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MINDS. A transition from H₂O to C₂H₂ dominated spectra with decreasing stellar luminosity

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ABSTRACT

Context. The chemical composition of the inner regions of disks around young stars will largely determine the properties of planets forming in these regions. Many disk physical processes drive the disk chemical evolution, some of which depend on and/or correlate with the stellar properties.

Aims. We aim to explore the connection between stellar properties and the inner disk chemistry in protoplanetary disks, as traced by mid-infrared spectroscopy.

Methods. We use JWST-MIRI observations of a large, diverse sample of sources to explore trends between the carbon-bearing molecule C₂H₂ and the oxygen-bearing molecule H₂O. Additionally, we calculate the average spectrum for the T Tauri ($M_* > 0.2 M_\odot$) and very low-mass star (VLMS, $M_* \leq 0.2 M_\odot$) samples from JWST-MIRI MRS data and use slab models to determine the properties of the average spectra in each subsample.

Results. We find a significant anti-correlation between the flux ratio of C₂H₂/H₂O and the stellar luminosity. Disks around VLMS have significantly higher $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ flux ratios than their higher-mass counterparts, driven by the generally weak H₂O and strong C₂H₂ in disks around low-mass hosts. We also explore trends with the strength of the 10 μm silicate feature, the stellar accretion rate, and the disk dust mass, all of which show correlations with $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$, which may be related to processes driving the carbon-enrichment in disks around VLMS, but also have degeneracies with system properties (i.e., the M_*-M and M_*-M_{disk} relationships). Slab model fits to the average spectra show that H₂O emission in the VLMS sample is quite similar in temperature and column density to a warm (~ 600 K) H₂O component in the T Tauri spectrum, indicating that the high C/O gas phase ratio in these disks is not due to oxygen depletion alone. Instead, the presence of many hydrocarbons, including some with high column densities, suggests that carbon enhancement in the disks around VLMS is taking place.

Conclusions. The observed differences in the inner disk chemistry as a function of host properties are likely to be accounted for by differences in the disk temperatures, stellar radiation field, and the evolution of dust grains.

Key words. protoplanetary disks – stars: pre-main sequence – planets and satellites: formation

1. Introduction

Understanding the main factors impacting the protoplanetary disk chemistry is of great importance for understanding the conditions during planet formation and therefore for constraining what material is available for nascent planets, both rocky and giant (e.g., Öberg & Bergin 2021). The evolution and structure of the dust disk, both vertically and radially, and the stellar luminosity, which controls the disk temperature, are expected to have a strong impact on the gaseous composition of the inner, terrestrial-planet-forming regions of disks. Infrared spectroscopy is a critical tool, not just for determining what molecules are present in these inner few au of protoplanetary disks, but also for determining the conditions of the gas and the processes that are at play in setting the chemistry. Observations with the Infrared Space Observatory, *Spitzer*, and now JWST provide a unique window into these inner-disk regions, and the sensitivity and spectral resolution of JWST is ushering in new understandings of the first stages of planet formation.

With large, diverse samples of protoplanetary disks observed in the mid-infrared, trends between the chemistry and the physical properties of these systems can be investigated, providing a way to determine what factors are driving the chemistry. Large

samples observed with *Spitzer* using the Infrared Spectrograph (IRS) provided great insight into the links between inner disk chemistry with overall disk properties (e.g., Pontoppidan et al. 2014). For instance, a trend was found between the flux ratio of HCN/H₂O and the disk mass, potentially indicating that more massive disks lock up oxygen-rich ices in the cold outer regions, depriving the inner disk of H₂O enrichment (Najita et al. 2013). This conclusion was reinforced by trends found between the H₂O/HCN flux ratio and the disk dust radius, with smaller disks having more H₂O relative to HCN (Banzatti et al. 2020). Trends have also been found as a function of the stellar properties, largely the stellar mass and luminosity. Pascucci et al. (2009, 2013) found that cool stars (spectral type later than M5) have very different chemical signatures in the mid-infrared than earlier type stars (spectral type between K1 and M5), with the cool stars having higher C₂H₂ fluxes than HCN, where the opposite is true for earlier-type stars. These trends provided key insights into the impact of disk evolution and stellar properties on setting inner-disk chemistry and were only possible by access to large, diverse observational samples.

