

Report: Investigation of Infrared Dark Cloud in
Early Star Formation
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1 Introduction

Stars are usually formed in the massive clumps in the infrared dark cloud (IRDC). The infrared dark cloud was first discovered in ISO and MSX surveys. It exhibits significant mid-infrared opacity and processes some extreme properties with typical temperature smaller than $20K$ and enormous column densities to be larger than $10^{23} - 10^{25} \text{ cm}^{-2}$. Through studying the star-forming regions in the IRDCs, cloud dynamics and structures such as outflow behavior, dense core, filaments etc. could be investigated to better understand the early stage of star formation.

The SURE program offers me a precious opportunity to study this field from the beginner level. In section 2 of this report, the data cube and target cloud

studied in this project would be introduced, followed by imaging theory and procedures in section 3. Some preliminary analysis is briefly summarized in section 4.

2 Data

This project is conducted using the data set of the IRDC G14.225-0.506 (hereafter G14.225) observed by Atacama Large Millimeter/Submillimeter Array (ALMA). A N_2H^+ integrated intensity map of G14.225 cloud is shown in Fig.1 to illustrate the position of Northern and Southern fields (Field-N and Field-S).

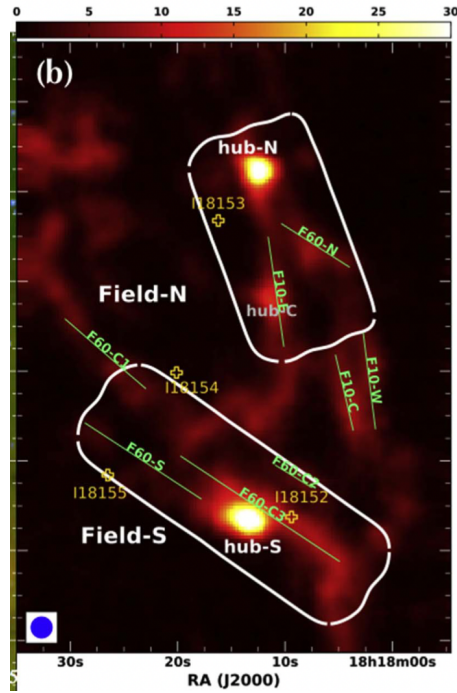


Figure 1: G14.225 map from Chen et al.(2019)[3], showing the relative positions of Northern and Southern mosaic field.

Data of 10 targets corresponding to 10 fields (relative position shown in Fig.2) are collected with Northern mosaic field including pointing at fields G14.225N.1, G14.225N.2 and G14.225N.3, Southern mosaic field including pointing at fields G14.225S.1, G14.225S.2, G14.225S.3, and G14.225S.4, and 3 single pointings (G14.225N.4, G14.225N.5 and G14.225N.7) in the Northern region.

Dust continuum data under band 6 (1.3mm) and the line emission data from CO (2-1), ^{13}CS (5-4), OCS (19-18), N_2D^+ (3-2) are recorded in spectral windows (spw) 0-2, 3-6 respectively.

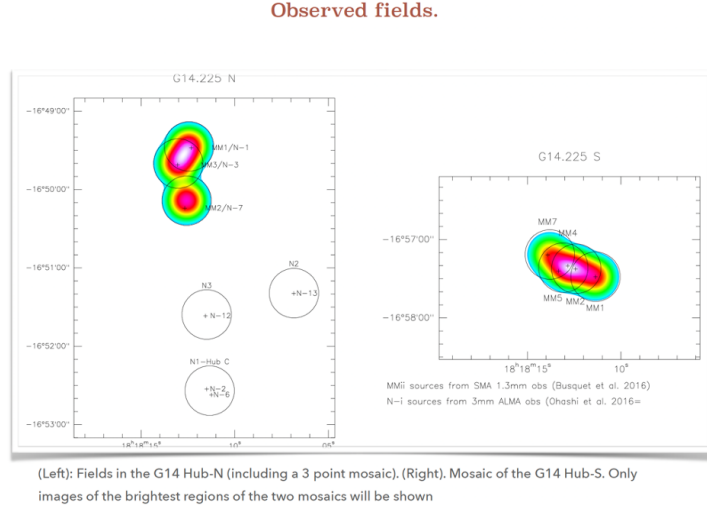


Figure 2: Observed fields with mosaic fields (combined pointings) in the Northern and Southern regions and 3 single pointings in Northern area.

