# SMA Observations of Dense Cores at Different Evolutionary Phases in Filamentary IRDCs

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***Abstract:*** Infrared dark clouds (IRDCs) are recognized as nurseries of high-mass stars in the Galaxy given that they are massive, dense, and cold. High angular resolution millimeter/sub-millimeter observations are necessary to penetrate the dense gas and resolve the embedded protostars in these clouds, in order to study the earliest phase of high-mass star formation. With the SMA, we selected four dense molecular clumps probably at quite different evolutionary phases in the IRDC G28.53-0.25, and obtained their dust emission and molecular spectral lines. We identified six dense cores. Those at very early phases exhibit few spectral lines, while those that are more evolved exhibit complex organic molecular lines as well as signature of outflows. Both types of cores are massive enough (a few tens of solar mass) to form high-mass (>8 M⊙) stars. Furthermore, we conducted a mini survey of four filamentary IRDCs with the SMA, in order to learn the relation between filaments and high-mass star formation. We found dense cores embedded in filaments, while it is to be established whether they will form stars.

## Dense cores in IRDC G28.53-0.25

At the distance of 5.4 kpc, G28.53-0.25 is a typical IRDC as shown by the dark shadows in Spitzer 8 μm image. It presents ten dust continuum peaks in the IRAM MAMBO 1.2 mm image (Rathborne et al. 2006). Previous SMA observations (Rathborne et al. 2008; Swift 2009) towards mm1 revealed that although being massive (~$10^3$ M⊙) and dense (~$10^{23}$ cm$^{-3}$), the cores lack strong molecular line emission and may be at an early phase of star formation.

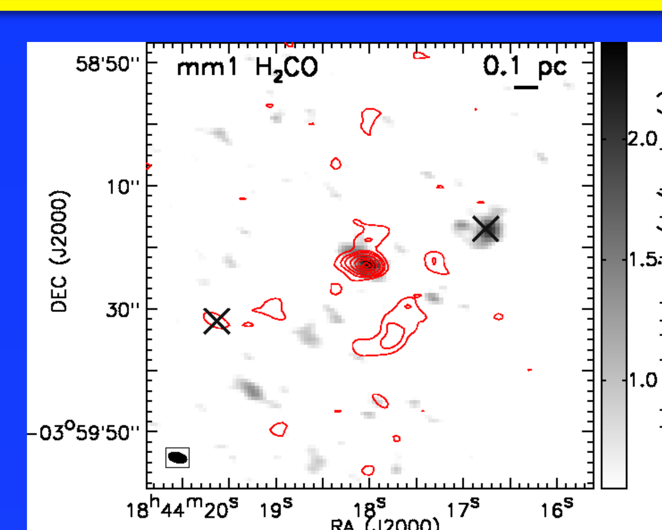
i) mm1 consists of at least three dense cores. The cores are either presenting CO outflows, or associated with masers. Thermal $CH_3OH$ emission is detected towards core1. They are the most active among the six cores we found.

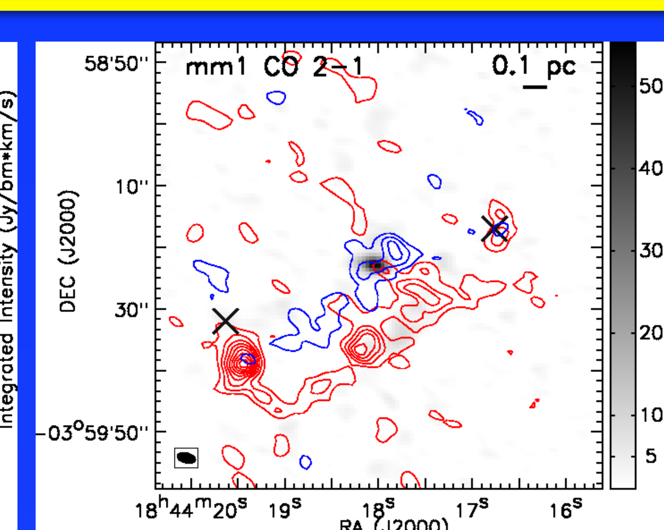
ii) In contrary, in mm7&8, only weak CO lines are detected, indicating cold dense cores where complex organic molecules might not be created yet. They are likely at the earliest phase of star formation.

