



An SMA Molecular Inventory of the Edge-on Protoplanetary Disk Gomez's Hamburger

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Abstract

Gomez's Hamburger (GoHam; IRAS 18059-3211) is a massive, edge-on protoplanetary disk that is potentially gravitationally unstable and hosts an overdensity that may be the site of a forming giant planet, making it a particularly interesting source for the study of planet formation in the direct collapse scenario. In this study, we present a molecular inventory of GoHam's disk combining several Submillimeter Array observations for a wideband survey at an angular resolution on the order of $\sim 1''$. We detect 11 different molecules, including 15 individual lines, and measure their disk-integrated fluxes. We also infer column densities for several species over a range of fixed excitation temperatures. We find that the molecular inventory of GoHam and the inferred column densities for select molecules are broadly consistent with the general population of large protoplanetary disks. We explore the putative gravitational instability (GI) in GoHam's disk via possible enhancements in the gas-phase H_2CO abundance but find no definitive evidence of GI. The results of this study can guide future, higher-resolution studies of GoHam, as well as efforts to characterize the giant protoplanet candidate GoHam b.

Unified Astronomy Thesaurus concepts: Protoplanetary disks (1300); Planet formation (1241); Chemical abundances (224); Submillimeter astronomy (1647); Gravitational instability (668)

1. Introduction

It is generally accepted that giant planet formation occurs primarily through two main scenarios: core accretion (CA; V. S. Safronov 1972; P. Goldreich & W. R. Ward 1973; H. Mizuno 1980; C. Hayashi et al. 1985; J. B. Pollack et al. 1996) and gravitational instability (GI; G. P. Kuiper 1951; A. P. Boss 1997). CA involves the accretion of planetesimals (R. Greenberg et al. 1978; J. B. Pollack et al. 1996; E. Kokubo & S. Ida 1998; H. Kobayashi et al. 2011) and pebbles (C. W. Ormel & H. H. Klahr 2010; M. Lambrechts & A. Johansen 2014; A. Johansen & M. Lambrechts 2017; J. Drazkowska et al. 2023), creating a core that efficiently accretes gas as it becomes more massive. This is expected to be the more common of the two scenarios (T. Matsuo et al. 2007) and can account for the formation of terrestrial planets and lower-mass giant planets (mass $< 4M_{\text{Jup}}$; N. C. Santos et al. 2017). In higher-mass regimes, it becomes more difficult to explain the existence of giant planets, as the time required for them to form via CA may exceed the lifetime of the disk, especially around higher-mass stars (K. E. Haisch et al. 2001). Thus, an alternate planet formation pathway, i.e., GI, is

required to explain more massive giant planets. In the GI scenario, instability within disks can cause fragmentation into self-gravitating clumps that collapse directly into giant gaseous protoplanets. This pathway is capable of producing giant planets on a much shorter timescale (on the order of $\approx 10^3$ yr for $M_{\text{disk}}/M_{\text{star}} \approx 0.1$; A. P. Boss 2000). HR 8799 is an example of a system for which CA alone struggles to explain the observed planets, whereas GI has been shown to be a plausible pathway for their formation (F. Meru & M. R. Bate 2010).

The GI scenario is particularly relevant to direct imaging observations that favor the detection of massive planets at large orbital separations (> 10 au) from their host star. Opportunities to study the disk conditions associated with the GI scenario of planet formation are rare, as the disk must meet the conditions necessary to produce gravitational instabilities that lead to direct collapse (i.e., a massive disk or a favorable disk-to-star mass ratio; K. Kratter & G. Lodato 2016; J. Cadman et al. 2020). Gomez's Hamburger (GoHam; IRAS 18059-3211) may be one such disk. With a disk mass of around $0.2 M_{\odot}$ and a central star mass of $\approx 2.5 M_{\odot}$, the GoHam system's disk-to-star mass ratio is around 1 order of magnitude above average (J. P. Williams & L. A. Cieza 2011), and with ^{12}CO emission extending out to 1500 au, it is among the largest and most massive known protoplanetary disks (K. Wood et al. 2008; E. De Beck et al. 2010; see M. D. Perrin et al. 2006, C. T. Berghea et al. 2024, and K. Monsch et al. 2024 for a discussion of similar rare sources). J. Cadman et al. (2020) find that disks around higher-mass stars

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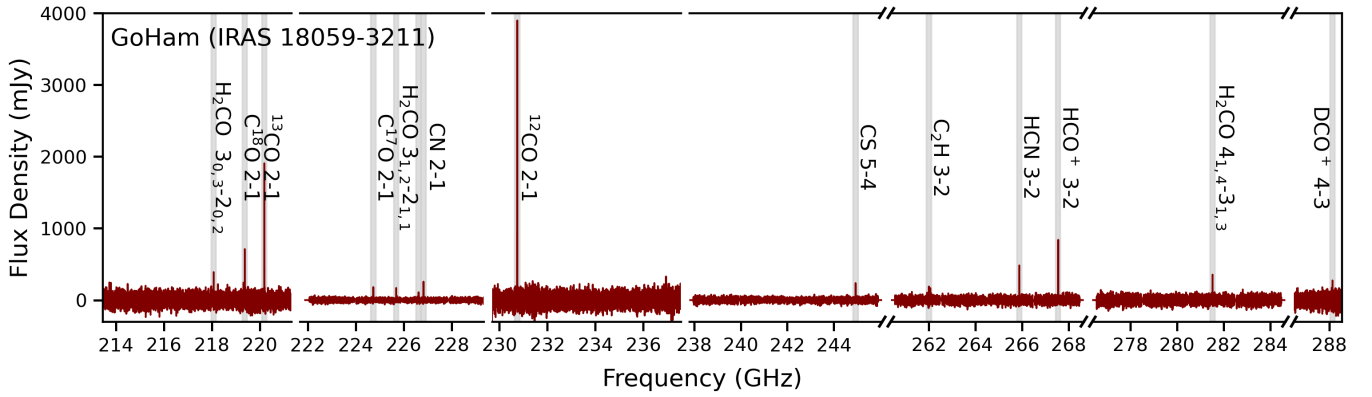


Figure 1. Summary of the frequency ranges observed and molecular lines (highlighted by vertical gray bars) detected within the SMA data. Note that the rms is nonuniform across the spectrum as several different datasets were used.

(i.e., $M_* \gtrsim 2M_\odot$) are more susceptible to fragmentation and GI and show that as stellar mass increases, the critical disk-to-star mass ratio needed for the occurrence of fragmentation decreases. O. Berné et al. (2015) estimate a Toomre Q parameter of $Q \lesssim 2$ for GoHam, which is consistent with marginal GI (A. Toomre 1964). Thus, GoHam may be within the GI regime and is an interesting target for the study of disk conditions present in this planet formation scenario.

As we seek to refine our understanding of the planetary nurseries that give rise to planets through GI, it is also particularly useful to study sources that are viewed edge-on. Highly inclined viewing angles enable tracing of the physical and chemical structure of the disk in the vertical (r, z) plane—information that is more difficult to access in less-inclined sources. At an inclination of $i \approx 85^\circ$, GoHam is among these highly inclined sources (V. Bujarrabal et al. 2008, 2009; K. Wood et al. 2008; E. De Beck et al. 2010; R. Teague et al. 2020).

The conditions present within GoHam may allow it to host particularly massive protoplanets at large orbital radii. L. Trapman et al. (2025) showed correlations between the gas mass and the dust disk size, which may suggest that more massive disks are capable of forming substructures farther from the central star. Indeed, GoHam contains a significant overdensity in its southern region at a radius of 350 au with a mass between 1 and 11 M_{Jup} (V. Bujarrabal et al. 2009; O. Berné et al. 2015; R. Teague et al. 2020). This overdensity is suggested to be the site of a forming giant planet, dubbed GoHam b, that is theorized to have formed through GI (V. Bujarrabal et al. 2008, 2009; O. Berné et al. 2015).

