

The Dust to Ice Ratio Varies Among and Within Interstellar Clouds

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ABSTRACT

Cold molecular clouds host some of the best conditions for the formation of interstellar ice as CO freezes out of the gas phase onto dust grains. These icy mantles provide an important environment for the chemical reactions that create large organic molecules. The Central Molecular Zone (CMZ) hosts cold molecular clouds in an extreme environment where the gas is warmer, more turbulent, and a higher irradiation than the disk. Here we present JWST observations of molecular clouds associated with the CMZ dust ridge, a stream of gas and dust thought to be passing in front of the nuclear stellar disk. We measure the CO ice column densities toward these clouds and find that the relative amounts of ice and dust vary from cloud to cloud. We find that the variations in some clouds can be explained by the clouds being foreground to the CMZ, because the variations in ice measured toward foreground clouds are dominated by radial Galactic variations in metallicity. However, other clouds are thought to be within the same quadrant of the CMZ, and yet have measurable variations. We test different explanations for the differences seen in CO ice column densities among clouds and find that differences in the composition of gas are the most likely option.

1. INTRODUCTION

Interstellar ice forms as molecular gas freezes onto dust grain surfaces. Molecules in these ices have a complex chemistry, which helps drive the formation of complex molecules (E. Herbst & E. F. van Dishoeck 2009). Cold molecular clouds host some of the best conditions for ice grain growth, because they are cold ($T \leq 20$ K T. Pillai et al. 2006) and dense ($n_H \geq 1 \times 10^4$ cm⁻³ M. J. Butler & J. C. Tan 2012) regions of the interstellar medium (ISM). These properties make cold molecular clouds the sites of catastrophic freezeout of CO (A. K. Hernandez et al. 2011; C. Gainey et al. 2022; S. D. Clarke et al. 2024; G. Cosentino et al. 2025). Cold molecular clouds are also thought to be the progenitors to massive star formation (J. Kauffmann & T. Pillai 2010; J. M. Rathborne et al. 2010).

Common molecules that freeze onto dust grains include H₂O, CO, NH₃, and CO₂. The solid states of these molecules have absorption features throughout near-infrared wavelengths, making JWST key to observing interstellar ices. JWST NIRSpec observations of the Chameleon molecular cloud reveal the relative abundances of molecular species (M. K. McClure et al. 2023),

while a survey toward a protostellar object in the cloud identified numerous other ice species (W. R. M. Rocha et al. 2024).

Interstellar ices play an important role in astrochemistry, as the icy mantles of dust grains act as a catalyst for solid-phase chemistry that builds more complex molecules. Nitrogen-bearing ices such as ammonia (NH₃) and OCN⁻ are thought to be precursors to the formation of pre-biotic molecules such as amino acids, which have been detected on interstellar bodies in samples from comets (Stardust) and asteroids (OSIRIS-REx, Hayabusa2). Both NH₃ and OCN⁻ ices are detected in the near infrared with JWST toward molecular clouds (M. K. McClure et al. 2023; W. R. M. Rocha et al. 2024). NH₃ and OCN⁻ are both directly involved in the formation of isocyanic acid (HNCO) (R. L. Hudson et al. 2001; G. Fedoseev et al. 2015), which has not been detected in its solid phase in the ISM (G. Fedoseev et al. 2018), is rarely detected in its gas phase in the disk of the Galaxy, but is strongly detected in gas emission toward the Galaxy’s center.

The Galactic Center’s Central Molecular Zone (CMZ) is a region of dense, warm, turbulent molecular gas (A. Ginsburg et al. 2016) at the center of the Galaxy. The CMZ is thought to be somewhat ring-like, with a radius of ~ 100 pc. Recent studies of molecular clouds associated with the CMZ investigate its structure by placing clouds

either on the near or far side of the CMZ by matching infrared extinction measurements to far-infrared emission (D. Lipman et al. 2025). Additional observations of the CMZ at different wavelengths have been incorporated to reveal that the gas likely orbits the center on several approximately elliptical orbits at a range of radii (D. R. Lipman et al. 2026). Forefront in studies of the structure of the CMZ are the dust ridge clouds, which are a stream of infrared dark clouds thought to be on the near side of the CMZ due to how they block light from the nuclear stellar disk, appearing silhouetted against its light.

The CMZ is home to uniquely widespread chemical enhancement not seen elsewhere in the Galaxy (M. A. Requena-Torres et al. 2006, 2008; P. A. Jones et al. 2012). One potential driver of this chemistry is the CMZ’s high cosmic-ray ionization rate (CRIR), which is higher in the CMZ (N. Indriolo et al. 2015) likely due to the abundance of supernova remnants and presence of extreme, high energy sources like Sgr A*. Cosmic rays drive gas-phase chemistry and the build of complexity in interstellar ices in the shielded centers of molecular clouds, as they are able to pierce through dense material shielded from UV radiation and provide a source of energy for reactions (B. A. L. Gaches & S. Viti 2026).

Another potential driver of chemical enhancement are the thermal properties of the gas and dust in the CMZ. While the gaseous material of molecular clouds in the CMZ is warm and turbulent, the dust temperature in the CMZ is decoupled from the gas temperature (P. C. Clark et al. 2013), meaning that CMZ dust is cold (T_d varies between ~ 12 to 35 K) (S. N. Longmore et al. 2012; C. Battersby et al. 2025; Y. Tang et al. 2021a,b). These temperature conditions in CMZ clouds create ideal conditions for molecules to freeze onto the icy mantles of dust grains (C. N. Shingledecker et al. 2024), as high gas temperatures create more encounters between gas phase molecules and dust grains, while cold dust temperatures make it more likely that the molecules stick to their surfaces.

2. DATA

2.1. Observations

We observe the Galactic Center’s Central Molecular Zone (CMZ) with JWST NIRCам as part of GO program 2221, which observed with filters F182M, F187N, F212B, F410M, F405N, and F466N. This program observed various Infrared Dark Clouds (IRDCs): the brick (G0.253+0.016), dust ridge cloud C (G0.380+0.050), dust ridge cloud D (G0.412+0.052), a foreground filament (G0.342+0.024). Alongside these major clouds, we also observe inter-cloud regions and minor clouds whose locations in the Galaxy are unknown.

We use the ACES ALMA large program (S. N. Longmore et al. 2026; A. Ginsburg et al. 2026; D. L. Walker et al. 2026; X. Lu et al. 2026; P.-Y. Hsieh et al. 2026) data cubes for spectral line information.

2.2. Cataloging

The data reduction and stellar cataloging methods for the JWST data used in this paper are as previously described in S. Gramze et al. (2026b), and are available as a dataset at (S. Gramze et al. 2026a). The sole difference is that we improve the accuracy of the catalog by including only magnitudes with errors ≤ 0.05 instead of 0.1.

For every star in the catalog, we measure its dust extinction A_V with $[F182M] - [F212N]$ using the following equation,

$$A_V = \frac{[F182M] - [F212N]}{\text{ext}(1.82 \mu\text{m}) - \text{ext}(2.12 \mu\text{m})} \quad (1)$$

where **ext** is the extinction law from J. E. Chiar & A. G. G. M. Tielens (2006).

2.3. Red Clump Selection

We select red clump (RC) stars for further analysis. The RC is a population of stars all with nearly the same intrinsic luminosity and temperature. Because of this, their color is nearly constant, thus any deviation in their observed color can be attributed to variations in the ISM in front of the stars and not their intrinsic colors.

We select the RC by plotting the stars in $[F182M] - [F212N]$ vs $[F182M]$ color-magnitude space and selecting for RC stars by identifying the dense, diagonal distribution of stars above the RGB stars. These are RC stars made redder by dust extinction (F. Nogueras-Lara 2022). RC stars not detected in the F182M and F212N bands are not included in this selection. This selection does not exclude non-RC stars that happen to be in the same color-magnitude space as the RC, but it is expected that most foreground interlopers, as in stars in the foreground intrinsically red in this color, are removed via this method.

2.4. Region Selection

We separate the data spatially by manually drawing regions around each area of interest. We decided to select regions with manual selections instead of sampling the data in a grid because of limitations on how small a region can be before there are too few stars to make conclusions about it. Each region is shown in the top left panels of Figures 2 and 3. Perturbations in the boundaries of these regions cause shifts in measurements in agreement with their error bars. Regions targeting infrared dark clouds

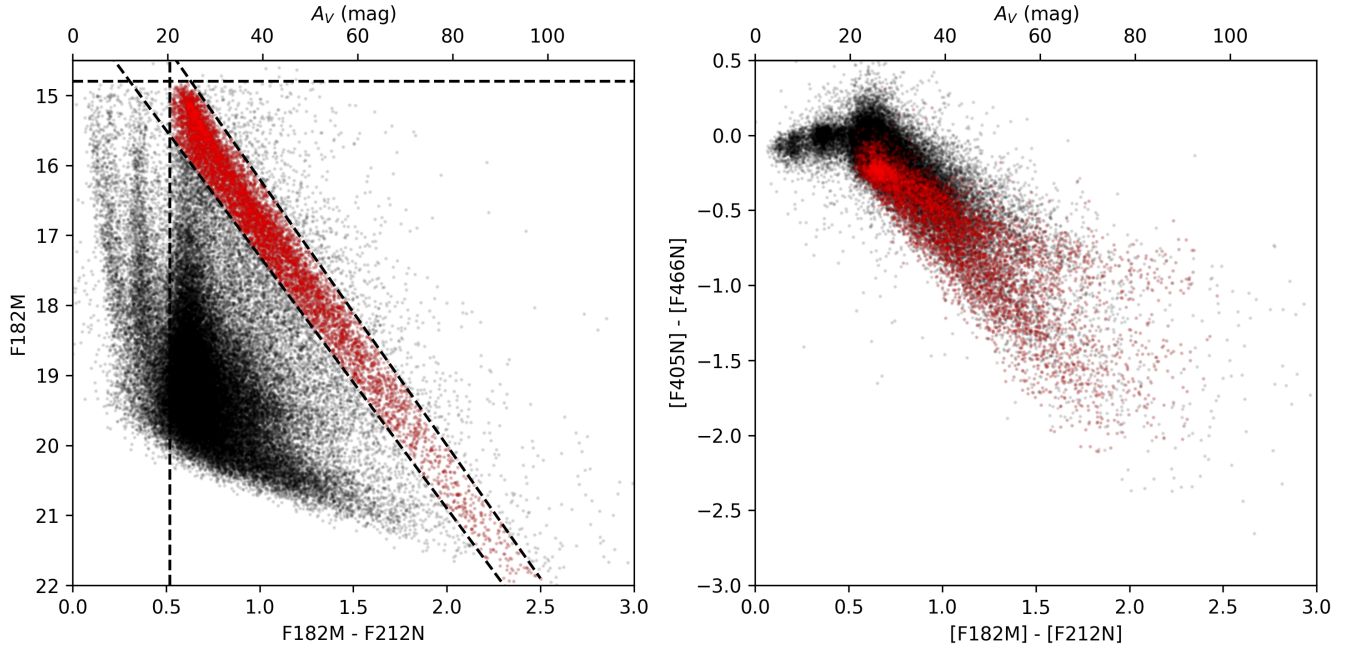


Figure 1. Color-magnitude and color-color diagrams showing the selection of red clump stars in the cloud C data. The black points are all of the stars in the field, while red points are the selected red clump stars. The dashed lines represent filters on the data to select for red clump stars.

were selected based on their extent in the F405N image and Spitzer GLIMPSE I4 and their line of sight velocity in ACES CS 2–1 and D. L. Walker et al. (2025)’s HNC O ($4_{0,4} - 3_{0,3}$) and H₂CO ($3_{0,3} - 2_{0,2}$). Additional regions were created to fill in the spaces between cloud selections.