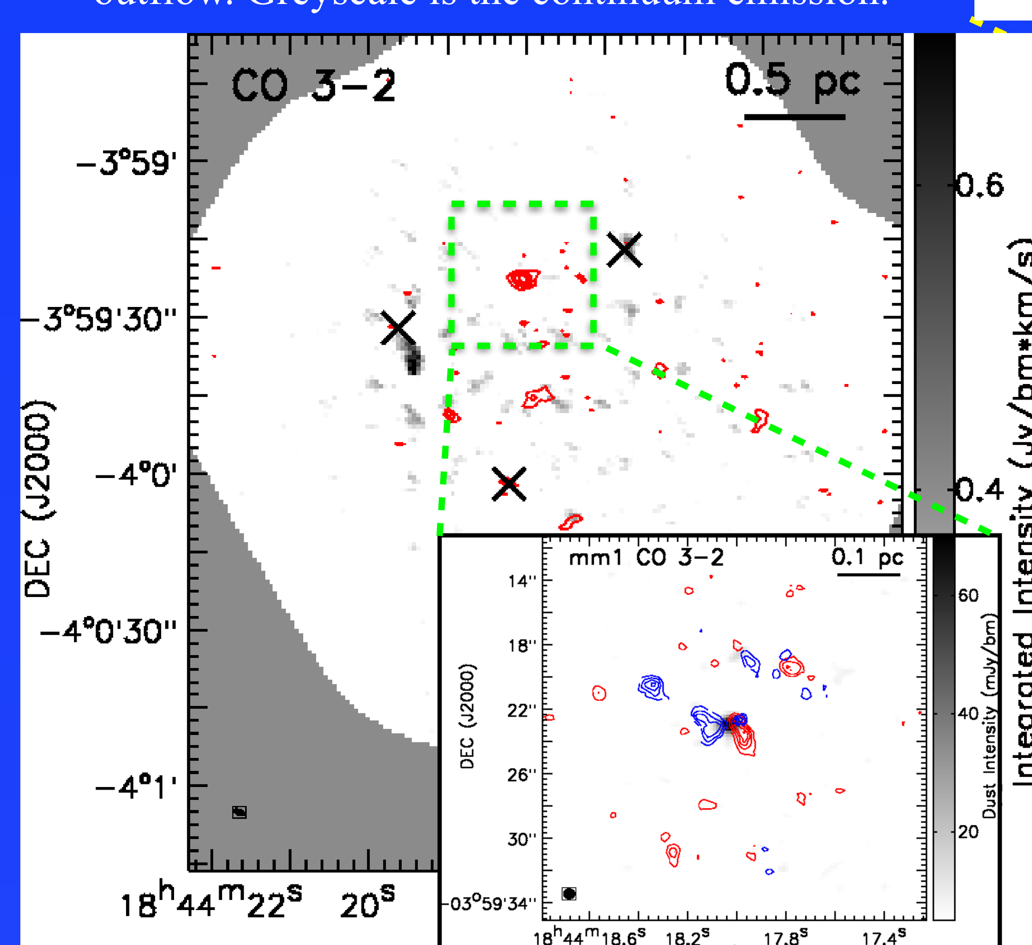
iii) mm5 shows signature of CO outflow. It also presents concentrated $H_2CO$ emission. However no $CH_3OH$ emission nor masers are found. It is likely at an intermediate phase.