Characterizing disk chemistry by identifying which molecules are present and abundant is crucial for our understanding of planet formation. In that regard, understanding how disk mass may affect disk chemistry and relative abundances of molecules is an important step. A rare disk such as GoHam, being massive, large, and potentially self-gravitating, may have different gas-phase molecular abundances than the general population of protoplanetary disks due to the effects of shock heating (J. D. Ilee et al. 2011; M. G. Evans et al. 2015). In this work, we present a molecular inventory of GoHam as observed with the Submillimeter Array (SMA) and infer column densities for several species. In Section 2, we describe the observations, calibration, and data reduction. In Section 3, we outline the methods of line detection and column density calculation and present the results. In Section 4, we

discuss these results and place them within the context of similarly massive, well-studied disks. In Section 5, we conclude with a summary of the study.

2. Observations

2.1. SMA Data Reduction and Calibration

We present SMA observations of GoHam from several separate spectral setups as outlined in Appendix A in SMA projects 2020A-S033 (with IDs 9929 and 9969; PI: R. Teague) and 2020B-S057 (with ID 10613; PI: C. Qi). All observations had SMA pointing center coordinates J2000 $18^{\text{h}}09^{\text{m}}13^{\text{s}}.37 - 32^\circ 10'49''.5$ with reference velocity offsets of -2.8 km s^{-1} . One single track was collected for the SMA’s “Extended” (EXT) configuration, and two tracks were collected for the SMA’s “Compact” (COM) configuration, with the aim of maximizing the signal to noise on higher spatial frequencies while minimizing sensitivity losses to larger angular scales. These SMA configurations provide projected uv-baselines that span 16.4–226.0 m, over a total of ~ 641 min (on-source). Total frequency coverage is approximately 213.5 to 288.5 GHz, with small gaps at some frequencies (see Figure 1).

Standard flux, bandpass, and gain calibration sources were used, the latter referenced to the target location, each of which are detailed in Table 4 of Appendix A. To obtain products that could be calibrated in the Common Astronomy Software Applications (CASA) measurement set format (Team CASA et al. 2022), we converted each raw SMA data product with `pyuvdata` version 3.1.3 (B. J. Hazelton et al. 2017; G. Keating et al. 2025), with a spectral rebinning factor of 2. Autoflagging and gain-phase, gain-amplitude, bandpass, and flux solution tables were calculated with the SMA “COMPASS” tool, version 0.11.0 (G. Keating et al. 2026, in preparation). This routine follows that of J. B. Lovell et al. (2025), where the same calibration procedure was conducted to analyze the edge-on disk around IRAS 23077+6707. We manually checked for remaining interference spurs in all converted measurement sets with the `CASA plotms` tool prior to applying the calibrator solutions to our target data. We used the standard SMA reduction script¹² in CASA v6.6.3 and used the task `applycal` to apply the calibration tables to each measurement set. We manually inspected the phases and amplitudes, as

¹² Which can be accessed via <https://github.com/Smithsonian/sma-data-reduction>.

Table 1
Disk-integrated Fluxes and Additional Parameters of the Lines Identified in GoHam

Molecule	$N' - N''$	$J' - J''$	$F' - F''$	ν_0 (GHz)	Integrated Flux (Jy km s ⁻¹)	Beam (arcsec × arcsec, deg)	rms (mJy beam ⁻¹)
H ₂ CO	...	3 _{0,3} – 2 _{0,2}	...	218.222	2.1 ± 0.7	1.90 × 1.61, 3.0	60
	...	3 _{1,2} – 2 _{1,1}	...	225.698	2.0 ± 0.4	4.48 × 3.21, 156.9	90
	...	4 _{1,4} – 3 _{1,3}	...	281.527	2.5 ± 1.9	4.00 × 2.19, 161.0	120
C ¹⁸ O	...	2 – 1	...	219.560	6.6 ± 1.1	1.89 × 1.60, 2.8	70
¹³ CO	...	2 – 1	...	220.399	19.2 ± 2.0	1.88 × 1.59, 3.2	80
C ¹⁷ O	...	2 – 1	...	224.714	3.3 ± 0.4	4.49 × 3.22, 156.8	90
CN	2 – 1	3/2 – 1/2	5/2 – 3/2	226.660	1.5 ± 0.2 ^a	4.46 × 3.20, 156.9	90
		...	1/2 – 1/2	226.664	...	...	...
		5/2 – 3/2	5/2 – 3/2	226.874	4.7 ± 0.6 ^a	4.45 × 3.19, 156.9	90
		...	7/2 – 5/2	226.875	...	...	...
		...	3/2 – 1/2	226.876	...	...	...
¹² CO	...	2 – 1	...	230.538	47.5 ± 4.9	1.80 × 1.52, 3.1	70
CS	...	5 – 4	...	244.936	2.6 ± 0.5	4.29 × 2.90, 157.5	90
C ₂ H	3 – 2	7/2 – 5/2	4 – 3	262.004	2.0 ± 0.4 ^a	4.29 × 2.40, 161.0	110
		...	3 – 2	262.006	...	...	...
		5/2 – 3/2	3 – 2	262.065	0.8 ± 0.3	4.29 × 2.40, 161.0	110
HCN	...	3 – 2	...	265.886	5.1 ± 0.6	4.24 × 2.37, 161.1	110
HCO ⁺	...	3 – 2	...	267.558	8.0 ± 0.9	4.20 × 2.35, 161.1	110
DCO ⁺	...	4 – 3	...	288.144	0.2 ± 0.3	3.95 × 2.14, 161.1	120

Notes. The errors reported on the integrated fluxes are the quadrature sum of statistical uncertainties (the calculation of which is described in Section 3.1) and systematic uncertainty introduced by flux calibration, which is taken to be 10%. Here N is the rotational angular momentum quantum number excluding electron and nuclear spins, J is the total angular momentum quantum number excluding nuclear spins, and F is the total angular momentum quantum number. Molecules for which F transitions are reported have observed hyperfine structure. All lines were imaged at a channel width of 0.5 km s⁻¹.

^a Blended lines.

functions of both time and frequency separated by antenna, for all postcalibration target and calibrator data, which showed exceptional stability and band-to-band consistency.

With the CASA task `concat`, we combined the measurement sets and split these into GoHam-only spectral regions for analysis purposes with the CASA task `mstransform`, which map to the lower and upper sidebands for both SMA receivers. No time averaging nor spectral averaging was performed. No self-calibration was performed on the data.

2.2. Line Imaging

The continuum was removed from the data using the CASA routine `uvcontsub`. Continuum-subtracted data were imaged in CASA using `tcLEAN` until the noise level of the residuals was approximately equivalent to the noise of non-signal-containing regions (rms on the order of 100 mJy beam⁻¹; see Table 1 for specific values). Cleaned data cubes were subsequently processed using the `GoFish` package (R. Teague 2019) to correct for the systemic velocity of 2.793 ± 0.034 km s⁻¹ (R. Teague et al. 2020) and to plot spectra for preliminary line identification. To maximize the signal-to-noise ratio, all identified line transitions were imaged at a downsampled channel width of 0.5 km s⁻¹. We specified a Briggs weighting scheme, a Hogbom deconvolver, and a robust parameter of 2.0. The resulting synthesized beam

sizes, ranging from $\sim 2'' \times 2''$ to $\sim 4'' \times 3''$, are reported in Table 1.