JWST results are now building on the legacy of *Spitzer* in the study of the inner regions of protoplanetary disks. The increased sensitivity and spectral resolution of JWST-MIRI, rela-

tive to *Spitzer*-IRS, is allowing for the detection of isotopologues (e.g., Grant et al. 2023; Tabone et al. 2023; Salyk et al. 2025), the de-blending of both ro-vibrational and pure rotational H_2O lines (e.g., Pontoppidan et al. 2024; Gasman et al. 2023), and detections of very weak emission to reveal previously unknown molecular content (e.g., Perotti et al. 2023; Arabhavi et al. 2024, 2025b). These advancements, along with analysis of increasingly large samples (e.g., Romero-Mirza et al. 2024; Arabhavi et al. 2025a; Arulanantham et al. 2025; Banzatti et al. 2025), are transforming our understanding of inner disk chemistry by allowing for a better accounting of the chemical complexity, providing tighter constraints on the gas properties, and by allowing us to explore relationships with system properties.

In this work, we take a large sample of disks observed with JWST-MIRI MRS and find a strong anti-correlation between the $\text{C}_2\text{H}_2/\text{H}_2\text{O}$ flux ratio and the stellar luminosity, spanning three orders of magnitude in stellar luminosity (and two orders of magnitude in stellar mass, including the transition from the stellar to sub-stellar regimes) and over three orders of magnitude in flux ratio. In Section 2 we present the sample, observations, and methods for calculating line fluxes and dust properties. In Section 3 we present the anti-correlations between $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ and the stellar luminosity, accretion rate, disk dust mass, and the strength of the $10\ \mu\text{m}$ silicate feature and the average spectrum for the T Tauri and VLMS samples, as well as a slab model fit to those average spectra. We discuss these results and the degeneracies between many of the system parameters in Section 4. We provide a summary of our findings in Section 5.

2. Sample, observations, and methods

2.1. Sample

Our sample comes from the Mid-Infrared Disk Survey (MINDS) JWST Guaranteed Time program (PID 1282, PI Henning, Henning et al. 2024; Kamp et al. 2023). The entire MINDS sample consists of 52 targets, spanning stellar masses from the sub-stellar brown dwarf regime to Herbig Ae stars and five debris disks. We do not include debris disks, highly inclined sources, Herbig Ae/Be systems, or sources dominated by PAH emission in our analysis. We also include the brown dwarf system TWA 27A/2MASS J12073346-3932539 from PID 1270, PI Birkmann; see Patapis et al. 2025). For this work, “T Tauri” sample is taken to be objects with a stellar mass above $0.2\ M_\odot$, while the “VLMS” is taken as those with host masses of $0.2\ M_\odot$ and below, including objects in the brown dwarf regime. Our sample thus consists of nine very low-mass stars and brown dwarfs ($M_* \sim 0.02$ to $0.16\ M_\odot$, SpT from M4.5 to M9, see Arabhavi et al. 2025a for more details on this sample) and 25 T Tauri stars ($M_* \sim 0.25$ to $1.5\ M_\odot$, SpT from M4 to G8). All of these sources were observed with the Mid-Infrared Instrument (MIRI), in the medium-resolution mode (MRS, Wright et al. 2023). This provides spectra from 4.9 to $28\ \mu\text{m}$ at a resolving power of $R \sim 1500$ – 3500 .

The stellar and disk properties for our sample are collected from the literature and provided in Table 1. The accretion rate and disk dust masses are taken from the compilation of Manara et al. (2023).

2.2. JWST observations and data reduction

The entire sample has been reduced using the standard pipeline reduction (version 1.16.1; Bushouse et al. 2024) and pmap 1315. Aperture photometry with an aperture size of $2\times$ the full width at

half maximum was used to extract the spectra. Residual fringes were removed using the default pipeline.

Continuum-subtraction is done following the methods of Temmink et al. (2024b). Briefly, this is done via an iterative fitting with the continuum being fit using a Savitzky-Golay filter with a third-order polynomial. Emission lines above 2σ above the continuum are masked so as to not skew the continuum estimation. The continuum is then subtracted, and all downward spikes more than 3σ below the continuum are masked. Finally, the baseline is determined using PyBaselines (Erb 2022). Molecular pseudo-continuum is present in all of the VLMS. For these sources, the wavelength ranges where the pseudo-continua are obviously present are masked by eye from the continuum determination.