Cloud C was separated into two parts, Cloud C1 and Cloud C2, as C1 has a central velocity of $\sim 40 \text{ km s}^{-1}$, and C2 has a velocity closer to 10 km s^{-1} (D. L. Walker et al. 2025). They also have distinct, separate centers where extinction causes stars to drop out. As there seems to be two different, spatially separated velocity components, we separated these two regions. Cloud D, which has a line of sight velocity of $\sim 10 \text{ km s}^{-1}$ (D. L. Walker et al. 2025), was also selected as its own distinct region. All three of these clouds are close to each other on the plane of the sky and are associated with the CMZ’s dust ridge (D. C. Lis et al. 1999).

The Filament region was selected for the presence of a filamentary IRDC with a line of sight velocity of -55 km s^{-1} , firmly associating it with the 3 kpc arm (S. Gramze et al. 2026b). The area between the Filament and Cloud C1 has been left unselected due to potential confusion between stars associated with the two clouds.

The Cloud B region does not refer to the main part of dust ridge cloud B, which is outside of the JWST footprint, but a spur off of it that is dark in F405N and Spitzer I4. This cloud could be part of dust ridge cloud B, or a coincidental association. It has a multi-component

spectrum in CS 2–1, making it difficult to pin down a line of sight velocity concretely associated with the cloud.

The rest of the regions in the Cloud C JWST pointing fill in the areas between the clouds. Filament Right encompasses the area to the right of the Filament and Cloud B regions. This region includes a Br α emission filament most likely associated with an HII region and/or ionized gas, but without a clear origin star or stellar cluster exciting it. Left Cloud D refers to a region off to the side of Cloud D, which lacks evidence of the presence of a cloud. Cloud C South is the region between Cloud D, Cloud C, and the Filament. Just outside of this region beyond the field of view of the NIRCcam footprint is an HII region, G0.381+0.017. Cloud C North is the region between Cloud C, the Filament, and Cloud B. These four regions do not select for obvious IRDCs, but it is possible that there is dense, molecular material along the line of sight deeper into the CMZ.

For the Brick NIRCcam data, the main body of the Brick was separated into Brick North and Brick South because of its size and based on the multiple velocity components of the cloud detailed in J. D. Henshaw et al. (2019). Brick South roughly corresponds to the “D” ($\sim 33 \text{ km s}^{-1}$) component and Brick North to “A” ($\sim 3 \text{ km s}^{-1}$). Brick Head, South Fluff, and Brick North Fluff were also separated into their own distinct regions from the Brick as

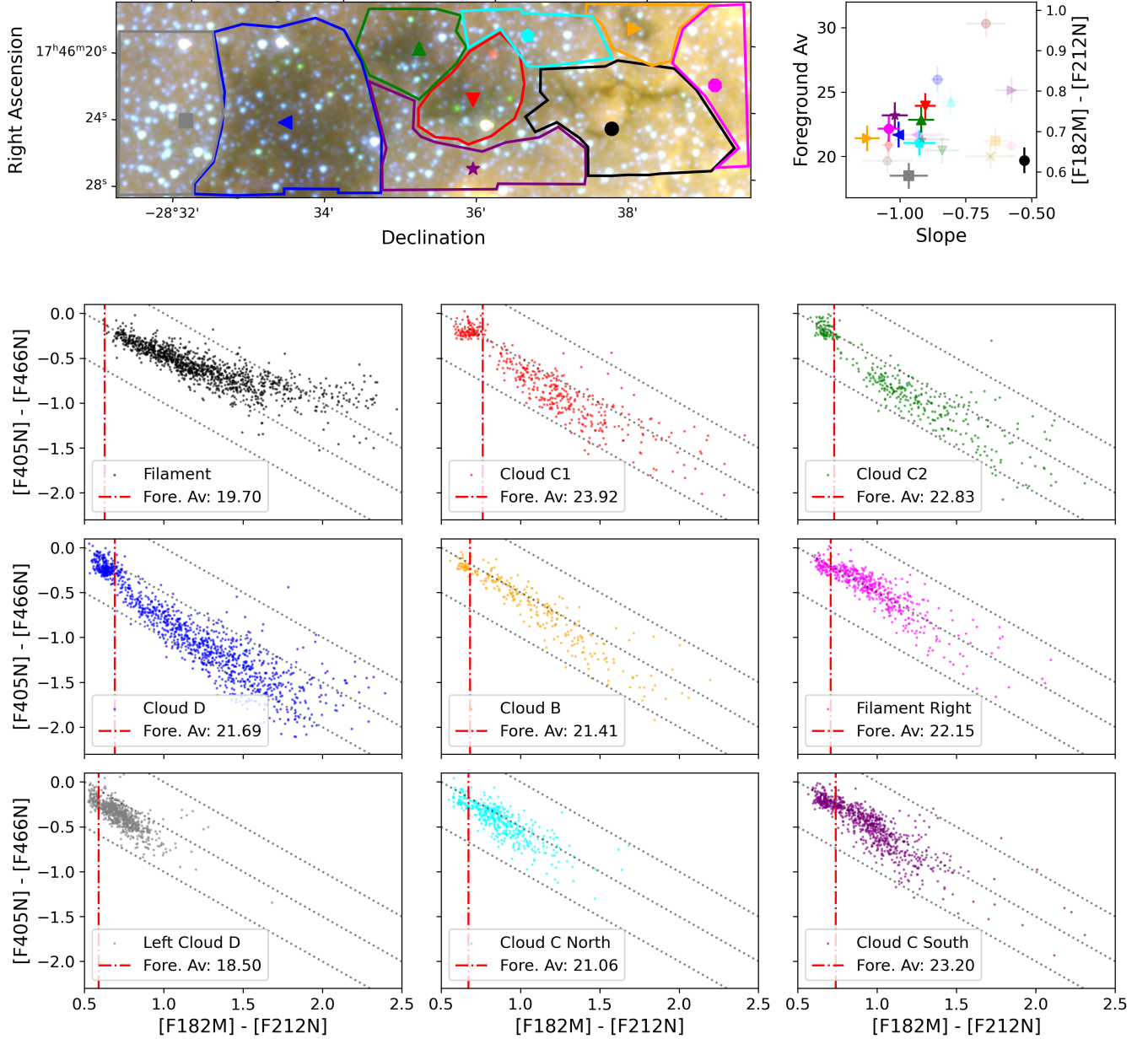


Figure 2. Cloud definitions and red clump star colors for the JWST Cloud C region. Top Left Panel: The spatial selection for the nine regions within the Cloud C region as described in Section 2.4 overlaid over a Spitzer GLIMPSE image of the surveyed region (E. Churchwell et al. 2009; GLIMPSE team 2020). Top Right Panel: Slope versus foreground A_V measurements for every region as described in Section 3.2. Points associated with the Brick region are made transparent. Bottom nine panels: The measured colors of red clump stars spatially associated with each region indicated in the top panel. The dot-dashed red line represents the measured foreground A_V for each region. The grey, dotted lines each have a slope of -1 and have intercepts spaced 0.5 apart.

they both have reddened stars, but do not have the same drop out of extinguished stars at their centers.

The Brick SFR and Brick SFR Wide regions select for a high mass star formation region (HMSFR) G0.207+0.001 spatially separated from the Brick. This HMSFR has an HII region, an IRDC, and a line of sight velocity of $\sim 40 \text{ km s}^{-1}$. Brick SFR Wide encompasses Brick SFR,

which is a small region selecting for only the IRDC. Brick SFR Wide expands around it to include what seems to be a cluster of stars associated with the HMSFR, but as a consequence includes background stars associated with the CMZ.

The Brick Claws region selects for a rough area surrounding three small, narrow IRDCs with line of sight

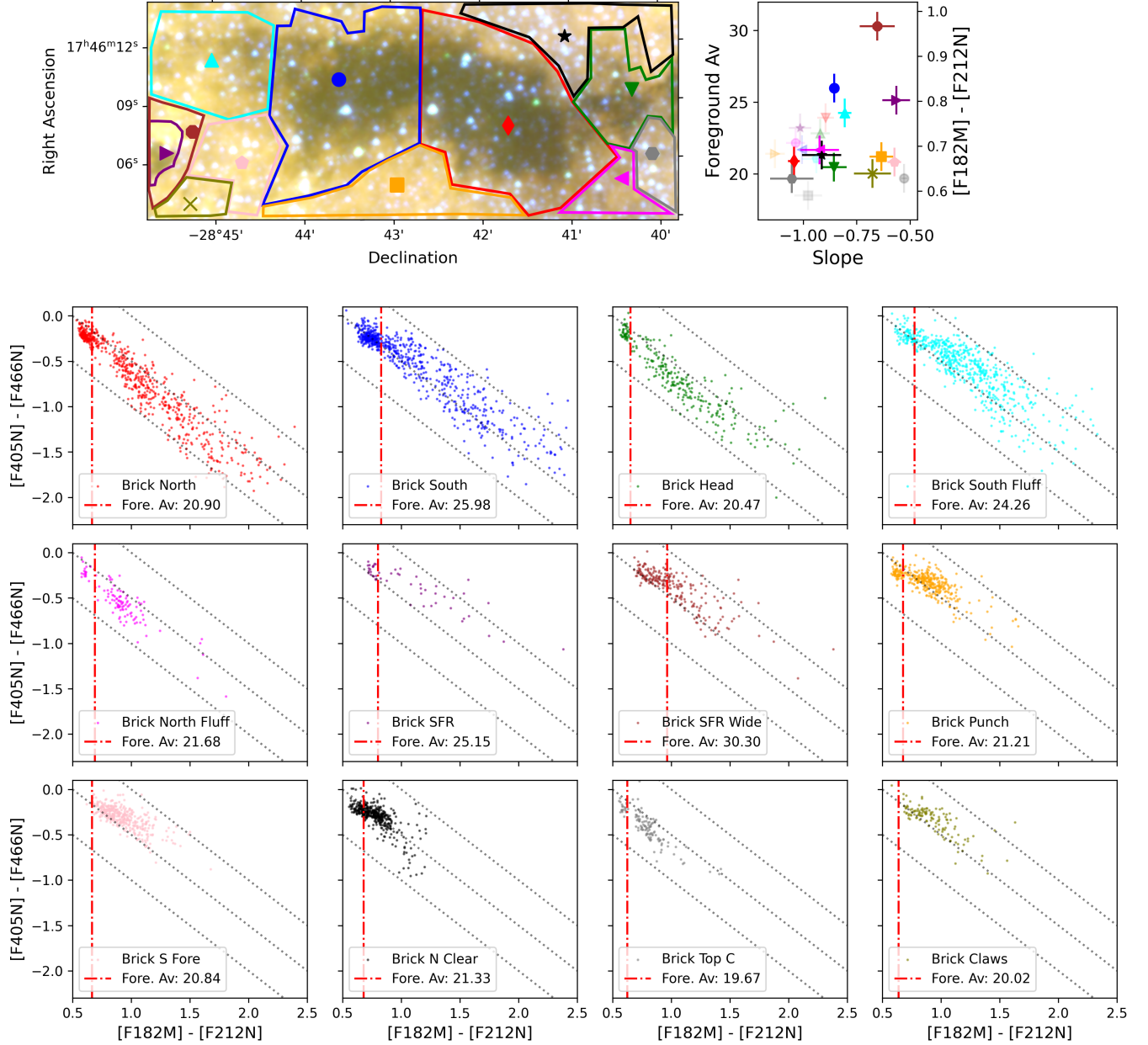


Figure 3. As Fig 2, but for the twelve regions identified within the Brick region. Top Right Panel: Slope versus foreground A_V measurements for every region as described in Section 3.2. Points associated with the Cloud C region are made transparent.

velocities of $\sim 18 \text{ km s}^{-1}$. Because of how small these features are on the plane of the sky, most of the stars within the region are between the IRDCs and do not trace them.

Brick S Fore, Brick Punch, Brick N Clear, and Brick Top C are all regions filling in the spaces between clouds.