2.3. Continuum Imaging

The continuum data were processed in `tcLEAN` with a Briggs weighting scheme, a Hogbom deconvolver, and a robust parameter of 0.5 and cleaned down to the theoretical sensitivity (on the order of 0.1 mJy). Using `IMFIT`, a 2D Gaussian fitting tool in CASA, the integrated flux of the continuum was measured as 278 ± 30 mJy at 1.3 mm, consistent with previously measured values (V. Bujarrabal et al. 2008; R. Teague et al. 2020). The uncertainty on this value is the quadrature sum of the statistical uncertainty produced by `IMFIT` and the standard 10% flux calibration uncertainty. This value is consistent within error bars across all datasets listed in Table 3 of Appendix A. A map of the continuum is presented in the top panel of Figure 2.

2.4. Molecule Detections

We detect multiple H₂CO, CN, and C₂H transitions (some hyperfine) and four CO isotopologues: CS, HCN, HCO⁺, and DCO⁺. This chemical complexity is consistent with the population of molecules that have been detected thus far in disks at (sub)millimeter wavelengths (e.g., K. I. Öberg et al. 2023).

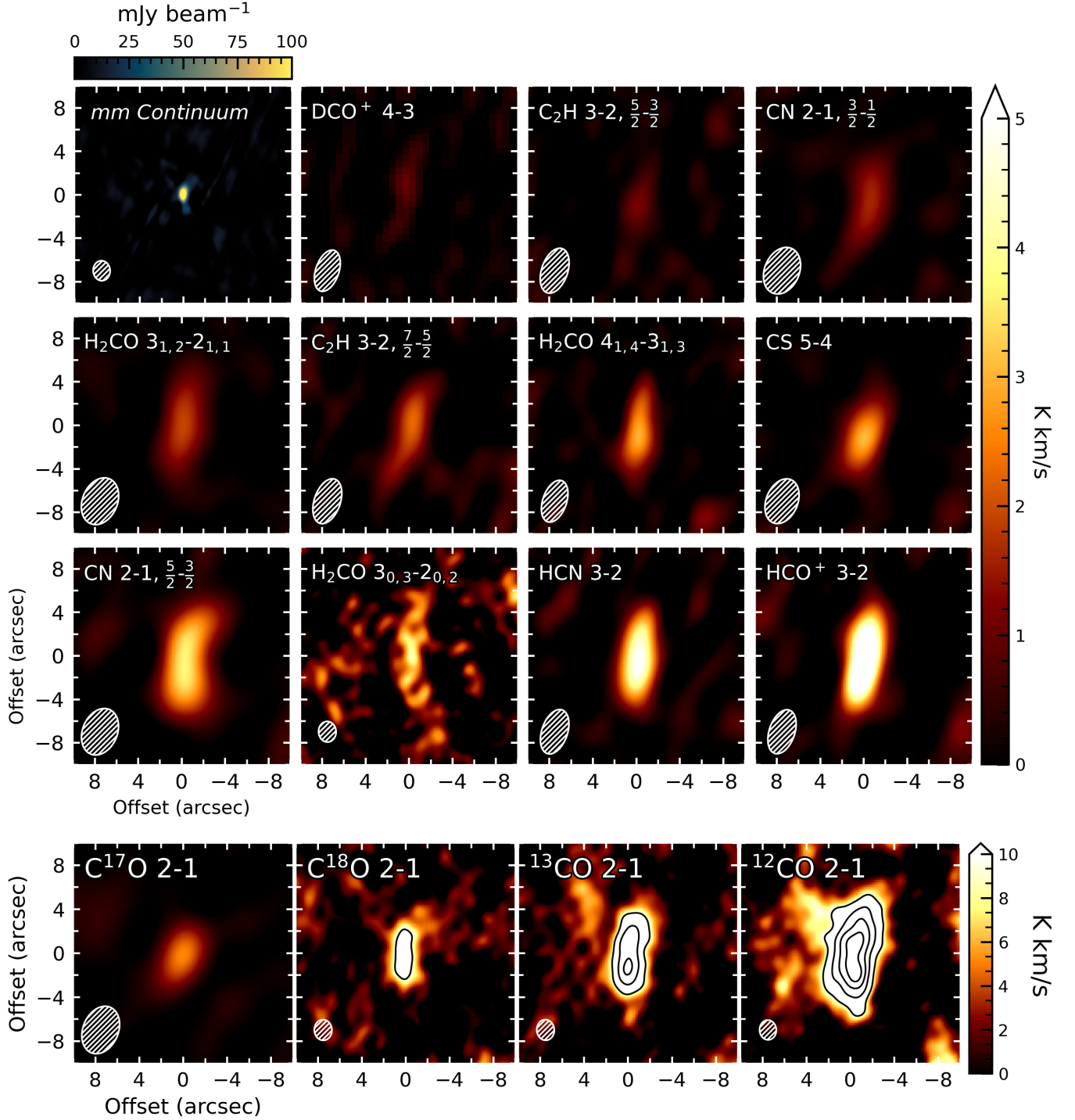


Figure 2. Continuum and zeroth-moment maps showing the relative intensities of the lines detected in GoHam, ordered from faintest to brightest. The first panel of the top figure shows the 1.3 mm continuum emission, with a color bar cutoff at $100 \text{ mJy beam}^{-1}$ to highlight the continuum morphology. The dimmest lines are presented in the top figure. The bottom figure shows CO isotopologues with a color bar cutoff at 10 K km s^{-1} to emphasize the signal of the faintest lines. Contours are plotted starting at 10 K km s^{-1} and increasing in steps of 10 K km s^{-1} . Maps show brightness temperatures computed with the Rayleigh–Jeans approximation. The synthesized beam is shown in the bottom-left corner of each panel.

In total, 15 lines were identified in the data, including hyperfine structure. See Figure 1 for a summary of the lines detected and the frequency coverage of this study. Close-up spectra of all 15 detected lines, processed with GoFish, can be found in Figure 6 of Appendix B. Figure 7 in Appendix B shows some individual channel maps of $^{12}\text{CO } 2-1$ emission.

3. Results

3.1. Integrated Fluxes

For each of the lines reported in Table 1, integrated fluxes were obtained by integrating over a broad elliptical mask. The mask was specified with a position angle of 175° (the PA of

the GoHam system), a major axis of $16''$, and a minor axis of $8''$ to best encompass the entire emission area, determined by a curve of growth analysis for ^{12}CO 2–1 and ^{13}CO 2–1. Both lines had clear maximum disk-integrated fluxes for this mask size. These lines were chosen as their spatial extents on a zeroth-moment map are the greatest ($\sim 12''$). The resulting conservative mask was applied to all lines to ensure no loss of true emission, but we note that this choice does introduce additional noise. We also note that the use of identical, large masks (assumed emission areas) for all lines means the column densities derived in our analysis are underestimates for molecules with a smaller extent than ^{12}CO . Elliptical masks (rather than Keplerian masks) were used as GoHam’s emission morphology is not well represented by an inclined 2D disk; being viewed edge-on, GoHam’s minor axis on the sky is dominated by its vertical extent.

Statistical uncertainties on integrated fluxes were obtained for each line by offsetting the mask described above at spatial offsets of $-10'', 0'',$ and $10''$ along the horizontal axis and $-25'', 0'',$ and $25''$ along the vertical axis, as well as offsetting central velocity by 20 km s^{-1} before, 10 km s^{-1} before, and 10 km s^{-1} after the range of channels containing emission. This resulted in a total of 27 samples of the noise in nonemission channels, integrated over an identical mask size and number of channels for each line. The standard deviation of each of these sets of flux measurements was taken to be the statistical uncertainty for each line. Systematic uncertainties from flux calibration are assumed to be 10% of the measured fluxes, as is standard. The quadrature sum of these statistical and systematic uncertainties is given in Table 1 as the total uncertainties on the disk-integrated fluxes. In Figure 2 we present a gallery of the integrated fluxes of each line, converted to K km s^{-1} using the Rayleigh–Jeans approximation.

