550-8258	15.505916	–82.580650	308.272	–22.047	0.11	6.3	0.352	0.0261	0.242 (0.040)	<0.158
J1617-7717	16.174928	–77.171846	313.426	–18.854	0.09	6.2	2.464	0.0044	0.059 (0.007)	<0.022
J1723-7713	17.235085	–77.135020	315.688	–21.800	0.26	7.7	0.309	0.0322	1.507 (0.052)	1.731(0.049)
J1733-7935	17.334070	–79.355537	313.606	–23.268	0.14	7.3	0.597	0.0149	0.057 (0.020)	<0.078

Notes. [a] Schlegel et al. (1998). [b] N(H I) = $\int T_B \, dv \times 1.823 \times 10^{18}$ cm^{-2} from the Gass III H I profile (Kalberla & Haud 2015). [c] Line/continuum rms at 89.2 GHz at zero optical depth. [d] N(HCO^+) = 1.10×10^{12} cm^{-2} W_{HCO^+}. [e] N(HCN) = 1.89×10^{12} cm^{-2} W_{HCN}. Upper limits are 3σ. [f] Quantities in parenthesis are the standard deviation.

Table 2. Target by target sightline gas and dust properties in descending N(DNM) order.

N(DNM) (10^{20} cm^{-2})	Source	E_{B-V} (mag)	N(H I)$\vert_{tot}$[a] (10^{20} cm^{-2})	N(H I)$\vert_{cham}$[b] (10^{20} cm^{-2})	N(DNM)[c] (10^{20} cm^{-2})	2N(H_2)[d] (10^{20} cm^{-2})	N(H)/E_{B-V}[e] (10^{21} cm^{-2} mag^{-1})	N(H_2)/X^0_{CO}[f] (K-km s^{-1})
$\gtrsim$2	J1152[g]	0.28	9.8	5.05	5.15	1.76	4.1	0.5
	J1312	0.46	11.0	6.71	3.96	1.98	2.8	0.5
	J0942[g]	0.33	9.1	6.17	3.82	8.20 8.99	5.2	2.0
	J1058	0.15	6.0	4.70	3.71	1.50	5.0	0.4
	J1224[g,h]	0.26	8.7	5.63	3.35	7.20	6.1	1.8
	J1145[g,h]	0.38	16.8	9.98	2.23	6.20	6.1	1.5
	J1723[g,h,i]	0.26	7.7	5.00	1.95	11.1 12.70	7.2	2.8
	J1136[g,h]	0.47	21.7	9.15	1.72	9.1 11.18	7.0	1.6
	mean(σ)	0.33 (0.11)	12.7 (6.3)	6.6 (2.0)	3.3 (1.3)	5.6 (3.6)	5.4 (1.4)	1.4 (0.9)
$\lesssim$0.5	J1617	0.09	6.2	4.31	0.45	0.43	7.3	0.1
	J1550	0.11	6.3	4.16	0.27	1.90	7.4	0.5
	J1147	0.30	23.0	7.73	0.00	0.40	7.8	0.1
	B1251[g]	0.28	17.0	6.60	0.00	0.84	6.0	0.2
	J1733[g]	0.14	7.3	5.25	0.00	0.58	5.2	0.2
	mean(σ)	0.18 (0.10)	12.7 (8.6)	5.6 (1.5)	0.14 (0.21)	0.83 (0.62)	6.7 (1.1)	0.22 (0.16)

Notes. [a] As in Table 1. [b] N(H I)$\vert_{cham}$ is N(H I) associated with the Chamaeleon complex. [c] N(DNM) from Planck Collaboration Int. XXVIII (2015). [d] N(H_2) = N(HCO^+)/3 × 10^{-9}. [e] N(H) = 2N(H_2) + N(H I)$\vert_{tot}$. [f] The predicted integrated CO $J = 1-0$ brightness (W_{CO}) for $X_{CO} = 2 \times 10^{20}$ H_2 cm^{-2} (K-km s^{-1})$^{-1}$. [g] C_2H detected. [h] HCN detected. [i] W_{CO} = 2.4 K-km s^{-1}.

Possibilities

1. Optically thick atomic (HI) gas
2. CO-dark molecular (H_2) gas

Conclusion

Detecting large amounts of H_2 in the sightline where CO emission is not detected (or less detected) using the HCO^+ absorption line

→ DNM has a high probability of being a **CO-dark molecular gas** that could not be detected due to low sensitivity