3. RESULTS

3.1. Color-Color Diagrams

We plot color-color diagrams (CCDs) for each region, which are shown in the bottom panels of Figures 2 and 3. The horizontal axes of these plots are $[F182M] - [F212N]$,

and the vertical axes are $[F405N] - [F466N]$. The horizontal axes trace dust extinction, and the vertical axes trace ice absorption where $[F405N] - [F466N]$ becomes bluer when stars are behind more ice. The filter F466N overlaps with a substantial CO ice feature (A. Ginsburg et al. 2023; S. Gramze et al. 2026b; A. Ginsburg et al. 2026) that dominates the color plotted. The amount of CO ice absorption increases with dust extinction.

Each plot is overlaid with grey, dotted lines to show the differences between each panel. By comparing the distribution of stars in the CCDs with the lines, it becomes clear that the relationship between dust extinction

and CO ice differs between different lines of sight. For example, there are stars in the dust ridge cloud D region with measurements below the lowest line, while the stars in the dust ridge cloud C regions tend to stay above. Checking against the whole catalog, not excluding stars that are not RC stars, the CO ice feature seems to only affect stars with dust extinctions of $A_V \gtrsim 17$.

Every region, including the ones between obvious IRDCs, seem to be impacted by ice absorption. This is discussed further in Section 4.

3.2. Linear Fitting

To better compare the dust extinction versus CO ice relationship in color-color space, we fit each color-color diagram with a line. First, in this analysis and the plotted CCDs, we use only the RC clump stars selected as described in Section 2.3. Next, we fit a histogram of the dust extinction A_V of each region with a bimodal Gaussian distribution using `scipy.optimize.curve_fit`. For each region, we fit one Gaussian component to the “foreground” and another to the “background” stars. These fits are shown in Appendix Figures 7 and 8.

We find either the intersection between the two Gaussian components or the minimum between the peaks and assign it to the foreground A_V for each region. By default, we use the intersection, but in cases where that intersection is too close to the center of one component or the Gaussian components do not intersect, we use the minimum instead. The minimum is not used by default due to some fits not having a minimum. We then use the intersection or minimum to measure the A_V for each region that ideally corresponds to where CO ice starts to impact the color of the stars. For regions like the Filament, where this fitting fails due to there being no separate “foreground” population, we fit the distribution of A_V with a single Gaussian and set the foreground A_V to the mean of the Gaussian minus $1.5 \times$ its sigma, which in this case corresponds to the start of the distribution of stars.

This foreground A_V represents the amount of dust extinction to the region. For the CMZ, the typical foreground A_V is 20 mag due to its distance and the material present in the spiral arms in front of the CMZ. RC stars are limited to the bulge in this sample due to saturation, so we are less sensitive to extinction features in the disk.

The bimodal and single Gaussian fits are shown in Appendix Figures 7 and 8. The “foreground” stars represent bulge and nuclear stellar disk stars in front of the source of dust extinction and ice absorption shifting the colors of the “background” stars, which are bulge and/or nuclear stellar disk stars embedded in or behind the clouds. Some of these distributions would be better

fit with more than two components, and a Gaussian may not be the perfect representation of the data, but for the purposes of identifying the foreground A_V for each region, we use this method. We attempted to apply a Gaussian mixture technique to the data, but it failed to effectively separate out foreground populations with too few stars as effectively as the manual fit, and it was more sensitive to gaps in the data at high A_V . These “gaps” in the data could represent additional extinction features along the line of sight.

Filtering out the “foreground” stars, we then fit the remaining stars with a linear least squares fit, including a bootstrap analysis with $N_{\text{repeats}} = 100$ to find the distribution of slopes. We then plot the mean of the bootstrapped slopes and foreground A_V in Figure 4. The error for the slopes is the standard deviation of the bootstrap fitted lines, and the error for the foreground A_V is a representative error bar of 1 magnitude of A_V .

Also included in the plot are vertical lines representing the slope in color-color space of different ice models (A. Ginsburg et al. 2026) assuming various CO abundances ($\text{CO}/\text{H}_2 = 1.6 \times 10^{-4}$ and 2.5×10^{-4}) and ice compositions with differing ratios between H_2O , CO, and CO_2 as an attempt to explain the variations.

3.3. CO Ice Column Density

We use the method described in A. Ginsburg et al. (2026) and S. Gramze et al. (2026b) to measure the CO ice column density for each star impacted by ice absorption. In short, we first model the impact of different ice column densities on the flux from stars using lab measurements of molecular ice opacities (CO (P. A. Gerakines et al. 2023), H_2O (R. M. Mastrapa et al. 2009), and CO_2 (P. A. Gerakines & R. L. Hudson 2020)) and stellar atmosphere models (R. L. Kurucz 1979). We assume an ice composition ratio for $\text{H}_2\text{O}:\text{CO}:\text{CO}_2$ of 10:1:1. We then remove the impact of dust extinction from our measurements of $[\text{F}405\text{N}] - [\text{F}466\text{N}]$ by measuring A_V with $[\text{F}182\text{M}] - [\text{F}212\text{N}]$, assuming the J. E. Chiar & A. G. G. M. Tielens (2006) Galactic Center extinction law. Using these de-extincted colors, we finally apply the modeled impact of the ice and measure its column density in CO.

Figure 5 shows the relationship between dust extinction A_V and CO ice column density $N(\text{CO Ice}) [\text{cm}^{-2}]$ for each region. Plotted over each panel are two curved lines showing the theoretical limit of the amount of CO ice observable in a cloud where 100% of the CO is in ice, assuming $N(\text{H}_2) = 1.1 \times 10^{21} A_V$ (T. Güver & F. Özel 2009), for different abundances of CO.

The solid line is for an abundance of 1.6×10^{-4} , the solar abundance of CO (J. H. Lacy et al. 2017), while

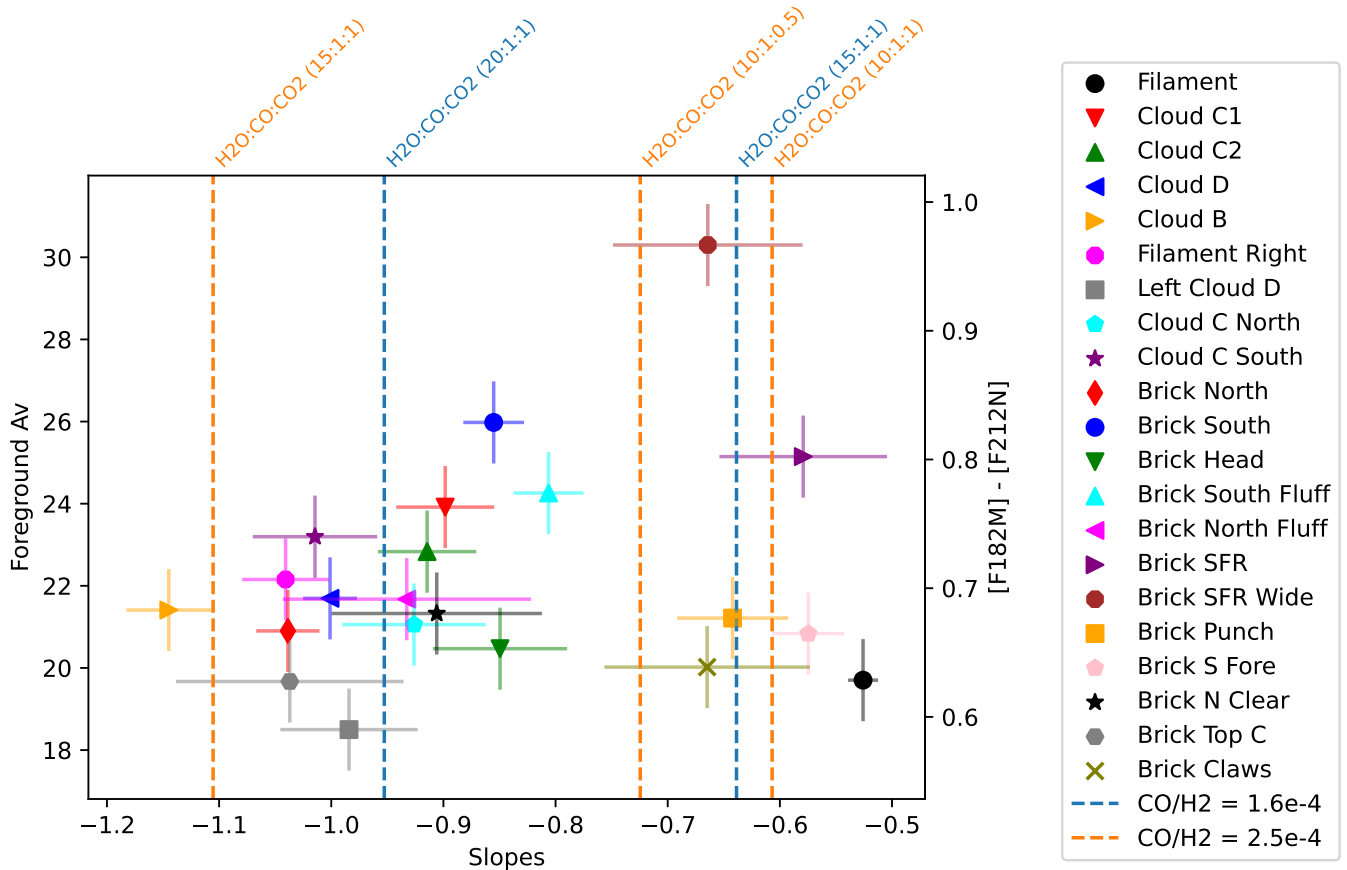


Figure 4. For each region, we identify the A_V where ice absorption starts to affect the color of the stars and then fit a line to the distribution of the stars at higher A_V in $[F182M] - [F212N]$ versus $[F405N] - [F466N]$ color-color space. This plot shows this fitted slope plotted against the measured A_V . The vertical error bar is a representative error of 1 mag in A_V . We also show the expected slopes for different modeled ice compositions at different CO abundances as vertical lines.

the dashed line is for an abundance of 5×10^{-4} . Other than in cases of catastrophic freeze out ($A_V \geq 9$ and $n \geq 10^5 \text{ cm}^{-3}$), the amount of CO in ice should not approach 100% and never surpass it. Despite this, as shown by nearly all of the RC stars in Figure 5, the CO ice column density measurements in our sample surpass the limit for solar abundances of CO, suggesting that these regions have a higher abundance of CO. However, such a high abundance of CO that suggests that there is either significant enrichment of carbon and oxygen, or we are missing a systematic factor. This is discussed further in Section 4.

4. DISCUSSION

As shown by Figure 4, the slopes representing relationship between CO ice column density and dust extinction vary from region to region, and from cloud to cloud. Even for clouds with similar foreground A_V , there is variation in the slope. We now discuss potential physical causes for this variation and the relative amounts of ice observed.

4.1. Ice is Ubiquitous in the CMZ

For all of the regions cataloged, there is evidence of CO ice impacting starlight. This threshold starts at $A_V \gtrsim 20$, which roughly corresponds to the amount of foreground extinction to the CMZ, implying that on these lines of sight, only stars in the bulge are impacted by ice absorption. As shown in the second panels of Figure 1 and Appendix Figure 6, the stars turn bluer on average in $[F405N] - [F466N]$ after reaching this threshold. Figures 2 and 3 show a breakdown of the RC stars for every region. In each region, even for those where there is no evidence of the presence of an IRDC, stars become bluer in $[F405N] - [F466N]$.

