High Mass Star Formation Studied through IRDCs

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Abstract

One of the open questions in stellar astrophysics is the formation of massive young stars. Two models best explain how massive protostars grow: the turbulent core and the competitive accretion models. However, the fast timescale of these objects and the distance of the massive protostar formation regions make it difficult to find them and get observational constraints that favour one or another model. In this context, the Infra-Red Dark Clouds (IRDC) are crucial sources for understanding the process. The IRDCs are composed of many cores of dust condensations and low-temperature dense gas, named dark because they appear as dark compared to the galactic Infrared background emission. This project aims to explore the ALMA archive by searching for molecular emissions in clumps of the IRDCs, constrain the temperature and column density as well as identify possible targets for future studies of massive star formation. We looked at two surveys consisting of five total sources. We found outflows and many sources with molecular line emission.

1 Introduction

It is well known that star formation occurs through the gravitational collapse of cold gas (Yorke & Sonnhalter 2002). The collapsing gas will begin to form a sphere called a protostar (e.g., Schneider & Arny 2015; Yorke & Sonnhalter 2002). This protostar will continue to collect infalling gas; getting more dense, hotter, and spinning faster (e.g., Schneider & Arny 2015; Yorke & Sonnhalter 2002). Eventually, the protostar will reach the temperature to fuse hydrogen into helium at its core. Once this stage occurs, stellar winds will push the remaining gas away from the object, and a star is born (Schneider & Arny 2015). However, this explanation for star formation might only apply to low-mass stars (Beuther 2007). The reason for this is due to the difficulty of studying the early stages of high-mass star formation (Kong 2017). Contrary to its low mass counterpart, high-mass stars are further away, evolve faster, and change the molecular cloud they originate from (Kong 2017). However, research has led to two models for the beginning stage of high-mass star formation.

One model for star formation is called the turbulent core model. This model states that, much like low-mass stars, high-mass stars form from a single accreting object. However, the core experiences turbulent motion that increases systematically with radius (e.g., Caselli & Myers 1995; Mckee & Tan 2003). These turbulent cores will lead to an increase accretion rate with time (e.g., Caselli & Myers 1995; Mckee & Tan 2003). This property, coupled with dense gas, will be able to form a protostar massive enough to develop into a high-mass star (e.g., McLaughlin & Pudritz 1997; Mckee & Tan 2003). The second model for high-mass star formation is the accretion model. Unlike the turbulent model, the accretion model states that the high-mass stars form from the combination of multiple accreting objects (Beuther 2007). Firstly, anywhere from 50 to 90 percent of stars form in clusters (Lada et al. 1991). Secondly, these clusters are shown to harbor both low and high-mass stars (e.g., Hillenbrand 1997; Bonell et al. 2001; Wang et al. 2010). Leading to the idea that if multiple low-mass stars form in a region close to one another, then they could combine to form a high-mass star. Yet in order to study these models, we need to observe regions in which high-mass stars could form. One such region is an Infra-red Dark Cloud

IRDCs were first discovered in 1996 by the Infrared Space Observatory (Perault et al. 1996), IRDCs are seen as dark silhouettes on an otherwise bright infrared background. The reason IRDCs are excellent candidates for high-mass star formation is that observations tells us they are very cold and very large (Egan et al. 1998). Molecular gas needs to be cold in order to collapse under gravity (Schneider & Arny 2015). Furthermore, there also need to be an abundance of gas in order to form such massive objects (Ahli 2022). Because of their
temperatures, the thermal emission peaks at the submillimeter range. So, although those sources are fainter, the best chance of detection is with a high-frequency radio observation. That is why we focus on data obtained with the ALMA radio telescope.

The Atacama Large Millimeter/sub-millimeter Array (ALMA) is a series of baseline radio telescopes consisting of 66 antennas with 12 meter dishes that operates at frequencies from 84 to 950 GHz. Therefore, this radio observatory is crucial for the observation and study of IRDCs. ALMA started its operation on 2011 and since then many IRDCs have been observed, eventually, with molecular lines been identified. So, the ALMA public archive is a rich database where researchers can explore those sources carefully. All data obtained with ALMA became public after one year of being delivered to the principal investigator. This works explores the IRDCs at the archive data.

2 Goals

The goal of our research was to explore the ALMA archive to find molecular lines in clumps localized in the IRDCs. These lines would then be used to constrain properties of regions that could harbor high-mass stars, like temperature and column density. Finding values for these properties could also help identify outflows and constrain the nature of those forces. Moreover, knowing these properties could allow us to characterize the stages of the IRDC to understanding the evolution of the cloud. This knowledge would then be used to try and understand the early stages of high-mass star formation. To try and achieve these goals, we studied individual sources from two different ALMA surveys.