3 Imaging

3.1 Interferometry

Interferometry technique is applied to transform the visibility data from interferometers into images for data analysis. The radio interferometers detect the radiations from the source and process to visibility data. By Van Cittert-Zernike Theorem

$$V_\nu(u, v) = \iint I_\nu(l, m) e^{-i2\pi(ul+vm)} dl dm,$$

brightness (Intensity I) could be obtained from this 2-dimensional inverse Fourier transform:

$$I_\nu(l, m) = \iint V_\nu(u, v) e^{i2\pi(ul+vm)} du dv.$$

In real data collection, interferometer samples discretely in the (u, v) space and dirty beam (point spread function) would be included in the dirty image. A dirty image is given by

$$I_\nu^D(l, m) = \iint S(u, v) V_\nu(u, v) e^{i2\pi(ul+vm)} du dv,$$

where sampling function $S(u, v) = 1$ at sampling point, and $S(u, v) = 0$ elsewhere. The dirty beam is related to sampling function by

$$B(l, m) = \iint S(u, v) e^{i2\pi(ul+vm)} du dv,$$

and thus dirty image is the convolution of 'true' brightness with the dirty beam:

$$I_{\nu}^D(l, m) = I_{\nu}(l, m) \otimes B(l, m).$$

The cleaning task performed based on CLEAN algorithm is briefly introduced as follows. The aim is to construct a model image that could estimate the "true" brightness image which gets rid of the 'dirty' beam. The mechanism iteratively removes a fraction of flux from the brightest region as model image and subtracts the data by model to obtain the residual part [4]. Deconvolution algorithm would be applied to update the sky model image for next iteration cycle. After primary beam correction, imaging process is completed with image files and other files containing residual, primary beam information generated for further supplementary analysis.

3.2 CASA

The imaging is achieved using the Common Astronomy Software Applications (CASA). For spectral line emission imaging, the first step is to subtract the continuum emission from line spectral windows. The line-free channels are flagged and included the continuum emission estimation, and then continuum subtraction would be performed to obtain the line emission in better accuracy. Take the CO (2-1) emission in spectral window 3 (spw=3) in field G14.225S.1 as an example. The amplitude against frequency plots before and after continuum subtraction are shown in Fig.3.

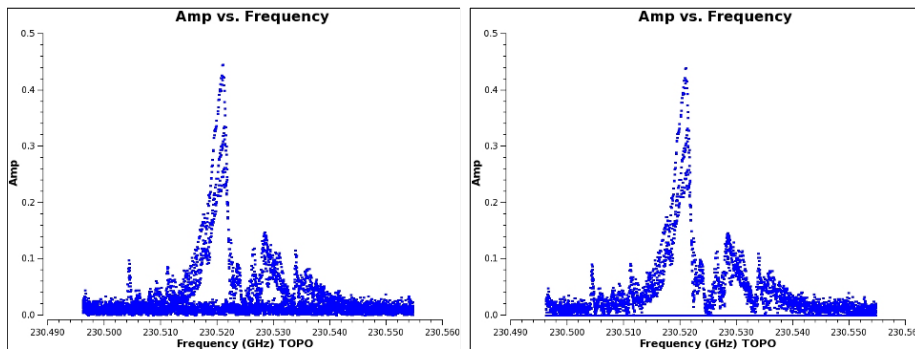


Figure 3: (left) Amplitude vs. frequency map of CO (2-1) emission in spw=3 in G14.225S.1 field before continuum subtraction; (right) Amplitude vs. frequency map of CO (2-1) after continuum subtraction.

After subtraction, the cleaning procedure is conducted with multiple input parameters. Parameters including rest frequency, velocity channel width (Table.1), interaction times, spectral definition mode (specmode='cube') deconvolution mode (deconvolver='multiscale'), pixel sizes ($0.2'' \times 0.2''$), weighting scheme (weighting = 'briggs'), automask thresholds (sidelobethreshold=2.0, noisethreshold=4.25, lownoisethreshold=1.5, minbeamfrac=0.3, growiterations=75,

Molecule	Rest Frequency	Velocity Width
CO	230.538 GHz	0.3 & 1.0 km/s
OCS	231.060993 GHz	0.5 km/s
¹³ CS	231.220686 GHz	0.5 km/s
N ₂ D ⁺	231.321828 GHz	0.5 km/s

Table 1: rest frequency and velocity width of molecules

negativethreshold=15.0[2]), etc. are input. Normally, for 100,000 iteration times, it takes around 8-10 hours to finish the cleaning.