Ices such as H_2O form in a wide range of environments, but are thought to typically require high densities ($\geq 1 \times 10^3 \text{ cm}^{-3}$), low temperatures ($< 90 \text{ K}$), and weak interstellar UV radiation fields ($G_0 \leq 0.07$ at $A_V \geq 1.6 \text{ mag}$) (D. Hollenbach et al. 2009; A. A. Boogert et al. 2015). CO ice is expected to form deeper into clouds ($A_V \geq 3 \text{ mag}$) at higher densities ($n \geq 1 \times 10^5 \text{ cm}^{-3}$),

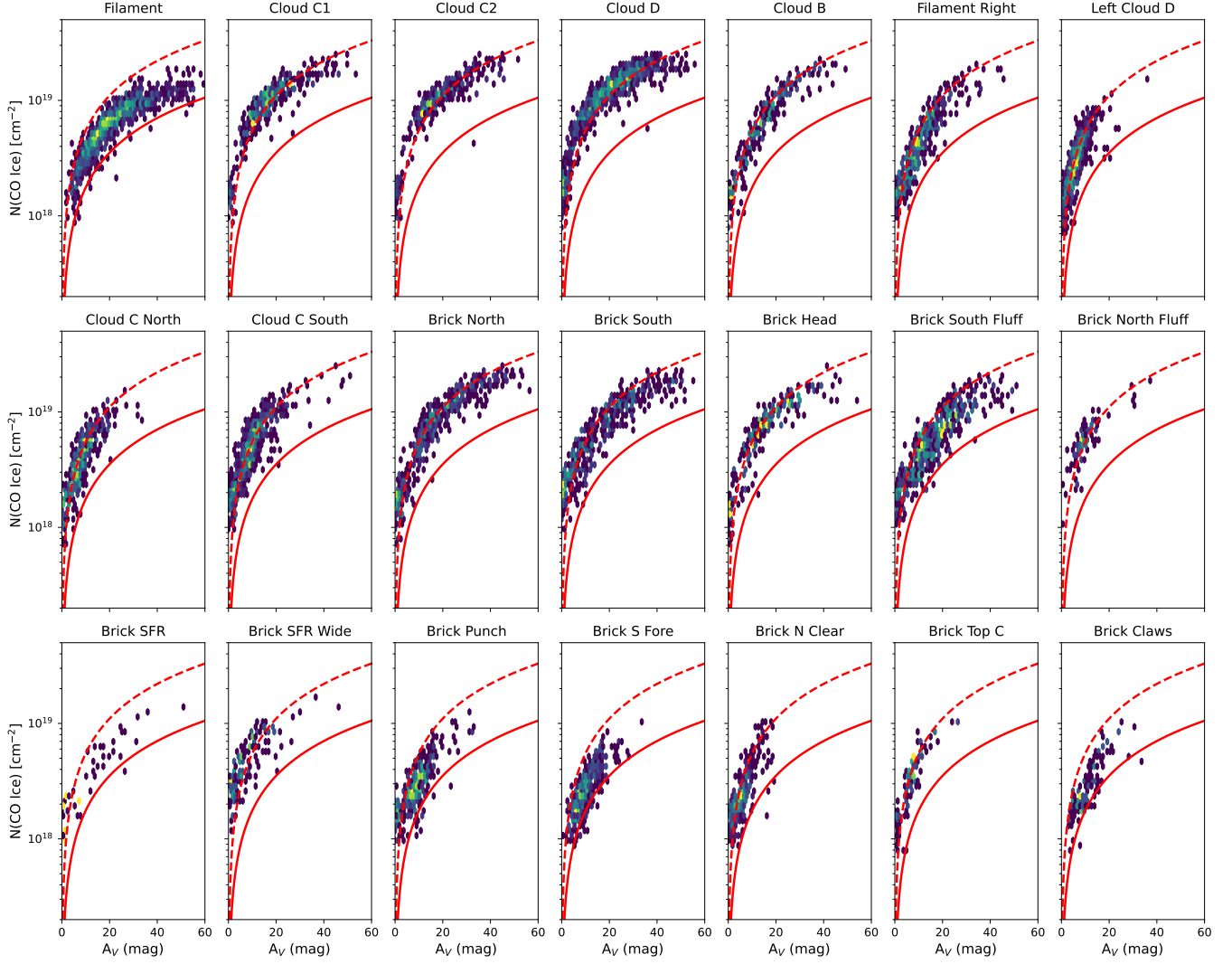


Figure 5. Each panel shows dust extinction versus CO ice column density for each red clump star. The A_V for each star is subtracted by the foreground A_V for the region it is associated with. Overlaid are red lines showing the theoretical maximum amount of CO ice, where 100% of the gaseous CO is in the ice phase. The solid red line uses the local $\text{CO}/\text{H}_2 = 1.6 \times 10^{-4}$ (J. H. Lacy et al. 2017), while the dashed line uses an elevated abundance of $\text{CO}/\text{H}_2 = 5 \times 10^{-4}$ that better fits many of the regions.

where the interstellar radiation field is weaker and dust temperatures are ≤ 20 K (A. A. Boogert et al. 2015).

We do not expect to see CO ice absorption along lines of sight without the cold, dense conditions required for it to freeze out of the gas phase. At lower N_{dust} , the dust temperature is warmer due to less shielding from ultraviolet radiation. The interstellar radiation field outside of giant molecular clouds is thought to be very high in the CMZ, a thousand times that of solar (P. C. Clark et al. 2013), which should easily heat the dust. As shown by dust temperature maps of the CMZ (Y. Tang et al. 2021a,b) and of specifically the Brick (S. N. Longmore et al. 2012), dust temperatures increase near the edges of clouds, so it is surprising that ice is detected outside of these clouds.

Why is CO ice so widespread in the CMZ? The threshold for CO ice formation is met throughout the regions surveyed.

One possible explanation is that cold dust still exists at low N_{dust} in the CMZ. The presence of so much CO ice along these lines of sight means that there must be cold dust present, as otherwise there would be nowhere to CO ice to form. Cold dust requires shielding from the UV radiation, which heats it. As CO ice forms at $A_V > 3$ mag, or about $\Delta([F182M] - [F212N]) \sim 0.1$, this level of shielding is possible in the regions probed. A possible explanation why this cold dust has not yet been detected by CMZ dust temperature maps is that to date, they have tended to use only a single temperature component. At low cold dust column densities, warm

dust dominates the spectrum, masking the cold dust. Instead of cold, dense blobs of self-shielding gas that are small on the sky, we see extended, widespread evidence of cold dust everywhere, which means that there is extended shielding of dust from UV radiation throughout these regions of the CMZ.

Another option, which does not exclude the previous possibility, is that our observations are picking up on the extended shells of the IRDCs. These extended shells are where there is little dust extinction relative to their interiors, but the conditions for CO ice to form still exist. Where exactly does CO freeze out begin and end in giant molecular clouds? What is their extent? How much of the CMZ do they fill? As long as we detect dust extinction in the CMZ, we detect CO ice, so this could mean that there is no CO ice edge in these clouds, or at least that our observations do not reach this edge.

Figure 11 of [A. Ginsburg et al. \(2026\)](#) shows the spatial distribution of stars in the Brick selected to have colors significantly impacted by absorption features from CO ice and what is most likely CH₃OH ice. It is difficult to compare the extents of the two ice species due to the differing field of views and sensitivity to the ice column. However, it is clear that the stars with colors impacted by CH₃OH ice become less frequent further away from the center of the Brick and eventually fall out of detection almost entirely. It is difficult to definitively make the same conclusion for CO ice, as stars impacted by it fill the entire field observed with F466N, but there is a radial trend of the ice column decreasing further away from the cloud. As CO ice requires less shielding than CH₃OH ice to form ([A. C. A. Boogert et al. 2011](#); [J. E. Chiar et al. 2011](#); [D. C. B. Whittet et al. 2011](#); [A. A. Boogert et al. 2015](#)), we would expect CO ice to be even more spatially extended than CH₃OH ice, thus explaining why it is detected throughout our observations.

Yet another explanation is that the cycle of ice formation is different in the CMZ, making CO ice show up in unexpected locations. The typical expectation is that the ISM goes through a cycle of contraction and expansion. Gas and dust is triggered in some way to gravitationally collapse, becoming dense enough for molecules to freeze out and then stars to form, which then cause the ISM to “reset” as feedback processes destroy dust grains, causing ices to disappear. However, in the CMZ, the same processes of star formation happen differently. [R. G. Tress et al. \(2025\)](#)’s findings show that stars decouple from their natal clouds of gas on much shorter timescales than in the disk. Gas is sheared away from massive stars, undergoing compression and expansion phases unrelated to star formation feedback. These simulations also show that gas sloshing around as it passes the perihelion point

of its orbit. If orbital timescales are fast enough, gas could be constantly being tossed and mixed enough that icy grains end up everywhere. Without the presence of massive stars nearby to irradiate and destroy dust grains, perhaps CO survives on dust grains outside of the densest environments.

Another possibility is that a different ice species starts to dominate the F466N band outside of the interiors of dense molecular clouds. However, while multiple ice species are thought to impact this band, none are thought to do so more than CO ice. The absorption from water ice, while abundant, is not concentrated in this band, and the affect CO₂ ice has on the spectrum is more impactful near F405N. The remaining ice species, OCN⁻, is thought to be far less abundant, and impact the spectrum far less than CO ice in current JWST observations of background stars in nearby star forming regions [M. K. McClure et al. \(2023\)](#). We discuss this ice species further in 4.4.

4.2. Variations Between Clouds

Figure 4 shows the measured slopes in [F182M] – [F212N] versus [F405N] – [F466N] color-color space plotted against the A_V where the starlight begins to be affected by CO ice absorption. Slope corresponds to the relationship between dust extinction and CO ice absorption as traced by F466N for each region. When we measure the slope for each region, we find that the slopes measured from region to region vary. There are two populations of measured slopes, shallow and steep, where regions such as the Filament have shallower slopes than Cloud C1 and Brick North. Other than the differences between shallow and steep slopes, there are variations in slope and foreground A_V among the steeper and shallower slope populations themselves.

The measured foreground A_V for each region varies from region to region but doesn’t necessarily match the relative line of sight distances to each cloud. The Filament has been shown to be associated with the 3 kpc arm, which is foreground to the CMZ ([S. Gramze et al. 2026b](#)), yet its foreground A_V is only a magnitude or two away from regions such as Cloud D or Brick North, which are thought to be in the CMZ. If A_V is correlated to distance, then these clouds would be nearly next to each other in space, which we know is not the case.

Variation in slope is in part correlated to the location of a cloud in the Galaxy. As shown in [S. Gramze et al. \(2026b\)](#) comparing CO ice in the Filament to the Chameleon I low mass star forming region ([Z. L. Smith et al. 2025](#)), and in CMZ clouds in [A. Ginsburg et al. \(2026\)](#), the amount of CO ice column density with increasing dust extinction differs broadly depending on Galactic radius, tracing CO abundance and gas metallicity. How-

ever, Galactocentric variations in CO abundance do not necessarily account for all of the variation observed, especially among clouds thought to be within the CMZ. In the next subsections, we explore potential causes of variation in the measured slope.

4.2.1. *Metallicity*

Previous results (A. Ginsburg et al. 2026; S. Gramze et al. 2026b) show that differences in the amount of CO ice column density versus dust extinction are related to differences in the abundance of CO, which is directly related to the metallicity of the gas (A. A. Boogert et al. 2015). As shown by Figure 4, the Filament region has a shallower slope than the regions associated with the CMZ. These differences, as traced by CMZ dust ridge clouds (A. Ginsburg et al. 2026) ($R_{\text{gal}} \sim 100$ pc), the 3 kpc arm Filament (S. Gramze et al. 2026b) ($R_{\text{gal}} \sim 3$ kpc), and the Chameleon I star forming region (M. K. McClure et al. 2023; Z. L. Smith et al. 2025) ($R_{\text{gal}} \sim 8$ kpc), trace a clear trend of increasing CO abundance with decreasing Galactic radius.

However, an initial inspection of our results shows that there is variation that may not be explained by simple differences in Galactic radius. The CMZ’s dust ridge clouds, the Brick, cloud B, cloud C, cloud D, and clouds E/F are all thought to be on the same side of the CMZ (J. D. Henshaw et al. 2023; D. Lipman et al. 2025), tracing gas passing in silhouette in front of much of the nuclear stellar disk. Despite this, as shown by Figure 4, each dust ridge cloud sampled shows a different relationship between dust extinction and ice column density. Even the Brick shows differences between its two halves, which is further explored in Section 4.3.1.