We estimate the 50th percentile recoverable flux scale ($\Theta_{\frac{1}{2}}$) of the data using Equation (A11) of D. J. Wilner & W. J. Welch (1994),

$$\Theta_{\frac{1}{2}} = 8''6 \left(\frac{\nu}{217 \text{ GHz}} \right)^{-1} \left(\frac{S_{\min}}{16 \text{ m}} \right)^{-1}, \quad (1)$$

where ν is frequency in GHz and $S_{\min}$ is the minimum projected baseline length in meters. Using a reference frequency of 230 GHz and $S_{\min} = 16.44 \text{ m}$, we find $\Theta_{\frac{1}{2}} \approx 7''.90$ for these observations. Based on single-channel maps (i.e., Figure 7 in Appendix B), we find that the typical scale of disk emission is at most $\sim 5''$ —smaller than the 50th percentile recoverable flux scale of $\sim 7''.90$. Thus, we do not expect there to be significant loss of flux to spatial filtering or the addition of imaging artifacts. We note that, due to limited angular resolution, the shape of the emission is driven by the synthesized beam and thus is not particularly spatially resolved. For this reason, this study focuses on disk-integrated values. Possible limitations of this approach are discussed in Section 4.3.

3.2. Column Density Calculation

We infer average column densities (N) for H_2CO , C^{17}O , CN, CS, C_2H , HCN, and HCO^+ . We follow the methods first presented in P. F. Goldsmith & W. D. Langer (1999) and used in similar studies (e.g., R. A. Loomis et al. 2018; R. Teague et al. 2018). We note that DCO^+ is not included in this

calculation as the uncertainties on its integrated flux were too high to constrain its column density. We assume that all observed transitions are in local thermodynamic equilibrium (LTE) such that kinetic temperature is equal to excitation temperature ($T_{\text{kin}} = T_{\text{ex}}$). We caution that for radicals such as C_2H (and possibly CN), the emitting layer can be sufficiently tenuous that the lines are subthermally excited. In that case the inferred LTE T_{ex} should be interpreted as a rotational temperature and may underestimate T_{kin} , biasing N . Previous disk studies have discussed this degeneracy and interpreted low C_2H excitation temperature as evidence for subthermal excitation and/or beam dilution (J. B. Bergner et al. 2019). As discussed below, this study ultimately does not infer T_{ex} , and instead adopts a range of excitation temperatures to infer N . Still, this nuance should be noted when interpreting our inferred column densities and their associated excitation temperatures.

The Markov Chain Monte Carlo random sampler `emcee` (D. Foreman-Mackey et al. 2013) was used to model the posterior distribution of N given known parameters of each transition (i.e., frequency, upper energy level, degeneracy, and Einstein-A coefficient for spontaneous emission) and our measured disk-integrated fluxes. Known values for the molecules were obtained from the JPL, CDMS, and LAMDA databases (H. M. Pickett et al. 1998; F. L. Schöier et al. 2005; C. P. Endres et al. 2016). We include an optical depth correction following R. A. Loomis et al. (2018). We assume no line broadening beyond thermal, as the introduction of additional broadening was found to have a negligible impact on inferred column densities.

For the molecules for which two or more lines are detected (i.e., H_2CO , CN, C_2H), we attempted to fit for T_{ex} alongside N , but we found that T_{ex} was unconstrained in all cases. This is likely due to the N - T_{ex} degeneracy (limited E_u leverage and the fact that the disk-integrated fluxes sum emission over a broad range of radii and heights with different physical conditions), so for all species we report N marginalized over an adopted T_{ex} range of excitation temperatures from 10 to 50 K, following similar works (e.g., V. V. Guzmán et al. 2021; A. Dutrey et al. 2025). For CN and C_2H , one or more of the observed transitions contained blended hyperfine lines (see Table 1), so molecule-specific models were made to account for this. These blended lines were modeled individually (unblended), and the sum of their modeled fluxes was compared to the observed blended fluxes. This follows standard practice (e.g., J. B. Bergner et al. 2021).

We observed both ortho- and para- H_2CO transitions and found that the ortho-to-para ratio (OPR) was also unconstrained in attempts to allow it to vary as a free parameter. In thermal equilibrium the OPR is expected to be ~ 3 (the high-temperature limit), while the out-of-equilibrium OPR is expected to be ~ 2 (V. Guzmán et al. 2011). Thus, we assume fixed OPRs of 2 and 3, following the precedent of similar works that have calculated or assumed an H_2CO OPR value of 2–3 to infer column densities (e.g., J. E. Dickens & W. M. Irvine 1999; H. Roberts et al. 2002; J. Terwisscha van Scheltinga et al. 2021; A. Dutrey et al. 2025). We present column densities for both of these OPRs in Table 2 and show that using an OPR of 2 rather than 3 has minimal impact on inferred column density. Figure 3 shows that N varies very little across the range of excitation temperatures used. The final N values and uncertainties reported in Table 2 are the

Table 2
Column Densities (N) and Optical Depths (τ)

Molecule	$J' - J''$	$F' - F''$	$T_{\text{ex}} = 20 \text{ K}$		$T_{\text{ex}} = 50 \text{ K}$	
			τ	$N (\text{cm}^{-2} \times 10^{12})$	τ	$N (\text{cm}^{-2} \times 10^{12})$
H_2CO	$3_{0,3} - 2_{0,2}$	...	0.31/0.21	$2.45^{+0.43}_{-0.43}/2.27^{+0.40}_{-0.41}$	0.05/0.03	$1.59^{+0.28}_{-0.29}/1.41^{+0.26}_{-0.26}$
	$3_{1,2} - 2_{1,1}$	...	0.31/0.32	...	0.06/0.06	...
	$4_{1,4} - 3_{1,3}$	...	0.32/0.33	...	0.09/0.09	...
C^{17}O	$2 - 1$	...	0.51	3210^{+394}_{-398}	0.11	5020^{+611}_{-621}
CN	$3/2 - 1/2$	$5/2 - 3/2$	0.20	$6.14^{+0.58}_{-0.57}$	0.04	$9.38^{+0.88}_{-0.90}$
	...	$1/2 - 1/2$	0.06	...	0.01	...
	$5/2 - 3/2$	$5/2 - 3/2$	0.20	...	0.04	...
	...	$7/2 - 5/2$	0.31	...	0.07	...
	...	$3/2 - 1/2$	0.12	...	0.03	...
CS	$5 - 4$	...	0.34	$2.78^{+0.56}_{-0.58}$	0.07	$2.41^{+0.49}_{-0.50}$
C_2H	$7/2 - 5/2$	$4 - 3$	0.13	$8.45^{+1.55}_{-1.58}$	0.03	$9.98^{+1.83}_{-1.83}$
	...	$3 - 2$	0.10	...	0.02	...
	$5/2 - 3/2$	$3 - 2$	0.10	...	0.02	...
HCN	$3 - 2$	...	0.56	$0.34^{+0.04}_{-0.04}$	0.12	$0.44^{+0.05}_{-0.05}$
HCO^+	$3 - 2$	...	0.92	$3.15^{+0.36}_{-0.37}$	0.19	$3.70^{+0.42}_{-0.42}$

Note. τ and N values for H_2CO are presented for $\text{OPR} = 2/\text{OPR} = 3$.

median (50th) and 16th-to-84th percentile ranges of the posterior distributions, respectively.

4. Discussion

4.1. Chemical Complexity

We detect a total of 15 individual lines in the data, including multiple transitions of H_2CO , CN, and C_2H (some hyperfine), four CO isotopologues (C^{18}O , ^{13}CO , C^{17}O , and ^{12}CO), CS, HCN, HCO^+ , and a faint detection of DCO^+ . This chemical complexity is consistent with the population of molecules that have been detected in disks at (sub)millimeter wavelengths, and we do not detect any unexpected species (K. I. Öberg et al. 2023). Furthermore, within the frequency ranges covered by the data, none of the molecules we expected to see were undetected.