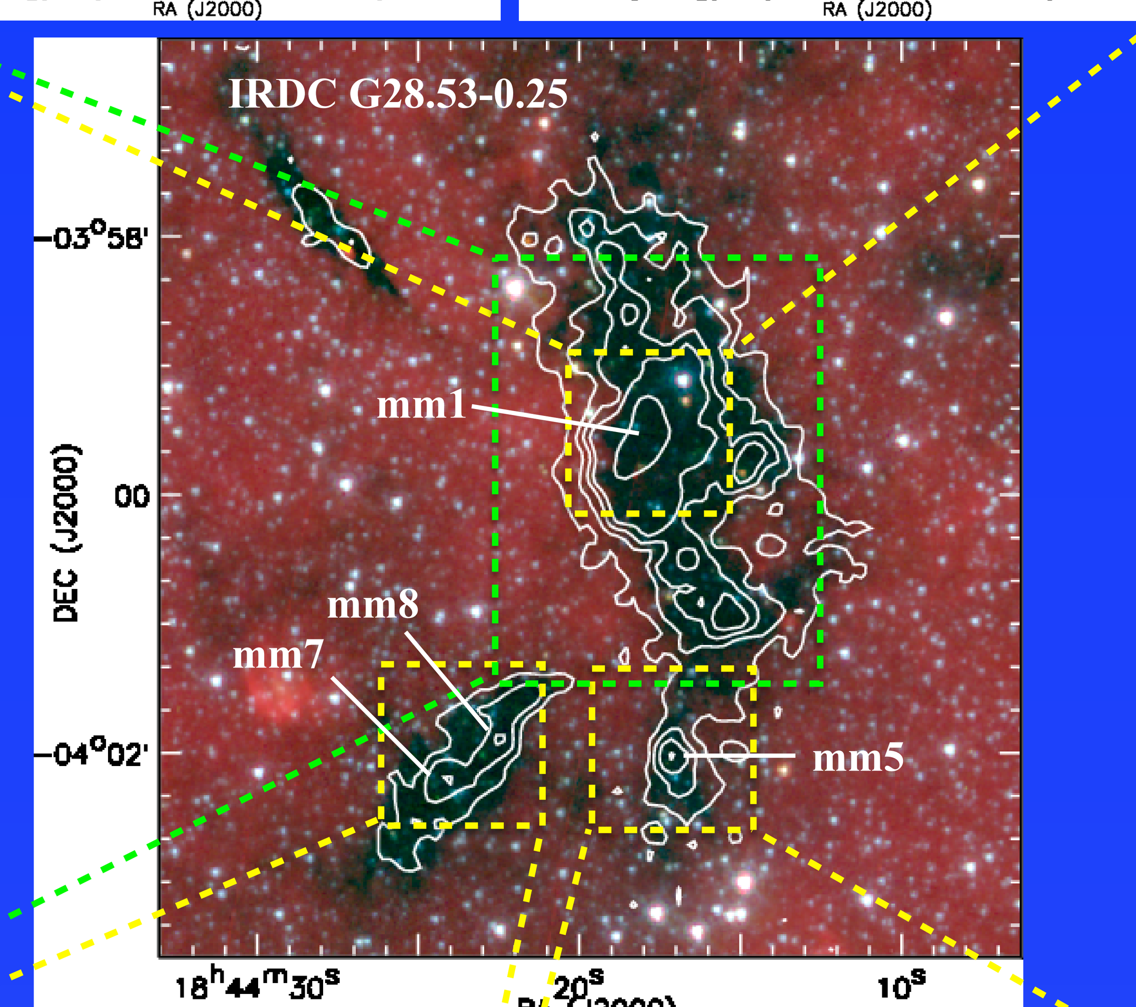
Physical parameters of the six cores are listed below.

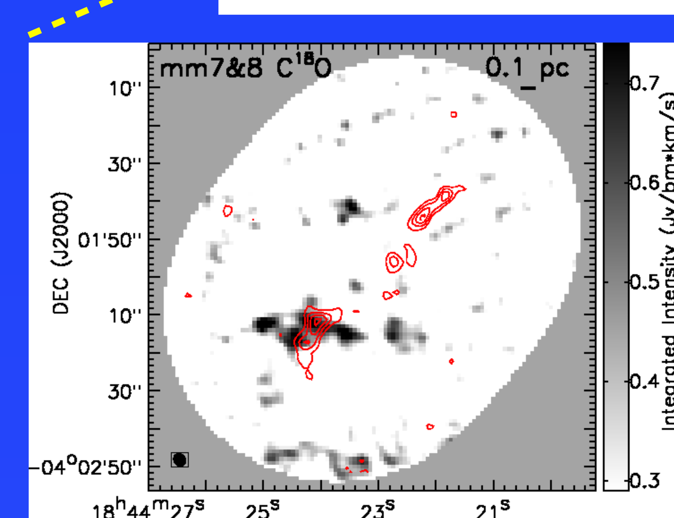
*Below*: 345 GHz SMA observations towards mm1. Contours show continuum emission in steps of 5mJy/beam×[3,6,9,15] with a beam size of 2.19”×1.28”. Greyscale is integrated CO 3-2 emission. Crosses are class II CH3OH masers.
*Inset*: Contours show integrated red/blue-shifted CO 3-2 emission of mm1, to highlight the outflow. Greyscale is the continuum emission.