If the relationship between CO ice and dust extinction varies solely on CO abundance, or gas metallicity, then we would expect clouds in the same environment to match. Cloud C and cloud D are within a projected distance of 4 pc, and yet cloud D has a steeper slope than cloud C. Brick North and Brick South seem to be two halves of the same cloud, yet the two halves have different measured slopes in color-color space. This then implies that these clouds are not formed from the same environment, they are not near each other in space, or the relationship between CO ice absorption and dust extinction depends on more than just gas metallicity.

If the relationship between CO ice and dust extinction is truly dominated by its dependence on CO abundance, then the differences in slope correspond to their relative locations in the Galaxy. We believe that clouds with a shallower slope are at higher R_{gal} . Previous results looking at clouds with known R_{gal} , the Filament (S. Gramze et al. 2026b) and Chameleon I (Z. L. Smith et al.

2025), show that there is less CO ice column density per unit A_V in Chameleon I than the Filament. Even if the difference in those results were due to an unknown systematic error, we can compare the Filament’s slope to clouds in the CMZ directly. We know that the Filament, which has the shallowest slope, is in front of the CMZ at $R_{\text{gal}} \sim 3$ kpc, so we speculate that clouds with similar slopes are also at higher R_{gal} . Therefore, the variations in slope among the steeper slope group could represent differences between clouds at different R_{gal} . The question is, how sensitive is slope to R_{gal} ?

A unique attribute of the CMZ that could also explain variations in CO abundance is the origin of its gas. Unlike the Galaxy’s disk, where orbits are nearly circular, the inner Galaxy has a bar-shaped potential with exotic orbits (E. Athanassoula 1992). This potential causes gas to flow from the inner disk to the CMZ along bar lanes, streams of gas and dust plummeting in toward the center of the Galaxy. We know that gas from the bar lanes accretes onto the CMZ, but not what happens when it gets there. Does bar lane gas have a CO abundance more similar to the Galaxy’s disk or the CMZ? Something in between? How long is the mixing time for gas entering the CMZ? Recent or ongoing accretion of bar lane gas is a possible source of gas metallicity variation in CMZ clouds, which would be reflected in the CO ice and measured slope of the clouds.

4.2.2. *Temperature and Density*

A potential cause for cloud to cloud variation in slope is differences in the temperature radial profile of the clouds. CO ice forms on cold (10 to 20 K) dust grains within dense molecular clouds. The temperature of dust grains depends heavily on the strength of the UV radiation field. If the interstellar radiation field is too intense, and the dust grains are warm, then ice will fail to form.

Say that for two clouds, the envelope of one is less dense than the envelope of another. The same depth into the cloud as measured by A_V would trace warmer dust in the less dense cloud than in the denser cloud, so at the same A_V , they would have different amounts of ice frozen out. A higher column of dust does not necessarily mean that the dust is colder.

4.2.3. *Ice Composition*

We assume an ice composition ratio of $\text{H}_2\text{O}:\text{CO}:\text{CO}_2 = 10:1:1$ for measuring the ice column density, but this ratio is based on measurements of a cloud in the solar neighborhood (M. K. McClure et al. 2023). The ratios between these molecules have not yet been measured toward background stars for clouds at smaller Galactic radii. Due to changes in gas metallicity and maybe the C/O ratio, the abundances of metals these ice species rely

on are different close to the center of the Galaxy. While the inherent properties for when each ice species freezes onto dust grains to change, the relative abundances of each molecules in the ISM might differ, thus affecting the ratio between the ice species.

As shown by the vertical dashed lines in Figure 4 representing models of how ice impacts color, different ratios between ice species and different abundances of CO result in different slopes in color-color space. These models are degenerate, meaning that different combinations of ice composition ratios and CO abundances result in nearly the same slopes, so both affect these colors and cannot be differentiated. However, for regions where we expect the CO abundance to be the same, variations in the ratios between the ice species could explain variations in slope.

Icy mantles, where CO ice collects, are perfect locations for molecular chemistry. However, chemistry does not happen instantaneously, taking time for reactions to happen. CO ice is thought to be involved in the formation of CH_3OH and other organic molecules on the surfaces of dust grains (N. Watanabe & A. Kouchi 2002; G. W. Fuchs et al. 2009; M. A. J. Simons et al. 2020), a process that could alter the ice composition enough to significantly change the overall properties of the clouds.

Chemical differences between clouds originating from differences in the chemical histories of clouds could affect the amount of ice absorption from CO. However, chemical differences between ices are thought to be an indication of the environment the ices exist in and how well shielded they are from UV radiation (A. A. Boogert et al. 2015), meaning that the ice composition is expected to vary at different depths into clouds instead of from cloud to cloud. This makes ice composition a less likely cause for variation, but could explain differences within the same cloud, especially radially.

For example, while the Filament’s slope is relatively well constrained, there is a visual shift in its CCD in Figure 2 at around $[\text{F182M}] - [\text{F212N}] = 1.5$ where the distribution of stars seems to begin to flatten. The affect of this change in slope is exaggerated in the Filament’s panel in Figure 5, where instead of continuing to increase with increasing dust extinction and following the trend set by the red lines like other regions, the distribution of the CO ice column density flattens at high A_V . At these high depths into the cloud, the amount of CO ice present is regulated by its chemical reactions to form larger organic molecules such as CH_3OH , which require high dust extinction and shielding to form (A. A. Boogert et al. 2015).

4.3. Locations of Clouds

Using the assumption that slope broadly corresponds to CO abundance and gas metallicity, based on results comparing the Filament to CMZ clouds, we find the relative locations of a subset of the clouds in our sample. Without more data points and a firmer understanding of how and why slope varies, especially in how much we can trust the relationship between measured slope and CO abundance, we cannot make conclusions about where most of the regions are in our sample. Especially since, for regions with no obvious IRDC, the source of the CO ice is ambiguous. For now, we set aside a deeper examination of most of the clouds and focus on the Brick and G0.207+0.001, the HMSFR within the Brick field of view.

4.3.1. The Brick is Multiple Clouds

At least one set of variations among regions can be explained by there being more than one cloud along the line of sight that overlap on the plane of the sky.

J. D. Henshaw et al. (2019) first separated the Brick into multiple velocity components along the line of sight, concluding that the giant molecular cloud is dynamically complex, impacted by the dynamic shear environment of the CMZ. Strikingly, we find evidence that the North and South sides of the Brick show measurable differences in their properties as derived from our JWST NIRCам observations. These results imply that the Brick is multiple clouds along the line of sight, possibly associated with the different velocity components described by J. D. Henshaw et al. (2019).

First, we compare the differences in foreground A_V between regions near Brick North and Brick South in Figure 4. Brick North’s surrounding regions, Brick N Clear, Brick Head, Brick North Fluff, and Brick Punch all have foreground A_V at or near 20 mag. Brick South and the regions spatially close to it, Brick South Fluff and Brick SFR, all have foreground $\Delta A_V \sim 5$ mag than Brick North. Somewhat unintuitively, a larger foreground A_V in this case implies that there is a dust feature along the line of sight to Brick South and its associated regions that is shifting the stars behind it to have redder colors than Brick North.

Comparing the color-color diagrams of the two regions in Figure 3, we find that there is a gap at around $[\text{F182M}] - [\text{F212N}] = 0.6$ in the distribution of stars in Brick South that is not present in the color-color diagram for Brick North. This gap is also present in the color-color diagrams of many of the regions surrounding Brick South. The histogram fits in Appendix Figure 8 clearly show that the “foreground” population of stars peaks at $A_V < 20$ mag for regions closer to Brick North,

and at $A_V > 20$ mag for regions associated with Brick South. The gap in the distribution of RC is evidence of a cloud being present where the stars are absent, as it reddens stars out of that color bin. There is a cloud in front of the CMZ making stars redder in this region.

In addition, Brick South has a shallower measured slope than Brick North. This implies that the relationship between dust extinction and CO ice freeze out is different between the two regions, which would be explained by the two regions being composed of different clouds. The differences in foreground A_V and slope result in Brick North and Brick South being at nearly opposite ends of the distribution of regions with steeper slopes in this data, which cannot be explained by the Brick being a single cloud.

It is unclear if the cloud foreground to the Brick is responsible for all of the dust extinction and CO ice observed toward it. The foreground cloud and the Brick overlap on the plane of the sky, making it difficult to separate them. Brick South could still be half of the Brick, just with another cloud in front of it.

4.3.2. *The Brick SFR is in front of the CMZ*

The Brick SFR is a HMSFR at the edge of the Brick’s JWST field of view with both an HII region and associated infrared dark cloud, not to be confused with the site of star formation detected in millimeter data within the Brick itself. Similar to the dust ridge clouds, it is backlit by the nuclear stellar disk. In ACES, we find that there is a morphological match between the cloud and a narrow linewidth velocity component at $\sim 40 \text{ km s}^{-1}$, matching the line of sight velocity of the Brick.

However, while the HMSFR has a line of sight velocity matching that of nearby CMZ clouds, there is evidence that it is at a larger Galactic radius than the CMZ. First, its narrow linewidth is $< 10 \text{ km s}^{-1}$, which does not necessarily mean that it is outside of the CMZ, but makes its location more ambiguous. Second, its slope in Figure 4 is very shallow, the shallowest of regions with IRDCs other than the Filament. While there are few RC stars impacted by CO ice absorption in this region due to its small size on the plane of the sky, making its measured slope among the most uncertain, it is clear from the distribution of stars in Figure 4 that its stars follow a shallower slope than regions like Brick North, setting it apart from the rest. Assuming that slope is correlated to the abundance of CO and thus R_{gal} , this would place the HMSFR at a Galactocentric radius more similar to the Filament.

However, the HMSFR’s line of sight velocity makes any location outside of the CMZ extremely awkward. It is moving too fast to be associated with any outer

foreground spiral arms, which tend to have line of sight velocities of 0 km s^{-1} near the Galactic Center. Some variation is expected from clouds being gravitationally attracted toward spiral arms, which can cause some variation in line of sight velocity, but the HMSFR’s velocity is extreme for that to be the case. For the inner Galaxy, where gas is less constrained by circular motion and more dominated by the bar-shaped potential, we expect clouds to have more negative line of sight velocities. For example, the Filament, which is associated with the 3 kpc arm thought to be the inner most ring of gas and dust before bar lanes start to dominate the inner Galaxy, has a line of sight velocity of -55 km s^{-1} .

To make matters even stranger, Brick SFR has a foreground A_V on par with Brick South, which implies that the HMSFR is also behind the cloud foreground to the region.

4.4. *CMZ Chemical Complexity*

F466N is sensitive to OCN^- , or the XCN ice absorption feature that is commonly attributed to the molecular species. We do not model this ice species, as it has limited laboratory data that is not contaminated by other ice species (A. Ginsburg et al. 2026). From what we know about the ice composition of local clouds with respect to OCN^- (M. K. McClure et al. 2023), we do not expect OCN^- to dominate the F466N band over CO. The molecule has been detected toward background stars in local clouds, but the column density of the species is low, with very little impact in ice absorption from the species in F466N, as CO ice dominates that part of the spectrum. OCN^- is detected toward YSOs, but we would not expect it to dominate over CO ice or the inherently red color of the dusty envelopes of YSOs for the stars we observe.

Ices in the CMZ differ from that of the Galactic disk. These differences can largely be attributed to differences in gas metallicity making the molecules that are commonly frozen out more abundant (A. Ginsburg et al. 2026). The CMZ is home to widespread gas phase molecular complexity not typically found in the disk, which we should expect to be mirrored in ices, where many of these molecules originate due to grain surface chemistry. Thus, we might expect OCN^- to be more abundant in the CMZ. The gas phase chemical complexity of the CMZ is likely due in part to its unique properties that promote their excitation, but it is also reliant on metals being more common.