4.2. Evidence for Changes Induced by GI

The high mass and disk-to-star mass ratio of the GoHam system, as well as its Toomre Q parameter of $Q \lesssim 2$, may place it within the GI regime. Astrochemical models show that the dynamical processes within a gravitationally unstable disk, i.e., shock heating, enhance the abundance of simple volatiles via desorption (J. D. Ilee et al. 2011). These models, along with planetary heating models (L. I. Cleeves et al. 2015), suggest that H_2CO may be particularly sensitive to these processes (compared to other species such as CN). This is likely because H_2CO is formed in abundance via grain-surface processes, so more of it is available for desorption (R. A. Loomis et al. 2015). Thus, if GoHam is indeed gravitationally unstable, we may expect to see an elevated abundance of H_2CO compared to non-GI disks.

In Figure 4 we place GoHam in the context of several other well-studied disks—the five disks in the Molecules with ALMA at Planet-forming Scales (MAPS) Large Program and AB Aurigae (AB Aur). Of these sources, two are thought to be at

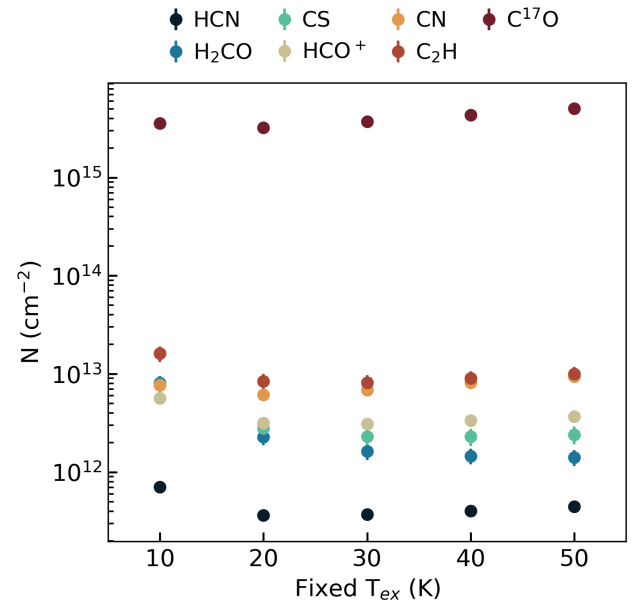


Figure 3. Disk-averaged column densities for HCN, H_2CO , CS, HCO^+ , CN, C_2H , and C^{17}O , assuming fixed excitation temperatures of 10, 20, 30, 40, and 50 K. For H_2CO , we present column densities calculated with a fixed OPR of 3.

least marginally gravitationally unstable: IM Lup (G. Lodato et al. 2023; T. Ueda et al. 2024) and AB Aur (J. Speedie et al. 2024). We compare the disk-to-star mass ratios of these seven sources (M. Simon et al. 2019; R. Teague et al. 2020, 2021; G. Lodato et al. 2023; P. Martire et al. 2024; J. Speedie et al. 2024), as high disk-to-star mass ratios can be associated with a higher likelihood of GI. See Table 5 of Appendix C for the current values we adopt. We also compare disk-averaged column densities for C^{17}O , C_2H , CN, HCO^+ , H_2CO , and HCN when available (P. Rivière-Marichalar et al. 2020;

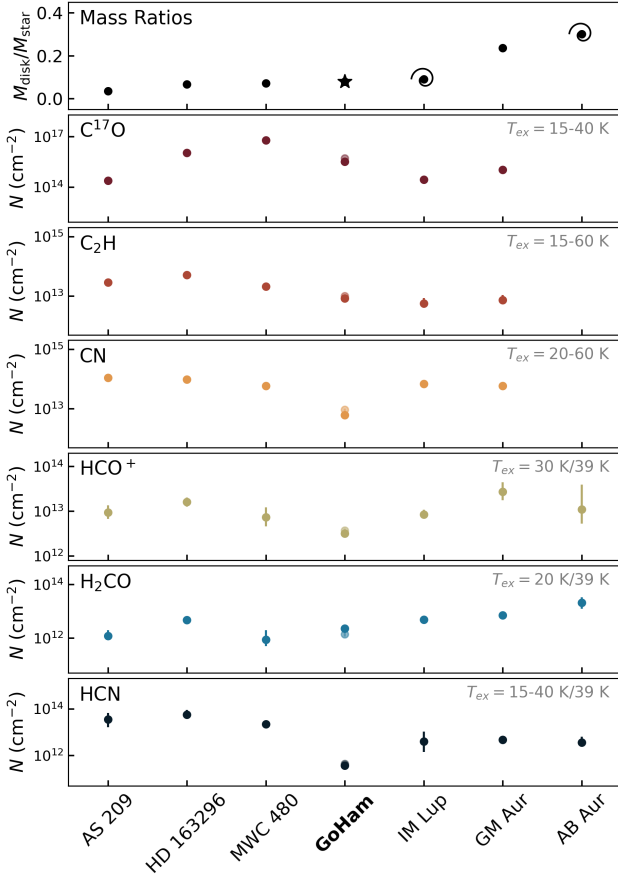


Figure 4. A comparison of disk-to-star mass ratios and average column densities of GoHam with the MAPS disks and an additional known GI source. Disks are presented in order of increasing disk-to-star mass ratio. Spiral markers are used to indicate known GI sources, and a star marker indicates GoHam in panel 1. The excitation temperatures associated with the given column densities are indicated in the top right of each panel; in some cases, T_{ex} was allowed to vary as a free parameter, in which case we present the approximate range of temperatures obtained across all radii. When a fixed T_{ex} was used, we present the single value. In the cases for which data were available for AB Aur in addition to the MAPS disks, we present temperatures in the format $T_{\text{ex,MAPS}}/T_{\text{ex,AB Aur}}$. Note that N values for CO, C_2H , and CN were not available for AB Aur. For GoHam, we present the column densities associated with $T_{\text{ex}} = 20$ K (opaque points) and $T_{\text{ex}} = 50$ K (transparent points). The H_2CO N values for GoHam assume an OPR of 3.

V. V. Guzmán et al. 2021; J. B. Bergner et al. 2021). For C^{17}O , we compare column densities we obtained from our observations of GoHam to column densities for MAPS disks using the modeled column density profiles from K. Zhang et al. (2021), which are consistent with full CO isotopologue ensemble. To obtain MAPS values for C^{17}O , we scaled values by the local ISM ratio of $^{12}\text{CO}/\text{C}^{17}\text{O} = 2005$ (T. L. Wilson 1999). We present column densities for GoHam inferred at excitation temperatures of $T_{\text{ex}} = 20$ K and $T_{\text{ex}} = 50$ K to demonstrate how the range of possible column densities compares to values obtained for these other disks.