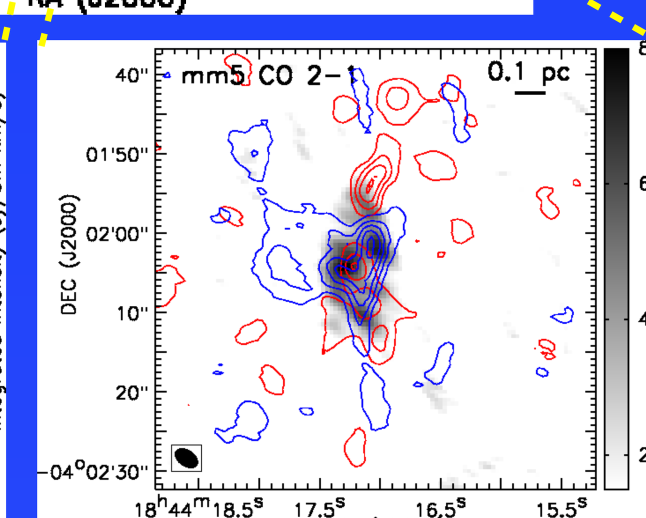












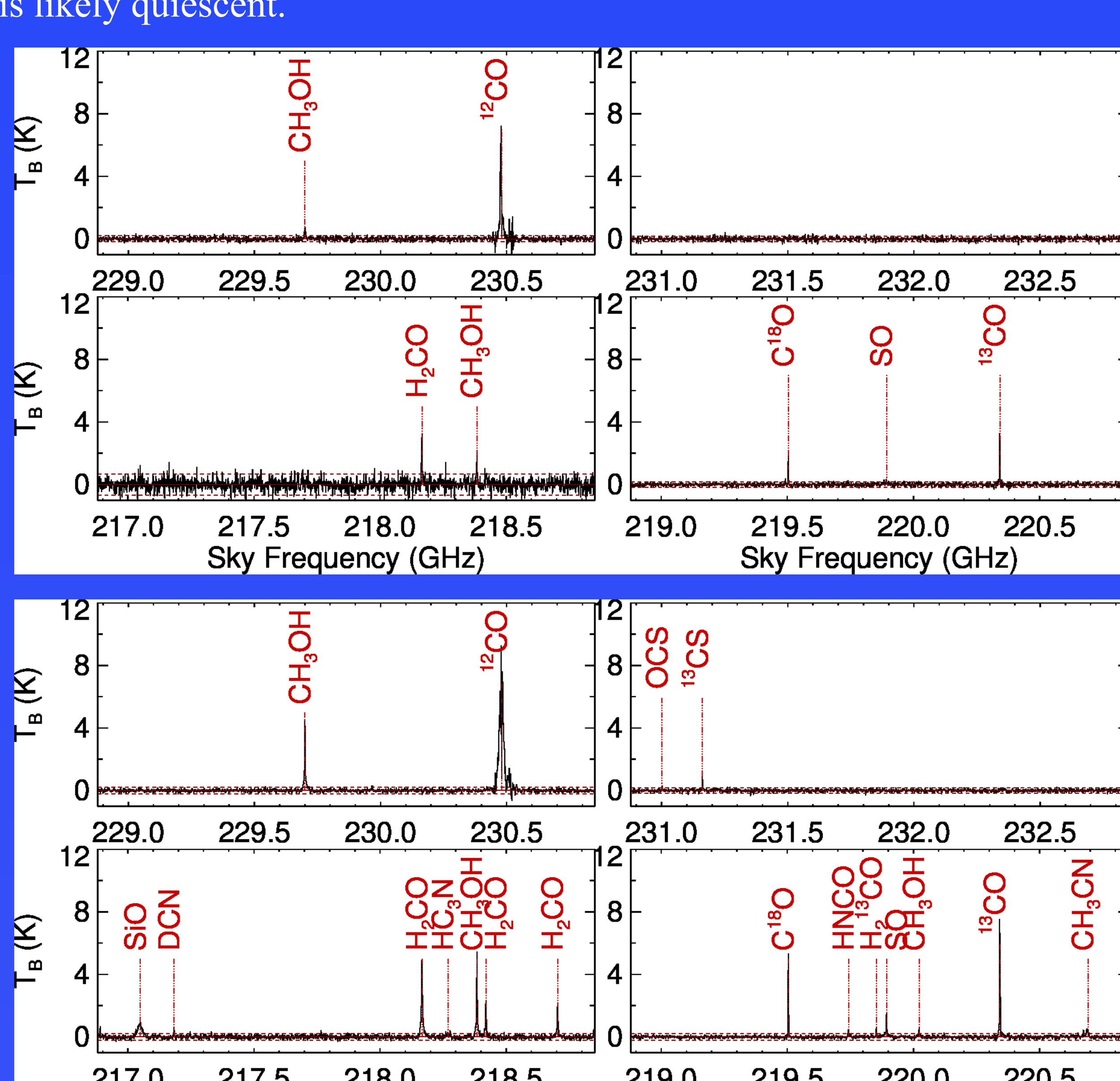
*Top left*: Contours show SMA 230 GHz continuum of mm1, in steps of 1.1mJy/beam×[3,6,9,15,25,35,45], with a beam size of 3.72”×1.73”. Greyscale is integrated $H_2CO$ emission. Crosses are class II $CH_3OH$ masers. Note that to the northwest of the central core, there is $H_2CO$ emission that is coincident with a maser, but show little continuum emission.
*Top right*: Contours are integrated red/blue-shifted CO 2-1 emission, to highlight the outflow. Greyscale is the continuum emission.
*Middle*: Contours show IRAM 30m MAMBO 1.2 mm continuum (Rathborne et al. 2006). Colors are Spitzer IRAC bands at 8 μm (red), 4.5 μm (green), and 3.6 μm (blue).
*Bottom left*: Contours show SMA 230 GHz continuum of mm7&8, in steps of 0.7mJy/beam×[3,5,7,9], with a beam size of 3.67”×3.17”. Greyscale is integrated $C^{18}O$ emission.
*Bottom right*: Contours are integrated red/blue-shifted CO 2-1 emission of mm5, to highlight the outflow. Greyscale is the continuum emission.