One molecule that is found much more commonly in the CMZ than in the Galactic disk is HNC. Formed from grain surface chemistry pathways involving solid CO and NH_3 ice (R. L. Hudson et al. 2001; G. Fedoseev

et al. 2015, 2018), HNC is observed throughout the CMZ (L. E. Snyder & D. Buhl 1972; S. Martín et al. 2008; S. N. Longmore et al. 2026; D. L. Walker et al. 2026). It is a reaction between HNC and NH_3 that forms OCN^- ice and its corresponding cation NH_4^+ as a salt (R. L. Hudson et al. 2001). In Galactic disk clouds, it is more limited, known to be associated with conditions found in high mass star formation regions and hot cores (B. E. Turner 1991; S. E. Bisschop et al. 2007). HNC is particularly abundant in the CMZ, being present in many giant molecular clouds at abundances typically only found associated with hot cores in the Galactic disk (B. E. Turner 1991; S. Martín et al. 2008). Because HNC is related to the formation of OCN^- on dust grains, it can be assumed that OCN^- ice is as widespread as HNC in the CMZ and has a higher abundance.

Shown by detections toward massive and low mass YSOs, OCN^- ice does not require cold dust temperatures that CO ice requires to remain on the surfaces of dust grains after it forms (A. A. Boogert et al. 2015). As both OCN^- and CO contribute to ice absorption in the F466N filter, the ice species could swap which is dominant at low dust column densities. This could explain why ice absorption in F466N is so widespread, as it could be tracing two different ice species in different environments. The presence of OCN^- on the outskirts of giant molecular clouds would be evidence for material leaving the clouds, as it is thought to require cold dust temperatures and CO freeze out to form in the first place.

Infrared Space Observatory (ISO) spectra toward the Quintuplet cluster (P. A. Gerakines et al. 1999; A. Moneti et al. 2001) show that the OCN^- ice absorption feature has a comparable depth to CO. If these spectra are representative for ice absorption throughout the CMZ, then that would mean OCN^- ice plays a major role in ice absorption in the F466N filter. However, A. Ginsburg et al. (2026) showed that synthetic photometry from these spectra would not result in colors like those we observe toward molecular clouds. These spectra target massive stars in a highly irradiated environment, so any ices found near these stars would have undergone thermal processing unlike what we observe toward IRDCs like the Brick. This thermal processing both makes CO ice less abundant and could increase the abundance of OCN^- ice in icy mantles (A. A. Boogert et al. 2015), explaining why the ice absorption features of the two species are comparable in this environment. However, extremely energetic processing near massive stars is thought to destroy ices entirely. If the ices being probed belong to some cloud foreground to the Quintuplet cluster still in the CMZ, then these ices could have formed in a more similar environment to the Brick.

A significant contribution from OCN^- ice alongside CO in the F466N band could also help explain the high column densities of ice in the CMZ, as the additional ice absorption would make $[\text{F405N}] - [\text{F466N}]$ even bluer.

In order to definitively show that OCN^- contributes to the ice absorption observed with F466N in the Brick and Cloud C data, spectroscopic surveys of these stars are required. A spectroscopic survey of stars in the Brick field is expected soon with JWST GO program 6927.

5. CONCLUSION

We evaluate the relationship between dust extinction and CO ice absorption using JWST NIRCcam photometry observations of clouds toward the CMZ. We find evidence of ice absorption throughout the CMZ, even in regions lacking clear signs of an IRDC. By measuring the slope of color-color diagrams associated with each region, we find that there are variations between clouds that do not fit our current understanding of how the clouds are related to each other with respect to where the clouds are located in the Galaxy. We evaluate explanations for the measured variations, including gas metallicity differences between CMZ clouds, differences in the clouds' structures, and ice composition variation due to chemistry. Some variations can be explained by clouds being located in different parts of the Galaxy, yet other variations have unclear origins. We also consider whether or not an increase abundance of OCN^- , an ice species that also absorbs light in F466N, could explain widespread observations of ice absorption and variations between clouds and conclude that it is possible.

We find that the relationship between dust extinction and CO ice column density differs between clouds, particularly among those within the CMZ. While differences in CO abundance and gas metallicity can explain variations in this relationship between clouds at different Galactic radii (A. A. Boogert et al. 2015; S. Gramze et al. 2026b; A. Ginsburg et al. 2026), this explanation should not hold for clouds formed in the same environment. Yet, we find clouds thought to be associated with the CMZ (D. C. Lis et al. 1999; C. Battersby et al. 2025; D. Lipman et al. 2025; D. R. Lipman et al. 2026), in the same part of the CMZ, that have different relationships between dust extinction and CO ice column density. This either implies that these clouds are not in the same part of the Galaxy and are at vastly different R_{gal} , the clouds are in the same part of the Galaxy and have different origins explaining their different CO abundances, or something other than just CO abundance determines the relationship between CO ice column density and A_V .

We evaluate several explanations for how clouds in the CMZ could have different relationships between dust ex-

tion and CO ice column density as traced by slope in $[F182M] - [F212N]$ versus $[F405N] - [F466N]$. The first is that CO abundance is varying from cloud to cloud in the CMZ, which could be explained by differences between CMZ gas and material brought into the CMZ by the dust lanes, which likely has a different gas metallicity. Regions with a shallower slope could represent areas where dust lane gas has not completely mixed with CMZ gas, while regions with steeper slopes could represent gas that has been enriched by the CMZ's environment. The second possibility is that the temperature and density structure of the clouds causes variations between clouds, which places a dependence on gas density which may not matter. Finally, we evaluate the possibility that the clouds have different ice compositions, tracing the chemical age of the gas. However, we expect ice composition to vary radially in clouds, which would not affect their bulk properties, making this explanation unlikely. Our most likely explanation is that CO abundance and gas metallicity varies more than expected between clouds at similar R_{gal} . It is also likely that similar variations exist for other clouds in the disk of the Galaxy.

High values of ice absorption in the CMZ point toward the region having solid phase chemistry that mirrors its gas phase chemistry in complexity, especially as many complex molecules observed at higher abundances in the CMZ are thought to originate from dust grain surface chemistry. An additional ice species that affects F466N, which we have not modeled due to a lack of laboratory measurements, is OCN^- . This ice species contributes to the formation of HNCO on the surfaces of dust grains (R. L. Hudson et al. 2001; G. Fedoseev et al. 2015), which is more abundant in the CMZ than local clouds (B. E. Turner 1991; S. Martín et al. 2008). In local clouds, CO dominates the part of the spectrum F466N

probes, but OCN^- may contribute more significantly to ice absorption in this wavelength space in CMZ clouds, which will be evaluated with future spectroscopic JWST observations of the Brick.

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APPENDIX

A. BRICK RED CLUMP SELECTION

Figure 6 shows the red clump selection for the Brick data in a color-magnitude diagram and a color-color plot, with red clump stars highlighted in red plotted over the whole catalog in black.

B. BIMODAL FITTING

Figures 7 and 8 show the bimodal Gaussian fits done to histograms representing the number of RC stars in each dust extinction bin for each region in Section 3.2. Two Gaussian curves were fit to the foreground nuclear stellar disk or bulge population and the background, ice-absorbed population for each region. The intersection or minimum between the Gaussian curves was then used to make a cut in A_V to select for RC stars impacted by CO ice absorption. For regions without an obvious foreground population, single Gaussian fits were used instead.

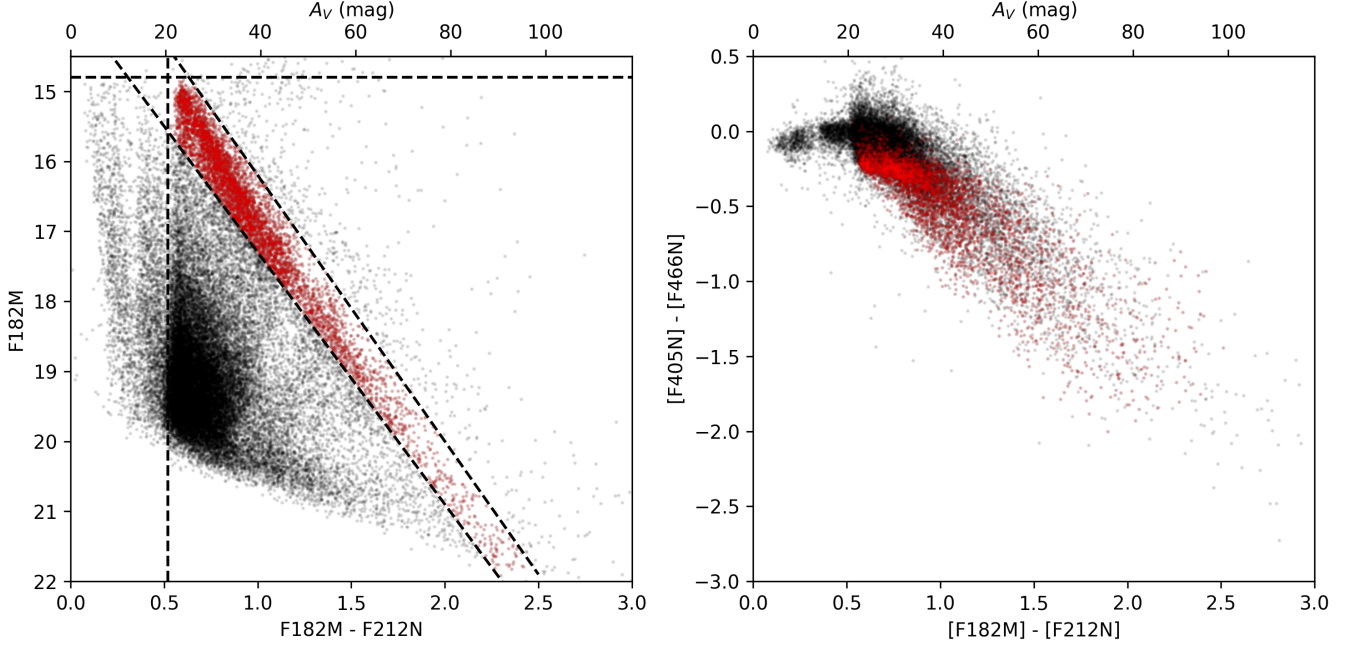


Figure 6. Color-magnitude and color-color diagrams showing the selection of red clump stars in the Brick data. The black points are all of the stars in the field, while red points are the selected red clump stars. The dashed lines represent filters on the data to select for red clump stars.