As we will discuss in Section 4.3, our use of disk-integrated values and integration over a large mask area for GoHam’s highly inclined disk introduces some limitations. Thus, for a better one-to-one comparison with other disks, we also consider the ratio of disk-averaged column densities between H_2CO and CN (See Figure 5) as a means of probing the relative abundances of these species in each disk. (Here CN is used as an example; other molecules could be used to illustrate

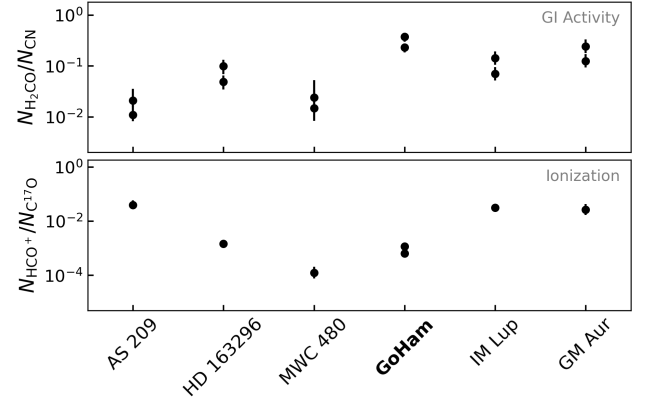


Figure 5. The top panel shows a comparison of disk-averaged H_2CO -to-CN column density ratios for GoHam and the MAPS disks. From the possible column densities available for different excitation temperatures, we present the highest and lowest ratios. These ratios are intended to probe H_2CO desorption resulting from GI activity in the disk. The bottom panel shows a comparison of disk-averaged HCO^+ -to- C^{17}O column density ratios for the same disks. These ratios are intended to demonstrate comparative ionization rates within the disks. Disks are presented in order of increasing disk-to-star mass ratio.

the same behavior.) From the possible column densities available for different excitation temperatures, we present the highest and lowest ratios. For MAPS disks, two sets of H_2CO column densities were available at $T_{\text{ex}} = 20$ and $T_{\text{ex}} = 50$ K, while only one set of CN column densities was available. For GoHam, we used column densities for both species at $T_{\text{ex}} = 20$ and $T_{\text{ex}} = 50$ K and present the highest and lowest ratios resulting from the four possible combinations of those values. It must be noted that H_2CO and CN typically trace different layers within the disk (e.g C. Walsh et al. 2010; A. Garufi et al. 2020), which our disk-averaging approach does not account for given our limited spatial resolution. Some variation in $N_{\text{H}_2\text{CO}}/N_{\text{CN}}$ values may be a result of these molecules tracing different layers within the disk. Higher-resolution studies that account for the differences in emitting layers between the molecules being compared may yield additional insights. Still, when comparing $N_{\text{H}_2\text{CO}}/N_{\text{CN}}$ values obtained for GoHam to values calculated for other disks using the same methods, we find that GoHam appears to have the highest ratio, ranging from $N_{\text{H}_2\text{CO}}/N_{\text{CN}} \approx 1.5$ to 3.7 depending on associated T_{ex} . This ratio may indicate that H_2CO is enhanced in GoHam compared to other species, such as CN, that we expect to be less susceptible to shock heating. This enhancement, if truly present, may be an indicator that some dynamical processes associated with GI are present within GoHam (J. D. Ilee et al. 2011). We note that this possibility would need to be verified with comparisons to abundance enhancements from shocks in a known GI-active disk whose disk-to-star mass ratio more closely resembles that of GoHam. We observe that GoHam has a higher disk-averaged $N_{\text{H}_2\text{CO}}/N_{\text{CN}}$ than IM Lup, a known gravitationally unstable disk. We suggest that this may be attributed to the fact that IM Lup does not have extensive spiral structure traced by the gas (which drives the shock heating), so it may not be sufficiently unstable to experience shock heating to the degree that may be present in GoHam. This may result in reduced H_2CO desorption within the IM Lup disk.

As Y. Aikawa et al. (2021) show, the column density ratio of HCO^+ to C^{17}O can be used to gain insight into the ionization rate within the disk. Although limited by our

disk-averaged approach, we present $N_{\text{HCO}^+}/N_{\text{C}^{17}\text{O}}$ for GoHam and the MAPS disks in Figure 5 and show that the ratios for GoHam are most consistent with the lower-mass-ratio sources. This appears to indicate a standard ionization rate within GoHam, from which we cannot make any conclusions about the presence of GI. A radially resolved study may provide insights into which regions of the GoHam disk experience comparatively higher ionization rates.

4.3. Limitations of a Disk-integrated Approach

Given the limited angular resolution of the data, disk-integrated fluxes were used in calculating column densities. This method yields column densities for the entire disk and does not preserve information about the radial and vertical variations of the molecules. J. D. Ilee et al. (2021) demonstrate the limitations of using disk-integrated values by performing both disk-integrated and radially resolved analyses to derive column densities and rotational temperatures for HC_3N , CH_3CN , and $c\text{-C}_3\text{H}_2$ in four MAPS disks (K. I. Öberg et al. 2021). They showed that their disk-integrated results were generally in agreement with previous observational results but that for small radii ($\lesssim 100$ au) their spatially resolved analysis revealed significantly higher column densities for some large organic molecules. Similarly, it may be that the disk-averaged column densities shown in Table 2 and Figure 3 are underestimates at small radii, as species may become optically thick in the inner disk, but are good estimates at higher radii.

Recent studies (e.g., L. Podio et al. 2020) have noted vertical stratification between various molecules, such as ^{12}CO and H_2CO . The large beam size of our observations introduces smearing effects that prevent the emitting layer from being well constrained. However, we qualitatively observe that ^{12}CO emission in the disk is elevated compared to ^{13}CO . Most other molecules we observe in the disk appear to be relatively consistent with the emission structure of ^{13}CO , and more extended than C^{18}O , suggesting they trace a similar emission layer to ^{13}CO (see Figure 2). Our analysis does not account for differences in vertical distribution of molecules. We note that this may introduce some additional uncertainty or bias into the resulting column densities we present. However, we do not expect this to significantly affect our conclusions given our disk-averaged approach.

We note that if GI-induced enhancement of molecular abundances is sufficiently localized, disk-averaged values may not capture such enhancements; a follow-up study examining radial variation of H_2CO in GoHam may yield additional insights into the possibility of GI. We also caution that, given the large size of GoHam on the sky and our use of a large mask for calculating integrated fluxes, our N values are averaged over a substantially larger area than the other disks we have discussed. This results in N values that are generally low compared to these other disks. Finally, inferring disk-averaged values from disk-integrated fluxes over an edge-on disk such as GoHam may produce different results than the same process for a less-inclined disk, as the observed emission area is not as comparable to the true face-on area of the disk.

5. Summary and Conclusions

We identify 15 molecular lines within GoHam’s disk from a wideband survey using several SMA datasets taken over multiple years. We present the disk-integrated fluxes for these lines and infer column densities for several species. While the H_2CO -to- CN column density ratio may indicate the presence of GI affecting the gas-phase chemistry, our findings for GoHam are broadly consistent with other well-studied high- $M_{\text{disk}}/M_{\text{star}}$ disks. We find that no definitive conclusions can be drawn about GI based on the chemistry of GoHam without additional, higher-resolution data. Future studies with ALMA can further explore the chemical complexity and the possibility of GI in GoHam by targeting the molecules detected in this study at higher angular resolutions. These results establish an inventory of which molecules and transitions are present and bright within GoHam and establish order-of-magnitude estimates for the average column densities of several common molecules. This study lays the groundwork for future targeted studies that can offer insight into the conditions of planet formation in high-mass disks and the characterization of the gaseous overdensity and giant protoplanet candidate GoHam b.

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Facility: Smithsonian Astrophysical Observatory (SAO)/Academia Sinica Submillimeter Array (SMA) at Mauna Kea Observatory.

Appendix A Summary of Observations

In Table 3, we provide a summary of the SMA datasets analyzed in this work. In Table 4, we provide details regarding the calibrators used alongside our GoHam observations.

Table 3
Observation Details

Project code	ObsID	Configuration	Exp. Time (minutes)	LO (RxA/RxB)	Obs. Date (UT)
2020A-S033	9929	SMA EXT Track	205 minutes	341.0/225.5	2020 Jun 12, 07:00:20–15:51:55
	9969	SMA COM Track	192 minutes	341.0/225.5	2020 Jul 2, 05:29:53–15:33:58
2020B-S057	10613	SMA COM Track	244 minutes	272.5/234.0	2021 May 27, 07:44:39 - 16:55:54

Note. All datasets have an intrinsic resolution of 139.648 kHz. Note that data centered at 340 GHz collected in some of these observations were not used in this study due to their lower quality.