| Core ID | r (pc) | M (Msun) | T (K)* | Δv(km/s)* | Mvirial (Msun) | Notes |
|---|---|---|---|---|---|---|
| mm1-core1 | 0.1 | 88 | 15.5 | 2.30 | 66 | CO outflow. Swift 2009. |
| mm1-core2 | 0.1 | 55 | 15.5 | 2.30 | 66 | Rathborne et al. 2008. |
| mm1-core3 | 0.1 | - | 16.5 | 1.29 | 21 | No dust emission. CH3OH maser. |
| mm5-core1 | 0.15 | 156 | 13.5 | 1.01 | 19 | CO outflow. |
| mm7-core1 | 0.2 | 80 | 13.0 | 0.75 | 14 | Weak CO emission. |
| mm8-core1 | 0.15 | 66 | 14.0 | 0.85 | 14 | Weak CO emission. |

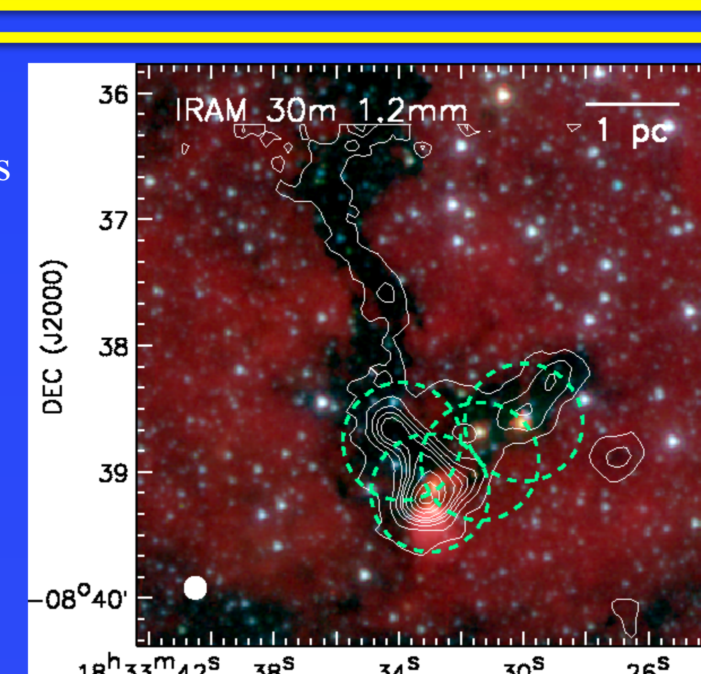
* *Temperatures and linewidths are derived from VLA $NH_3$ spectral lines data.*