REFERENCES

- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33, doi: [10.1051/0004-6361/201322068](https://doi.org/10.1051/0004-6361/201322068)
- Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, *AJ*, 156, 123, doi: [10.3847/1538-3881/aabc4f](https://doi.org/10.3847/1538-3881/aabc4f)
- Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, *ApJ*, 935, 167, doi: [10.3847/1538-4357/ac7c74](https://doi.org/10.3847/1538-4357/ac7c74)
- Athanassoula, E. 1992, *MNRAS*, 259, 345, doi: [10.1093/mnras/259.2.345](https://doi.org/10.1093/mnras/259.2.345)
- Battersby, C., Walker, D. L., Barnes, A., et al. 2025, *ApJ*, 984, 157, doi: [10.3847/1538-4357/adb844](https://doi.org/10.3847/1538-4357/adb844)
- Bisschop, S. E., Jørgensen, J. K., van Dishoeck, E. F., & de Wachter, E. B. M. 2007, *A&A*, 465, 913, doi: [10.1051/0004-6361:20065963](https://doi.org/10.1051/0004-6361:20065963)
- Boogert, A. A., Gerakines, P. A., & Whittet, D. C. 2015, *Annual Review of Astronomy and Astrophysics*, 53, 541, doi: <https://doi.org/10.1146/annurev-astro-082214-122348>
- Boogert, A. C. A., Huard, T. L., Cook, A. M., et al. 2011, *ApJ*, 729, 92, doi: [10.1088/0004-637X/729/2/92](https://doi.org/10.1088/0004-637X/729/2/92)
- Bradley, L., Deil, C., Ginsburg, A., et al. 2024, *astropy/regions: v0.10*, v0.10 Zenodo, doi: [10.5281/zenodo.13852178](https://doi.org/10.5281/zenodo.13852178)
- Bushouse, H., Eisenhamer, J., Dencheva, N., et al. 2025, *JWST Calibration Pipeline, 1.19.2* Zenodo, doi: [10.5281/zenodo.17101851](https://doi.org/10.5281/zenodo.17101851)
- Butler, M. J., & Tan, J. C. 2012, *ApJ*, 754, 5, doi: [10.1088/0004-637X/754/1/5](https://doi.org/10.1088/0004-637X/754/1/5)
- CASA Team, Bean, B., Bhatnagar, S., et al. 2022, *PASP*, 134, 114501, doi: [10.1088/1538-3873/ac9642](https://doi.org/10.1088/1538-3873/ac9642)
- Chiar, J. E., & Tielens, A. G. G. M. 2006, *ApJ*, 637, 774, doi: [10.1086/498406](https://doi.org/10.1086/498406)
- Chiar, J. E., Pendleton, Y. J., Allamandola, L. J., et al. 2011, *ApJ*, 731, 9, doi: [10.1088/0004-637X/731/1/9](https://doi.org/10.1088/0004-637X/731/1/9)
- Churchwell, E., Babler, B. L., Meade, M. R., et al. 2009, *PASP*, 121, 213, doi: [10.1086/597811](https://doi.org/10.1086/597811)
- Clark, P. C., Glover, S. C. O., Ragan, S. E., Shetty, R., & Klessen, R. S. 2013, *ApJL*, 768, L34, doi: [10.1088/2041-8205/768/2/L34](https://doi.org/10.1088/2041-8205/768/2/L34)
- Clarke, S. D., Makeev, V. A., Sánchez-Monge, Á., et al. 2024, *MNRAS*, 528, 1555, doi: [10.1093/mnras/stae117](https://doi.org/10.1093/mnras/stae117)
- Cosentino, G., Tan, J. C., Gainey, C., et al. 2025, *arXiv e-prints*, arXiv:2509.04864, <https://arxiv.org/abs/2509.04864>
- Fedoseev, G., Ioppolo, S., Zhao, D., Lamberts, T., & Linnartz, H. 2015, *MNRAS*, 446, 439, doi: [10.1093/mnras/stu2028](https://doi.org/10.1093/mnras/stu2028)
- Fedoseev, G., Scirè, C., Baratta, G. A., & Palumbo, M. E. 2018, *MNRAS*, 475, 1819, doi: [10.1093/mnras/stx3302](https://doi.org/10.1093/mnras/stx3302)
- Fuchs, G. W., Cuppen, H. M., Ioppolo, S., et al. 2009, *A&A*, 505, 629, doi: [10.1051/0004-6361/200810784](https://doi.org/10.1051/0004-6361/200810784)

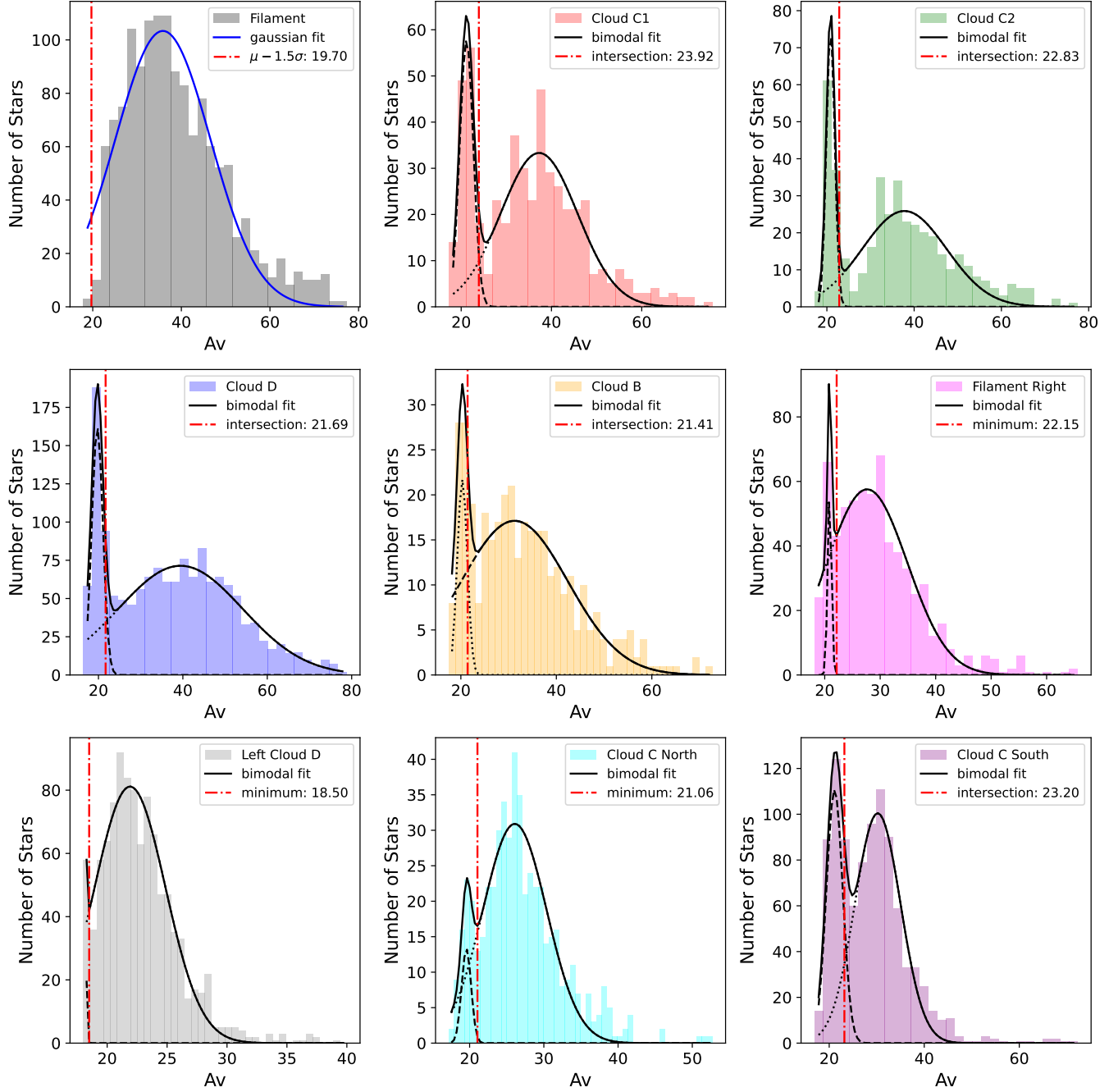


Figure 7. The bimodal or single Gaussian fits to histograms of the cloud C NIRC data, separated by region.

Gaches, B. A. L., & Viti, S. 2026, *ACS Earth and Space Chemistry*, 10, 276,
doi: [10.1021/acsearthspacechem.5c00304](https://doi.org/10.1021/acsearthspacechem.5c00304)

Gainey, C., Cosentino, G., Law, C., Entekhabi, N., & Tan, J. 2022, in *American Astronomical Society Meeting Abstracts*, Vol. 240, American Astronomical Society Meeting #240, 135.03

Gerakines, P. A., & Hudson, R. L. 2020, *ApJ*, 901, 52,
doi: [10.3847/1538-4357/abab39](https://doi.org/10.3847/1538-4357/abab39)

Gerakines, P. A., Materese, C. K., & Hudson, R. L. 2023, *MNRAS*, 522, 3145, doi: [10.1093/mnras/stad1164](https://doi.org/10.1093/mnras/stad1164)

Gerakines, P. A., Whittet, D. C. B., Ehrenfreund, P., et al. 1999, *ApJ*, 522, 357, doi: [10.1086/307611](https://doi.org/10.1086/307611)

Ginsburg, A., Henkel, C., Ao, Y., et al. 2016, *A&A*, 586, A50, doi: [10.1051/0004-6361/201526100](https://doi.org/10.1051/0004-6361/201526100)

Ginsburg, A., Koch, E., Robitaille, T., et al. 2019, *radio-astro-tools/spectral-cube: Release v0.4.5*, v0.4.5 Zenodo, doi: [10.5281/zenodo.3558614](https://doi.org/10.5281/zenodo.3558614)

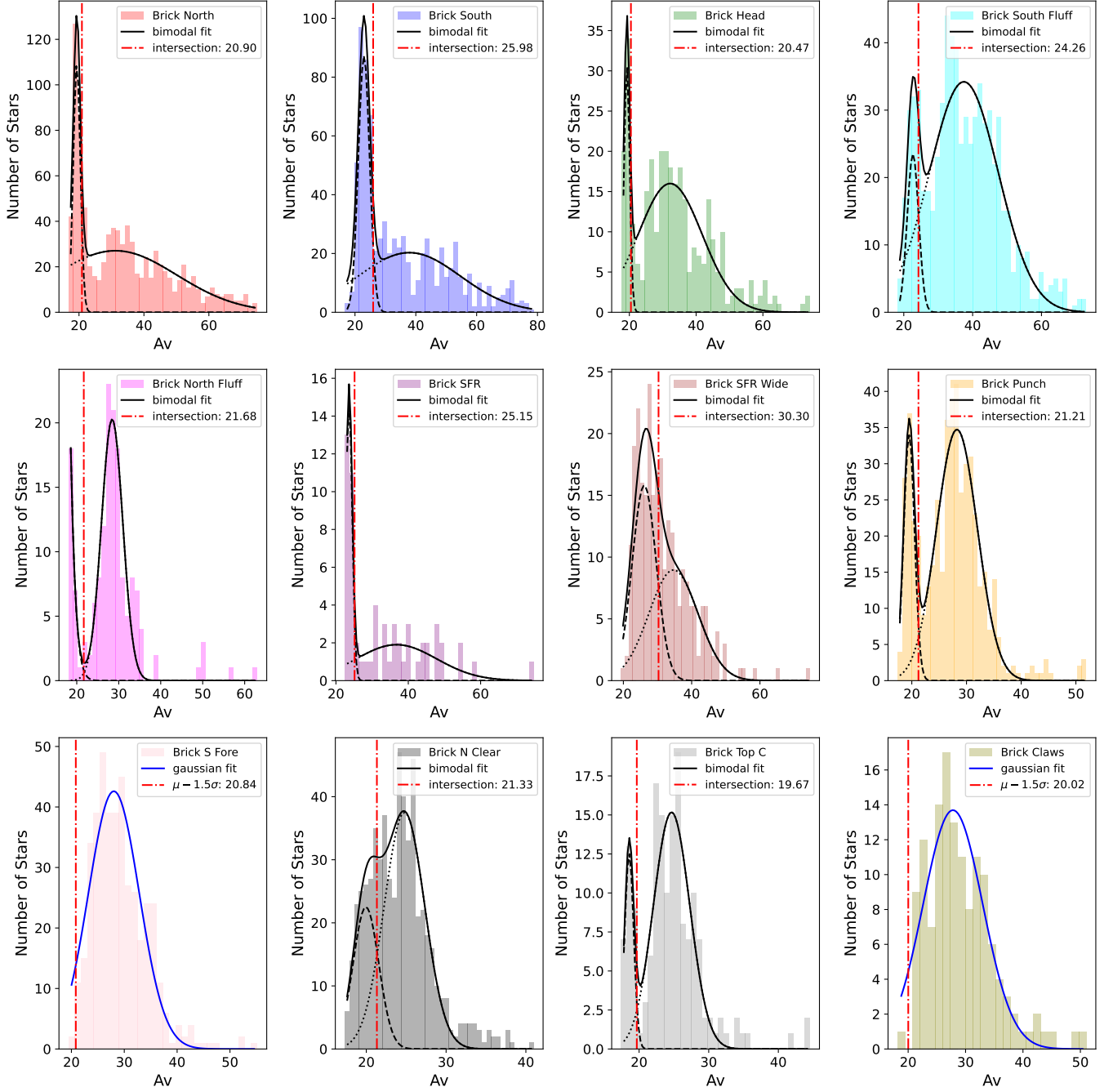


Figure 8. The bimodal or single Gaussian fits to histograms of the Brick NIRCcam data, separated by region.