With the line emission imaging carefully done, one obtains the images in the form of intensity map across velocity channels. Fig. 4 is some examples of intensity maps from different molecules in different fields.

Apart from line emission, continuum emission maps are generated after performing similar cleaning procedure but modifications in certain parameters (e.g., specmode='mfs', sidelobethreshold=2.0, noisethreshold=4.25, lownoisethreshold=1.5, minbeamfrac=0.3, growiterations=75, negativethreshold=0.0[2]).

4 Analysis

Images produced could be studied from multiple aspects including cloud kinetics such as outflow analysis (using CO, SiO, H₂CO, etc.) and structures such as dense core analysis with dust continuum data.

4.1 Outflow

Outflow analysis is performed mainly using CO (2-1) which is typically considered as a good tracer. Outflows are typically identified as spatially confined wings beyond the dense core emission by position-velocity diagram[5]. This diagram could also reveal the velocity range of the outflow gas (example shown in Fig. 5).

With the position-velocity diagram and examination of velocity channel map (Fig. 6), outflows in each field could be carefully identified and then masked using SAOImageDS9 region selection.

With selected spatial areas and velocity channel ranges, outflow parameters could then be computed. By assuming optically thin condition and relative abundance of CO and H₂ to be $[CO/H_2] = 10^{-4}$, outflow mass is calculated and other parameters are expressed as follows [5]:

$$\text{Momentum } P \propto \sum \int T_B(v) v dv$$

$$\text{Energy } E \propto \sum \int T_B(v) v^2 dv$$

$$\text{dynamical timescale } t_{dyn} = R/v$$

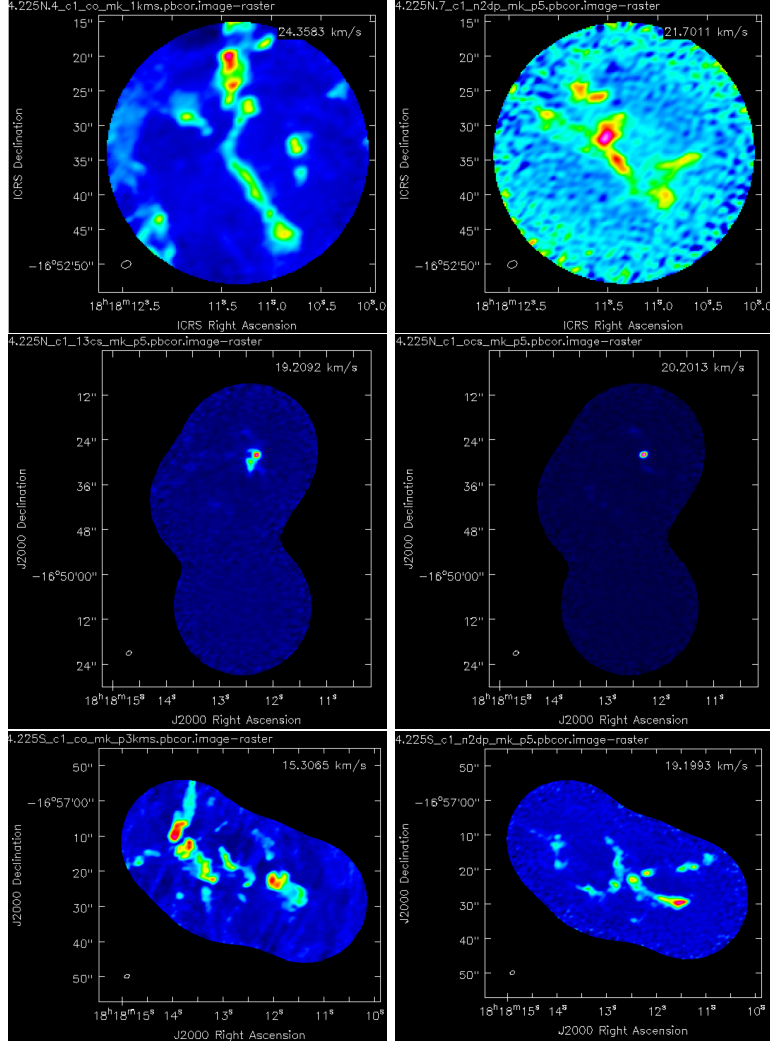


Figure 4: (upper left) CO (2-1) intensity map in G14.225N.4 field at velocity channel $v = 24.3583$ km/s; (upper right) N₂D⁺ (3-2) intensity map in G14.225N.7 field at velocity channel $v = 21.7011$ km/s; (middle left) ¹³CS (5-4) intensity map in G14.225N mosaic field at velocity channel $v = 19.2092$ km/s; (middle right) OCS (19-18) intensity map in G14.225N mosaic field at velocity channel $v = 20.2013$ km/s; (bottom left) CO (2-1) intensity map in G14.225S mosaic field at velocity channel $v = 15.3065$ km/s; (bottom right) N₂D⁺ (3-2) intensity map in G14.225S mosaic field at velocity channel $v = 19.1993$ km/s.

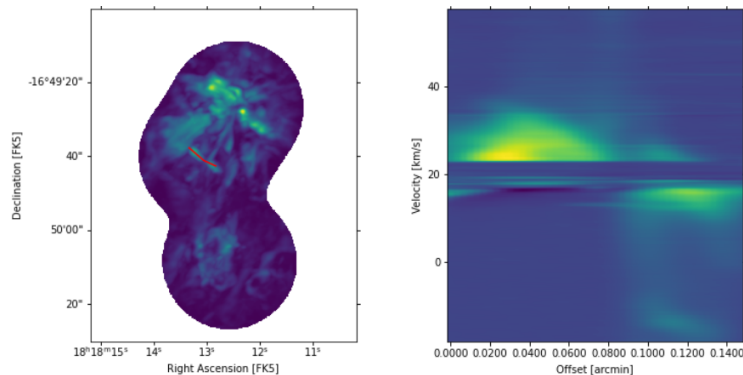


Figure 5: Position-velocity diagram example of CO (2-1) intensity map in G14.225N mosaic field. The red line in the left panel shows the outflow and right panel is the position-velocity diagram along the selected path of the marked red line. Relatively strong emissions are detected in both red-shifted and blue-shifted sides, with cloud velocity typically being around 20 km/s.

$$\text{rate of outflow mass } \dot{M}_{outflow} = M_{outflow}/t_{dyn}$$

Further analysis in outflow such as relation between outflow rate and luminosity is expected.

4.2 Dense Core

Dense core analysis is performed using dust continuum data. The parameters of dense core may reveal certain properties of dynamical state and be compared with other mass functions.

Dense cores are identified by dendrogram using *AstroDendro* [1]. Dendrogram could be analogous to a tree with trunks and leaves that imply the hierarchy of data structures (example shown in Fig. 6). Statistics from the dendrogram are now being computed for later analysis.

5 Conclusion

The dense and massive infrared dark cloud harbors clumps and cores where active star-forming activity occurs. Interferometry technique offers a useful tool in observation, and with images produced from CASA, multiple aspects such as gas outflows and pre-stellar and proto-stellar dense cores are being studied to better understand the structures and dynamics and furthermore the early stage of star formation.

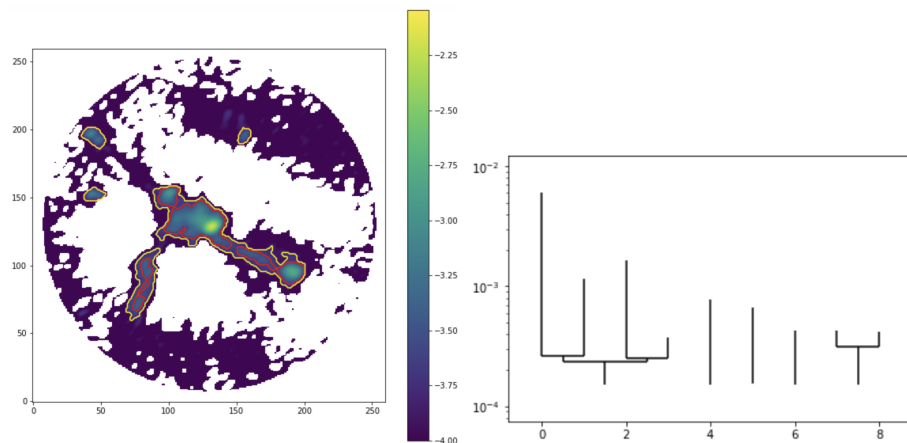


Figure 6: Dendrogram example in G14.225N.5 field. Intensity and color bar are plotted in log-scale. Leaves are shown in red color and trunks are in yellow.

References

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