3 Data and Data Analysis

For our research, we chose to look through this archive to find sources that could contain molecular lines. The two surveys where our data was taken was the ASHES and ATOMS survey. The ALMA Survey of 70 \(\mu\)m Dark High-mass Clumps in Early Stages (ASHES) was a survey originally designed to characterise the earliest stage and constrain theories of high-mass star formation (Sanhueza 2019). Since this survey’s goals align well with our research goals, we knew this survey would be excellent to look into. This survey also consisted of 12 target sources with 301 clumps. Moreover, observations of this survey was taken in band 6 (211-275 GHz) with a one arc-second resolution. The source that our research studied was IRDC G28.273-0.167. The ALMA Three-Millimeter Observations of 146 Massive Star-Forming Regions (ATOMS) was the next survey we studied. This survey also had a total of 453 compact cores, selected from a previous CS(Carbon Monosulfide J=2-1) single dish survey that was done through SEST (Swedish-ESO Submillimetre Telescope) in the 90s (Bronfman et al. 1996). By now, using ALMA, we can conduct a better analysis of the data due to higher space resolution. Furthermore, observations were taken in band 3 (84-116 GHz), and used both seven meter and twelve meter configurations. However, our research focused on twelve meter data, as this offers better resolution. Lastly, four sources were taken from this survey to use in our research. One thing to mention is that the cleaning process for this source was a difficult task. Unfortunately, this lead to some artifacts in the cube emission from the ASHES survey, which appear as parallel lines. This difficulty led us to explore more sources in the ATOMS survey rather than continuing with more sources in the ASHES survey.

4 Results

To image the data, we chose to pick four spectral windows to clean the continuum. This led to a total bandwidth of 2.0 GHz for the ASHES source and 1.8 GHz for the ATOMS sources. Once the continuum was clean and subtracted, a script was ran to clean the cube with a threshold of 10 mJy. The source from the ATOMS survey will be shown with the continuum image. While each cube image from the ATOMS will be shown with the brightest channel and the continuum contours outlined in black. Each corresponding spectra will be taken at the brightest source in the image.

4.1 ASHES Survey

We will first start describing our results relative to the analysis of a source from the ASHES survey, identified as IRDC G28.273-0.167.
The spectra in Figure 2 was taken in the region indicated by the red box in the image in Figure 1. IRDC G28.273-0.167 has a spectrum that peaks at 250 \( \mu \text{Jy/beam} \), corresponding to \(^{18}\text{C} \text{O} \) (Carbon Monoxide).

By looking closer at the spectrum, we find three lines of emission which we interpreted as \(^{18}\text{C} \text{O} \) outflows occurring at different velocities. Indeed, Li et al. 2020 also reported CO outflows in this source, also occurring at different velocities. Therefore, it is probably that we also have different velocities with \(^{18}\text{C} \text{O} \).

By changing the region where the spectra-graph is taken, indicated by the orange box in Figure 1, we also discovered an emission of \(^{18}\text{C} \text{O} \) peaking at 125 \( \mu \text{Jy/beam} \) and an absorption feature corresponding to 70 \( \mu \text{Jy/beam} \). This absorption feature is similar to a P-cygni profile, meaning that this source could harbor a gaseous envelope moving away from the source. This profile means that this region contains contraction (Israelian & Groot 1999).

4.2 ATOMS Survey

One of the clumps explored in an IRDC from the ATOMS survey has already detected many molecular emissions (Liu et al. 2021). We have used it as a reference to identify the molecular transitions we found in other sources. In Figure 6, we show this reference spectrum reported by Liu et al (2021).

Notice that even if we do not detect so many molecular lines as shown in Figure 6, since we are looking at the same frequency range, it is a good template to follow. Source I18089 - 1732 contained a promising amount of molecular activity.
We find bright CS emission of around 120 \( \mu \)Jy/beam as well as SO (Sulfur Monoxide J=2-1) emission of 100 \( \mu \)Jy/beam. We also see emissions of \( \text{C}_2\text{H}_5\text{CN} \) (Ethyl Cyanide J=10-9) and \( \text{CH}_3\text{OCHO} \) (Methyl Formate) which both correspond to 20 \( \mu \)Jy/beam. However, we also see a single emission of \( \text{CH}_3\text{OCH}_3 \) (Dimethyl Ether).