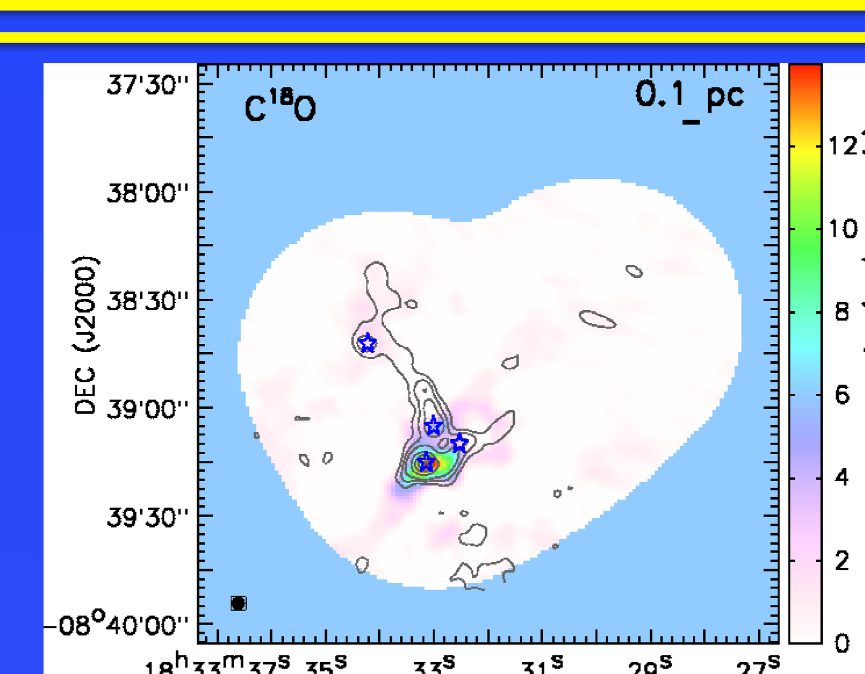
## Embedded cores in filamentary IRDCs

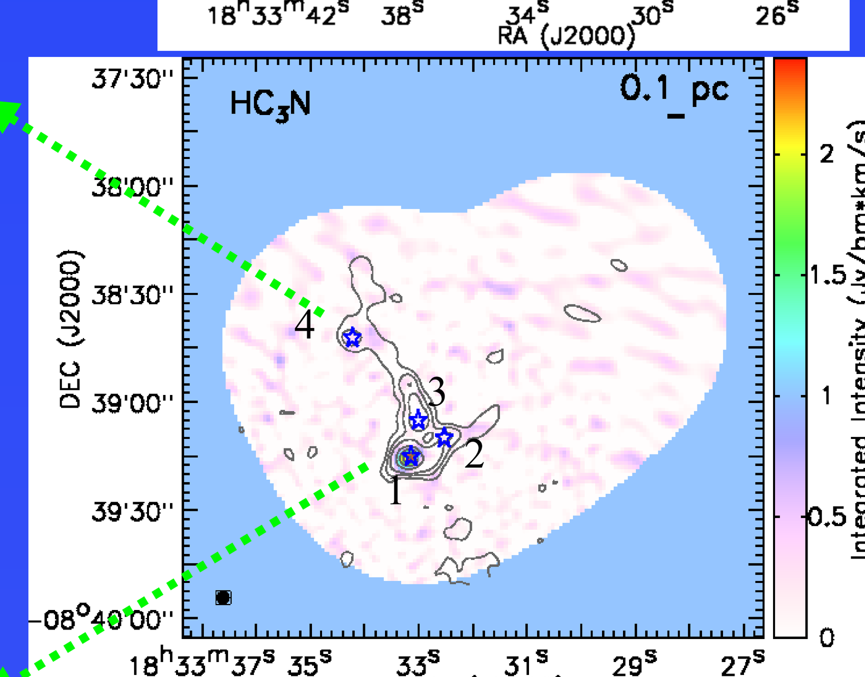
To study the role of filaments in high-mass star/cluster formation, we selected four prominent filamentary IRDCs in our $NH_3$ VLA survey (Lu et al. 2014). The SMA 230 GHz observations reveal embedded dust cores in the filaments as well as in the “hubs” where multiple filaments intersect. One example, IRAS 18308-0841, is shown here. Three dust cores (1-3) are found in the hub. The masses are 136, 15, and 45 M⊙, respectively. Another dust core (4) is in the filament, with a mass of 15 M⊙. The cores in the hub present signatures of active star formation while the one in the filament is likely quiescent.