Table 4
Calibrator Details

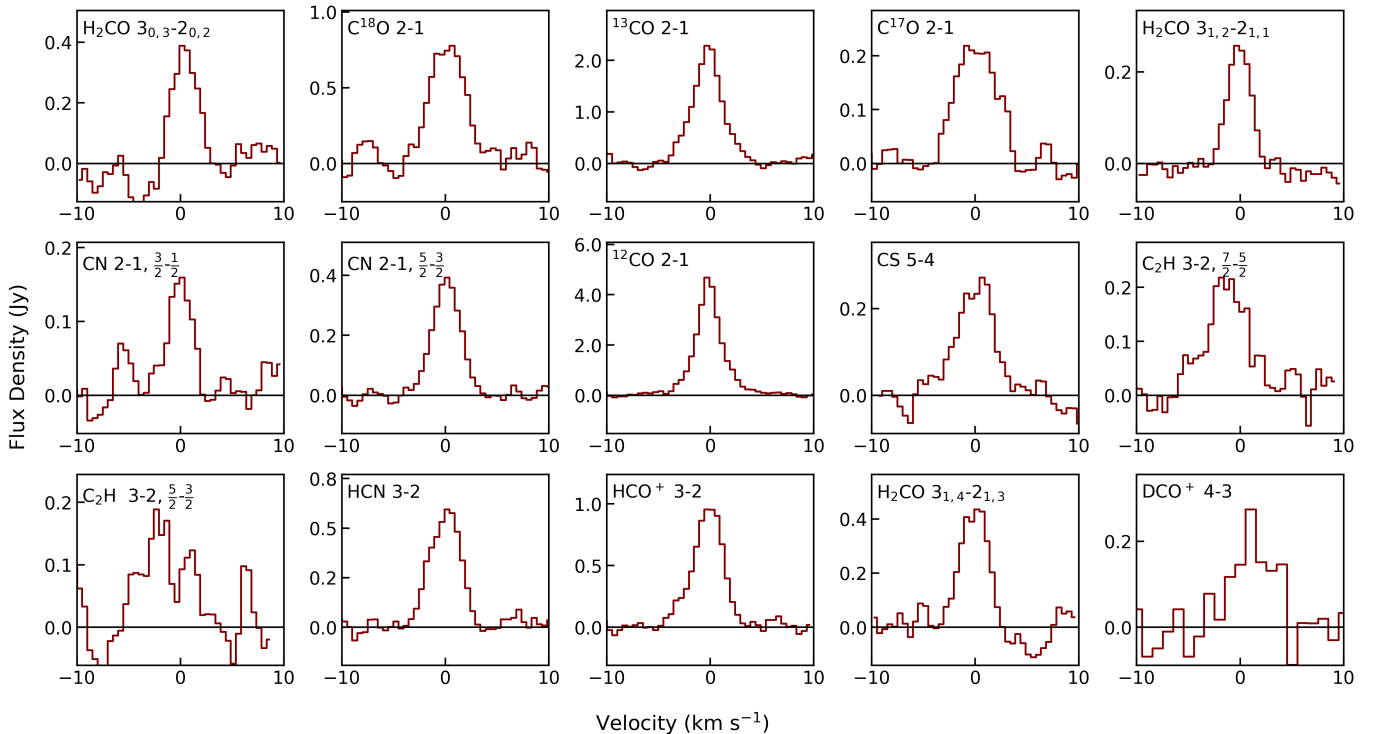
Project code	ID	Bandpass	Calibrators Flux	Gain
2020A-S033	9929	3c279	Titan	1744-312
	...	...	Ceres	1924-292
	...	...	Neptune	...
	9969	3c454.3	Titan	J1744-312
	...	...	Ceres	J1924-292
2020B-S057	10613	3c279	Callisto	1744-312
	...	3c454.3	...	1924-292
	...	...	...	...
	...	...	...	...
	...	...	...	...

Appendix B

Lines Observed

In Figure 6, we present close-up line profiles for the species discussed in this study. In Figure 7, we present several

consecutive channel maps for the ^{12}CO 2–1 transition at a velocity spacing of 0.5 km s^{-1} .

**Figure 6.** All individual molecular lines observed within the frequency ranges shown in Figure 1.

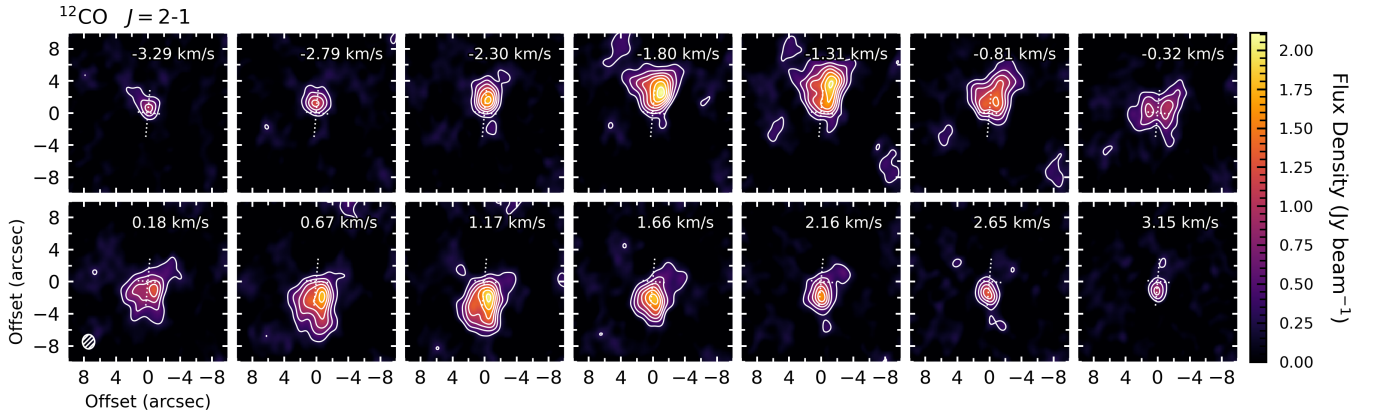


Figure 7. Channel maps of ^{12}CO 2-1 emission. Contours are plotted starting at 4σ and increasing in steps of 4σ , where $\sigma = 70 \text{ Jy beam}^{-1}$. The synthesized beam is plotted in the bottom left of the figure. Dotted lines show the orientation of GoHam's major and minor axes. The central velocity of each channel is shown in the top right of each panel.

Appendix C Disk-to-star Mass Ratios

In Table 5, we provide the current disk-to-star mass ratio estimates for the systems discussed in this work.

Table 5
Disk-to-star Mass Ratios Used in the Comparison Discussion

Source	$M_{\text{disk}}/M_{\text{star}}$	References
AS 209	0.04	R. Teague et al. (2021), P. Martire et al. (2024)
HD 163296	0.07	R. Teague et al. (2021), P. Martire et al. (2024)
MWC 480	0.07	M. Simon et al. (2019), P. Martire et al. (2024)
GoHam	0.08	R. Teague et al. (2020)
IM Lup	0.09	R. Teague et al. (2021), G. Lodato et al. (2023)
GM Aur	0.24	R. Teague et al. (2021), G. Lodato et al. (2023)
AB Aur	0.3	J. Speedie et al. (2024)

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References

Aikawa, Y., Cataldi, G., Yamato, Y., et al. 2021, *ApJS*, **257**, 13
 Berghea, C. T., Bayyari, A., Sitko, M. L., et al. 2024, *ApJL*, **967**, L3
 Bergner, J. B., Öberg, K. I., Bergin, E. A., et al. 2019, *ApJ*, **876**, 25
 Bergner, J. B., Öberg, K. I., Guzmán, V. V., et al. 2021, *ApJS*, **257**, 11
 Berné, O., Fuente, A., Pantin, E., et al. 2015, *A&A*, **578**, L8
 Boss, A. P. 1997, *Sci*, **276**, 1836
 Boss, A. P. 2000, *ApJL*, **536**, L101
 Bujarrabal, V., Young, K., & Castro-Carrizo, A. 2009, *A&A*, **500**, 1077
 Bujarrabal, V., Young, K., & Fong, D. 2008, *A&A*, **483**, 839