Ginsburg, A., Barnes, A. T., Battersby, C. D., et al. 2023, *ApJ*, 959, 36, doi: [10.3847/1538-4357/acfc34](https://doi.org/10.3847/1538-4357/acfc34)

Ginsburg, A., Walker, D. L., Barnes, A. T., et al. 2026, *arXiv e-prints*, arXiv:2602.20240, doi: [10.48550/arXiv.2602.20240](https://doi.org/10.48550/arXiv.2602.20240)

Ginsburg, A., Gramze, S. R., Ashby, M. L. N., et al. 2026, *The Open Journal of Astrophysics*, 9, doi: [10.33232/001c.163469](https://doi.org/10.33232/001c.163469)

GLIMPSE team. 2020, *Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE)*, IPAC, doi: [10.26131/IRSA405](https://doi.org/10.26131/IRSA405)

Gramze, S., Ginsburg, A., Ashby, M., & Gaches, B. 2026a, *Catalog of Stars in JWST GO 2221*, Zenodo, doi: [10.5281/zenodo.22102031](https://doi.org/10.5281/zenodo.22102031)

Gramze, S., Ginsburg, A., Budaiev, N., et al. 2026b, *The Open Journal of Astrophysics*, 9, doi: [10.33232/001c.165431](https://doi.org/10.33232/001c.165431)

- Güver, T., & Özel, F. 2009, MNRAS, 400, 2050, doi: [10.1111/j.1365-2966.2009.15598.x](https://doi.org/10.1111/j.1365-2966.2009.15598.x)
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, Nature, 585, 357, doi: [10.1038/s41586-020-2649-2](https://doi.org/10.1038/s41586-020-2649-2)
- Henshaw, J. D., Barnes, A. T., Battersby, C., et al. 2023, in Astronomical Society of the Pacific Conference Series, Vol. 534, Protostars and Planets VII, ed. S. Inutsuka, Y. Aikawa, T. Muto, K. Tomida, & M. Tamura, 83, doi: [10.48550/arXiv.2203.11223](https://doi.org/10.48550/arXiv.2203.11223)
- Henshaw, J. D., Ginsburg, A., Haworth, T. J., et al. 2019, MNRAS, 485, 2457, doi: [10.1093/mnras/stz471](https://doi.org/10.1093/mnras/stz471)
- Herbst, E., & van Dishoeck, E. F. 2009, ARA&A, 47, 427, doi: [10.1146/annurev-astro-082708-101654](https://doi.org/10.1146/annurev-astro-082708-101654)
- Hernandez, A. K., Tan, J. C., Caselli, P., et al. 2011, ApJ, 738, 11, doi: [10.1088/0004-637X/738/1/11](https://doi.org/10.1088/0004-637X/738/1/11)
- Hollenbach, D., Kaufman, M. J., Bergin, E. A., & Melnick, G. J. 2009, ApJ, 690, 1497, doi: [10.1088/0004-637X/690/2/1497](https://doi.org/10.1088/0004-637X/690/2/1497)
- Hsieh, P.-Y., Walker, D. L., Ginsburg, A., et al. 2026, arXiv e-prints, arXiv:2603.00863, <https://arxiv.org/abs/2603.00863>
- Hudson, R. L., Moore, M. H., & Gerakines, P. A. 2001, ApJ, 550, 1140, doi: [10.1086/319799](https://doi.org/10.1086/319799)
- Hunter, J. D. 2007, Computing in Science & Engineering, 9, 90, doi: [10.1109/MCSE.2007.55](https://doi.org/10.1109/MCSE.2007.55)
- Indriolo, N., Neufeld, D. A., Gerin, M., et al. 2015, ApJ, 800, 40, doi: [10.1088/0004-637X/800/1/40](https://doi.org/10.1088/0004-637X/800/1/40)
- Jones, P. A., Burton, M. G., Cunningham, M. R., et al. 2012, MNRAS, 419, 2961, doi: [10.1111/j.1365-2966.2011.19941.x](https://doi.org/10.1111/j.1365-2966.2011.19941.x)
- Kauffmann, J., & Pillai, T. 2010, ApJL, 723, L7, doi: [10.1088/2041-8205/723/1/L7](https://doi.org/10.1088/2041-8205/723/1/L7)
- Koch, E., Ginsburg, A., AKL, et al. 2025, radio-astro-tools/radio-beam: v0.3.9, v0.3.9 Zenodo, doi: [10.5281/zenodo.15677957](https://doi.org/10.5281/zenodo.15677957)
- Kurucz, R. L. 1979, ApJS, 40, 1, doi: [10.1086/190589](https://doi.org/10.1086/190589)
- Lacy, J. H., Sneden, C., Kim, H., & Jaffe, D. T. 2017, ApJ, 838, 66, doi: [10.3847/1538-4357/aa6247](https://doi.org/10.3847/1538-4357/aa6247)
- Lipman, D., Battersby, C., Walker, D. L., et al. 2025, ApJ, 984, 159, doi: [10.3847/1538-4357/adb5ee](https://doi.org/10.3847/1538-4357/adb5ee)
- Lipman, D. R., Battersby, C., Walker, D., et al. 2026, arXiv e-prints, arXiv:2603.23327, doi: [10.48550/arXiv.2603.23327](https://doi.org/10.48550/arXiv.2603.23327)
- Lis, D. C., Li, Y., Dowell, C. D., & Menten, K. M. 1999, in ESA Special Publication, Vol. 427, The Universe as Seen by ISO, ed. P. Cox & M. Kessler, 627
- Longmore, S. N., Rathborne, J., Bastian, N., et al. 2012, ApJ, 746, 117, doi: [10.1088/0004-637X/746/2/117](https://doi.org/10.1088/0004-637X/746/2/117)
- Longmore, S. N., Bally, J., Barnes, A. T., et al. 2026, arXiv e-prints, arXiv:2602.20340, doi: [10.48550/arXiv.2602.20340](https://doi.org/10.48550/arXiv.2602.20340)
- Lu, X., Walker, D. L., Ginsburg, A., et al. 2026, arXiv e-prints, arXiv:2602.20445, doi: [10.48550/arXiv.2602.20445](https://doi.org/10.48550/arXiv.2602.20445)
- Martín, S., Requena-Torres, M. A., Martín-Pintado, J., & Mauersberger, R. 2008, ApJ, 678, 245, doi: [10.1086/533409](https://doi.org/10.1086/533409)
- Mastrapa, R. M., Sandford, S. A., Roush, T. L., Cruikshank, D. P., & Dalle Ore, C. M. 2009, The Astrophysical Journal, 701, 1347, doi: [10.1088/0004-637X/701/2/1347](https://doi.org/10.1088/0004-637X/701/2/1347)
- McClure, M. K., Rocha, W. R. M., Pontoppidan, K. M., et al. 2023, Nature Astronomy, 7, 431, doi: [10.1038/s41550-022-01875-w](https://doi.org/10.1038/s41550-022-01875-w)
- Moneti, A., Cernicharo, J., & Pardo, J. R. 2001, ApJL, 549, L203, doi: [10.1086/319168](https://doi.org/10.1086/319168)
- Nogueras-Lara, F. 2022, A&A, 668, L8, doi: [10.1051/0004-6361/202244934](https://doi.org/10.1051/0004-6361/202244934)
- Perrin, M. D., Sivaramakrishnan, A., Lajoie, C.-P., et al. 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9143, Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, ed. J. M. Oschmann, Jr., M. Clampin, G. G. Fazio, & H. A. MacEwen, 91433X, doi: [10.1117/12.2056689](https://doi.org/10.1117/12.2056689)
- Pillai, T., Wyrowski, F., Carey, S. J., & Menten, K. M. 2006, A&A, 450, 569, doi: [10.1051/0004-6361:20054128](https://doi.org/10.1051/0004-6361:20054128)
- Rathborne, J. M., Jackson, J. M., Chambers, E. T., et al. 2010, ApJ, 715, 310, doi: [10.1088/0004-637X/715/1/310](https://doi.org/10.1088/0004-637X/715/1/310)
- Requena-Torres, M. A., Martín-Pintado, J., Martín, S., & Morris, M. R. 2008, ApJ, 672, 352, doi: [10.1086/523627](https://doi.org/10.1086/523627)
- Requena-Torres, M. A., Martín-Pintado, J., Rodríguez-Franco, A., et al. 2006, A&A, 455, 971, doi: [10.1051/0004-6361:20065190](https://doi.org/10.1051/0004-6361:20065190)
- Rocha, W. R. M., McClure, M. K., Sturm, J. A., et al. 2024, arXiv e-prints, arXiv:2411.19651, doi: [10.48550/arXiv.2411.19651](https://doi.org/10.48550/arXiv.2411.19651)
- Shingledecker, C. N., Vogt-Geisse, S., Mifsud, D. V., & Ioppolo, S. 2024, in Astrochemical Modeling, ed. S. Bovino & T. Grassi (Elsevier), 71–115, doi: <https://doi.org/10.1016/B978-0-32-391746-9.00011-0>
- Simons, M. A. J., Lamberts, T., & Cuppen, H. M. 2020, A&A, 634, A52, doi: [10.1051/0004-6361/201936522](https://doi.org/10.1051/0004-6361/201936522)
- Smith, Z. L., Dickinson, H. J., Fraser, H. J., et al. 2025, Nat Astron, 9, 883, doi: [10.1038/s41550-025-02511-z](https://doi.org/10.1038/s41550-025-02511-z)
- Snyder, L. E., & Buhl, D. 1972, ApJ, 177, 619, doi: [10.1086/151739](https://doi.org/10.1086/151739)
- Tang, Y., Wang, Q. D., & Wilson, G. W. 2021a, MNRAS, 505, 2377, doi: [10.1093/mnras/staa3230](https://doi.org/10.1093/mnras/staa3230)
- Tang, Y., Wang, Q. D., Wilson, G. W., et al. 2021b, MNRAS, 505, 2392, doi: [10.1093/mnras/stab1191](https://doi.org/10.1093/mnras/stab1191)
- Tress, R. G., Brucy, N., Girichidis, P., et al. 2025, arXiv e-prints, arXiv:2512.09981, doi: [10.48550/arXiv.2512.09981](https://doi.org/10.48550/arXiv.2512.09981)
- Turner, B. E. 1991, ApJS, 76, 617, doi: [10.1086/191577](https://doi.org/10.1086/191577)
- Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, Nature Methods, 17, 261, doi: [10.1038/s41592-019-0686-2](https://doi.org/10.1038/s41592-019-0686-2)

Walker, D. L., Battersby, C., Lipman, D., et al. 2025, ApJ, 984, 158, doi: [10.3847/1538-4357/adb5ef](https://doi.org/10.3847/1538-4357/adb5ef)

Walker, D. L., Ginsburg, A., Barnes, A. T., et al. 2026, arXiv e-prints, arXiv:2602.20276, doi: [10.48550/arXiv.2602.20276](https://doi.org/10.48550/arXiv.2602.20276)

Watanabe, N., & Kouchi, A. 2002, ApJL, 571, L173, doi: [10.1086/341412](https://doi.org/10.1086/341412)

Whittet, D. C. B., Cook, A. M., Herbst, E., Chiar, J. E., & Shenoy, S. S. 2011, ApJ, 742, 28, doi: [10.1088/0004-637X/742/1/28](https://doi.org/10.1088/0004-637X/742/1/28)