Since \( \text{CH}_3\text{OCH}_3 \) is a complex molecule, we expect to see multiple emissions at multiple frequencies in our spectra, yet in our finding we only see one. One more thing to note is that multiple molecular transitions could mean that this source contains a protostar. In order to fully understand this source, closer analysis is needed.

Our next source, I18079 - 1756, is far more simple in terms of molecular abundance compared to the last source.

We find the repeated emissions of CS and SO, this time at 90 and 20 \( \mu \)Jy/beam respectively. Yet this time we also find a faint \( \text{C}_2\text{H}_5\text{CN} \) emission at 5 \( \mu \)Jy/beam. Our explanation is that there could be other \( \text{C}_2\text{H}_5\text{CN} \) transitions hidden beneath the noise threshold of the spectra, making it undetectable. Making this source another candidate for further analysis.

The third source, I18110 - 1854, separates itself from the previous two sources by having an absorption emission corresponding to CS.

We also find a faint SO emission of 5 \( \mu \)Jy/beam as well as \( \text{C}_2\text{H}_5\text{CN} \) and \( \text{CH}_3\text{OCHO} \) at around 10 \( \mu \)Jy/beam. However, we also detected a large emission from \( \text{C}_2\text{H}_5\text{OH} \) (Ethanol) corresponding to 50 \( \mu \)Jy/beam. Since 99 GHz was not covered in Liu et al. spectrum of this source, we had to find what molecule could correspond to this frequency. While many transitions take place at 99 GHz, we believe the best candidate for this emission is \( \text{C}_2\text{H}_5\text{OH} \). However, a large peak from \( \text{C}_2\text{H}_5\text{OH} \) is not a common phenomenon.
The last source explored was I18116 - 1646.

Figure 14: I18116 - 1646 Cube Image

Figure 15: I18116 - 1646 Spectra

We again see a CS and SO emission at 60 and 20 µJy/beam. We also find emissions from C$_2$H$_5$CN and C$_2$H$_5$OH corresponding to 5 µJy/beam. Again, the problems relating to C$_2$H$_5$CN and C$_2$H$_5$OH are present in this spectra, and further analysis needs to be done to fully understand this source.

5 Conclusion

For source G28.273-0.167 in the ASHES survey, we find different C$^{18}$O emissions occur at different velocities. This could mean that the this source has C$^{18}$O outflows. Furthermore, an area of this source contains a P-cygni profile. Leading to the idea of contracting gas. However, due to artifacts in the image due to cleaning challenges, further analysis of this source needs to be conducted. Source I18089-1732 from the ATOMS survey revealed a plethora of complex molecular emissions. Such emissions included CS, SO, C$_2$H$_5$CN, CH$_3$OCHO, and CH$_3$OCH$_3$. The last of these emissions being subject to question due to the singular emission rather than multiple emissions. Our idea for this source is that the abundance of complex molecules means this source could harbor a protostar. Yet further analysis is required to verify that claim.

Source I18079-1756 showed fewer complex molecular lines compared to the previous source, but still contained emissions worth discussing. We again see emissions from CS and SO. However this time, we also find a singular emission of C$_2$H$_5$CN. Our interpretation is that this source contains multiple C$_2$H$_5$CN emissions, yet they are hidden behind the noise threshold of the spectrum. The source I18110-1854 contains emissions from SO, C$_2$H$_5$CN, and CH$_3$OCHO. However we also find an absorption feature corresponding to CS and emissions at 90 GHz. While many complex molecules could be responsible, we find that C$_2$H$_5$OH is the best fit for this emission. Yet, C$_2$H$_5$OH emissions as high as the one in our data is fairly rare to see. Leading to this source needing further analysis.

Lastly, source I18116-1646 showed emissions from CS, SO, C$_2$H$_5$CN, and C$_2$H$_5$OH. Earlier issues such as lack of C$_2$H$_5$CN and C$_2$H$_5$OH emissions are also prevalent in this source. Later in this research, we plan to explore how the spectra changes throughout the source. Doing this will allow us to reveal how the properties of the cloud change. Next, we want to create a rotational diagram using the emissions from source I18089-1732. This would constrain temperature, allowing us to understand a new property of the source. More broader goals include analyzing more sources form the surveys and the ALMA archive. The data present in this survey is only a small fraction of the data ALMA has to offer.

Finally, more properties of our sources need to be constrained in order for us to better understand the details of the cloud. As more details are found within these sources, so does the knowledge of the early stages of high-mass star formation.

6 References


Egan, M. P., Shipman, R. F., Price, S. D., Carey,