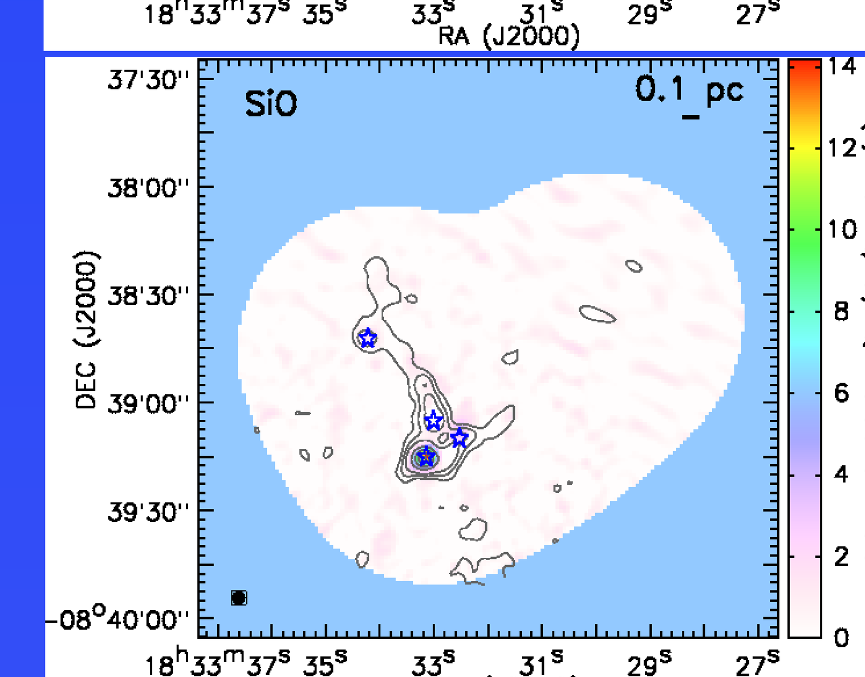


SMA 230 GHz spectral lines of core 1 and core 4. *Top*: Spectral lines of core 4. $^{12}CO$ 2-1, $^{13}CO$ 2-1, $C^{18}O$ 2-1, $H_2CO$ 3-2, and two $CH_3OH$ 8-7 lines are detected. *Bottom*: Spectral lines of core 1. The detected molecular spices can be sorted into four groups: i) diffuse gas tracers, $^{12}CO$, $^{13}CO$ and $C^{18}O$; ii) dense core tracers, $HC_3N$, $CH_3CN$ etc. iii) shock tracers, SiO, HNCO, $CH_3OH$ etc. iv) chemical tracers, $^{13}CS$, SO, OCS, DCN.









*Top left*: Overview of IRAS 18308-0841. Contours show IRAM 30m MAMBO 1.2 mm continuum (Beuther et al. 2006), in steps of 10.4mJy/beam×[3,6,9,12,15,20,30,40,50]. Colors show Spitzer 8 μm (red), 4.5 μm (green), and 3.6 μm (blue) emission. Four dashed circles show the SMA pointings of 56” primary beam.
*The other three panel*: Contours show SMA 230 GHz continuum, in steps of 1mJy/beam×[3,9,18,50,90,130], with a beam size of 3.6”×3.5”. The four dust cores are marked by stars. Colorscales show integrated intensities of three different types of tracers: $C^{18}O$ (diffuse gas), $HC_3N$ (hot molecular core), and SiO (shock).

***References*** [1] Lu, X., Zhang, Q., Liu, H. B., Wang, J., Gu, Q. 2014, ApJ accepted, arXiv:1405:7933 [2] Rathborne, J. M., Jackson, J. M., & Simon, R. 2006, ApJ, 641, 389 [3] Rathborne, J. M., Jackson, J. M., Zhang, Q., & Simon, R. 2008, ApJ, 689,1141 [4] Swift, J. J. 2009, ApJ, 705, 1456

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