Cadman, J., Rice, K., Hall, C., Haworth, T. J., & Biller, B. 2020, *MNRAS*, **492**, 5041
 Team CASA, Bean, B., Bhatnagar, S., et al. 2022, *PASP*, **134**, 114501
 Cleves, L. I., Bergin, E. A., & Harries, T. J. 2015, *ApJ*, **807**, 2
 De Beck, E., Decin, L., de Koter, A., et al. 2010, *A&A*, **523**, A18
 Dickens, J. E., & Irvine, W. M. 1999, *ApJ*, **518**, 733
 Drążkowska, J., Bitsch, B., Lambrechts, M., et al. 2023, *ASPC*, **534**, 717
 Dutrey, A., Denis-Alpizar, O., Guilloteau, S., et al. 2025, *A&A*, **704**, A33
 Endres, C. P., Schlemmer, S., Schilke, P., Stutzki, J., & Müller, H. S. P. 2016, *JMoSp*, **327**, 95
 Evans, M. G., Ilee, J. D., Boley, A. C., et al. 2015, *MNRAS*, **453**, 1147
 Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, *PASP*, **125**, 306
 Garufi, A., Podio, L., Codella, C., et al. 2020, *A&A*, **636**, A65
 Goldreich, P., & Ward, W. R. 1973, *ApJ*, **183**, 1051
 Goldsmith, P. F., & Langer, W. D. 1999, *ApJ*, **517**, 209
 Greenberg, R., Wacker, J. F., Hartmann, W. K., & Chapman, C. R. 1978, *Icar*, **35**, 1
 Guzmán, V., Pety, J., Goicoechea, J. R., Gerin, M., & Roueff, E. 2011, *A&A*, **534**, A49
 Guzmán, V. V., Bergner, J. B., Law, C. J., et al. 2021, *ApJS*, **257**, 6
 Haisch, K. E., Jr., Lada, E. A., & Lada, C. J. 2001, *ApJL*, **553**, L153
 Hayashi, C., Nakazawa, K., & Nakagawa, Y. 1985, in *Protostars and Planets II*, ed. D. C. Black & M. S. Matthews (Univ. Arizona Press), 1100
 Hazelton, B. J., Jacobs, D. C., Pober, J. C., & Beardsley, A. P. 2017, *JOSS*, **2**, 140
 Ilee, J. D., Boley, A. C., Caselli, P., et al. 2011, *MNRAS*, **417**, 2950
 Ilee, J. D., Walsh, C., Booth, A. S., et al. 2021, *ApJS*, **257**, 9
 Johansen, A., & Lambrechts, M. 2017, *AREPS*, **45**, 359
 Keating, G., Hazelton, B., Kolopanis, M., et al. 2025, *JOSS*, **10**, 7482
 Kobayashi, H., Tanaka, H., & Krivov, A. 2011, in *Joint Meeting 2011*, **242**
 Kokubo, E., & Ida, S. 1998, *Icar*, **131**, 171
 Kratter, K., & Lodato, G. 2016, *ARA&A*, **54**, 271
 Kuiper, G. P. 1951, *PNAS*, **37**, 1
 Lambrechts, M., & Johansen, A. 2014, *A&A*, **572**, A107
 Lodato, G., Rampinelli, L., Viscardi, E., et al. 2023, *MNRAS*, **518**, 4481
 Loomis, R. A., Cleves, L. I., Öberg, K. I., et al. 2018, *ApJ*, **859**, 131
 Loomis, R. A., Cleves, L. I., Öberg, K. I., Guzman, V. V., & Andrews, S. M. 2015, *ApJL*, **809**, L25
 Lovell, J. B., Trapman, L., Monsch, K., et al. 2025, *ApJ*, **989**, 69
 Martire, P., Longarini, C., Lodato, G., et al. 2024, *A&A*, **686**, A9
 Matsuo, T., Shibai, H., Ootsubo, T., & Tamura, M. 2007, *ApJ*, **662**, 1282
 Meru, F., & Bate, M. R. 2010, *MNRAS*, **406**, 2279
 Mizuno, H. 1980, *PThPh*, **64**, 544
 Monsch, K., Lovell, J. B., Berghea, C. T., et al. 2024, *ApJL*, **967**, L2
 Öberg, K. I., Facchini, S., & Anderson, D. E. 2023, *ARA&A*, **61**, 287
 Öberg, K. I., Guzmán, V. V., Walsh, C., et al. 2021, *ApJS*, **257**, 1
 Ormel, C. W., & Klahr, H. H. 2010, *A&A*, **520**, A43
 Perrin, M. D., Duchêne, G., Kalas, P., & Graham, J. R. 2006, *ApJ*, **645**, 1272
 Pickett, H. M., Poynter, R. L., Cohen, E. A., et al. 1998, *JQSTRT*, **60**, 883
 Podio, L., Garufi, A., Codella, C., et al. 2020, *A&A*, **642**, L7
 Pollack, J. B., Hubickyj, O., Bodenheimer, P., et al. 1996, *Icar*, **124**, 62
 Rivière-Marichalar, P., Fuente, A., Le Gal, R., et al. 2020, *A&A*, **642**, A32

- Roberts, H., Fuller, G. A., Millar, T. J., Buckle, J. V., et al. 2002, [A&A](#), **381**, 1026
- Safronov, V. S. 1972, *Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets* (Keter Publishing House)
- Santos, N. C., Adibekyan, V., Figueira, P., et al. 2017, [A&A](#), **603**, A30
- Schöier, F. L., van der Tak, F. F. S., van Dishoeck, E. F., & Black, J. H. 2005, [A&A](#), **432**, 369
- Simon, M., Guilloteau, S., Beck, T. L., et al. 2019, [ApJ](#), **884**, 42
- Speedie, J., Dong, R., Hall, C., et al. 2024, [Natur](#), **633**, 58
- Teague, R. 2019, [JOSS](#), **4**, 1632
- Teague, R., Jankovic, M. R., Haworth, T. J., Qi, C., & Ilee, J. D. 2020, [MNRAS](#), **495**, 451
- Teague, R., Henning, T., Guilloteau, S., et al. 2018, [ApJ](#), **864**, 133
- Teague, R., Bae, J., Aikawa, Y., et al. 2021, [ApJS](#), **257**, 18
- Terwisscha van Scheltinga, J., Hogerheijde, M. R., Cleeves, L. I., et al. 2021, [ApJ](#), **906**, 111
- Toomre, A. 1964, [ApJ](#), **139**, 1217
- Trapman, L., Zhang, K., Rosotti, G. P., et al. 2025, [ApJ](#), **989**, 5
- Ueda, T., Tazaki, R., Okuzumi, S., Flock, M., & Sudarshan, P. 2024, [NatAs](#), **8**, 1148
- Walsh, C., Millar, T. J., & Nomura, H. 2010, [ApJ](#), **722**, 1607
- Williams, J. P., & Cieza, L. A. 2011, [ARA&A](#), **49**, 67
- Wilner, D. J., & Welch, W. J. 1994, [ApJ](#), **427**, 898
- Wilson, T. L. 1999, [RPPh](#), **62**, 143
- Wood, K., Whitney, B. A., Robitaille, T., & Draine, B. T. 2008, [ApJ](#), **688**, 1118
- Zhang, K., Booth, A. S., Law, C. J., et al. 2021, [ApJS](#), **257**, 5