2.3. Line fluxes

The H_2O flux is determined by integrating the spectrum over three windows centered on lines with upper energy levels of 2400 to $6000\ \text{K}$ and Einstein A coefficients of 1 to $42\ \text{s}^{-1}$ in the $17\ \mu\text{m}$ range: 17.09 – $17.15\ \mu\text{m}$, 17.2 – $17.245\ \mu\text{m}$, and 17.3 – $17.42\ \mu\text{m}$. These transitions, and thus the integrated flux that we measure, largely trace a “warm” H_2O component, with a temperature of $\sim 400\ \text{K}$. However, H_2O has been found to have gradients in temperature in disks (e.g., Temmink et al. 2024a; Gasman et al. 2023; Banzatti et al. 2023; Grant et al. 2024; Muñoz-Romero et al. 2024), therefore we are only tracing a portion of the H_2O in these systems and some may have different reservoirs of hot and cold water. However, these lines are more commonly detected for the VLMS sample than hot ro-vibrational lines at shorter wavelengths and are less blended with hydrocarbon features between ~ 12 and $16\ \mu\text{m}$. Finally, the noise level is too high to access the very cold components at $\sim 24\ \mu\text{m}$ (Arabhavi et al. 2025b).

In H_2O -rich spectra, H_2O lines can contaminate the C_2H_2 Q -branch at $13.7\ \mu\text{m}$. Therefore, we follow the methods of Banzatti et al. (2020) to remove the H_2O contribution before determining the C_2H_2 flux. We take a local thermodynamic equilibrium H_2O slab model with a temperature of $600\ \text{K}$ and a column density of $10^{18}\ \text{cm}^{-2}$ (properties that have been found for H_2O lines near the C_2H_2 feature, e.g., Grant et al. 2023; Gasman et al. 2023), scale it to match the continuum and peak fluxes of water lines in two windows (13.415 to $13.445\ \mu\text{m}$ and 14.19 to $14.35\ \mu\text{m}$) close in wavelength to the C_2H_2 Q -branch peak. This H_2O model is then subtracted from the observed spectrum before the integrated C_2H_2 flux is measured. We note that removing the H_2O emission is not necessary for the VLMS, as the H_2O emission is very weak, if present at all, and any fit for H_2O will be greatly contaminated by the strong C_2H_2 and HCN emission. The C_2H_2 flux is integrated from 13.60 to $13.72\ \mu\text{m}$.

To determine whether H_2O and C_2H_2 are detected requires an understanding of the noise level in the spectrum. This can be very challenging in the line-rich MIRI spectra, as there is little pure continuum on which to measure the noise level. Based on model spectra of the common molecular species found in the 13 to $18\ \mu\text{m}$ wavelength range, we select wavelength regions which contain the least molecular emission in which to determine the noise (from 15.895 to $15.91\ \mu\text{m}$ for the T Tauris and 16.375 and $16.395\ \mu\text{m}$ for the VLMS). The species is considered detected if the line flux is greater than 3σ . However, there are several cases in which the spectra are very line-rich or are noisy, leading to 3σ “detections” that are not reliable when inspected by eye; for instance, the integrated flux over the C_2H_2 feature is high but the region has residual water lines and/or no discernible C_2H_2

Table 1. Stellar properties and line fluxes for our sample.

Target	M_* [$M_\odot$]	SpT	L_* [$L_\odot$]	$F_{9.8}$	$\log_{10}(\dot{M})$ [$M_\odot/\text{yr}$]	M_{dust} [$M_\oplus$]	$F_{\text{C}_2\text{H}_2}$ [$\times 10^{-14}$ erg s $^{-1}$ cm $^{-2}$]	$F_{\text{H}_2\text{O}}$ [$\times 10^{-14}$ erg s $^{-1}$ cm $^{-2}$]
J04390163+2336029	0.08	M6 ^a	0.1	1.43	-9.71	3.0	0.38 $\pm$ 0.01	0.04 $\pm$ 0.01
J11071668-7735532	0.05	M7.74 ^a	0.02 ^b	1.69	-11.69 ^c		1.19 $\pm$ 0.04	< 0.11
J11071860-7732516	0.08	M5.5	0.04	1.0	-10.4	0.38	0.49 $\pm$ 0.01	0.06 $\pm$ 0.01
J11074245-7733593	0.12	M5.5	0.06	1.18	-9.62	0.89	1.32 $\pm$ 0.02	< 0.06 [*]
J11082650-7715550	0.07	M5.5	0.02	1.0	-10.67	0.19	0.71 $\pm$ 0.02	< 0.05 [*]
J11085090-7625135	0.08	M5.5	0.04	1.13	-10.27	0.18	0.5 $\pm$ 0.02	< 0.05 [*]
J12073346-3932539	0.02 ^d	M9 ^a	0.01 ^d	1.0	-11.23 ^d	0.1 ^a	0.14 $\pm$ 0.0	< 0.01
J15582981-2310077	0.16	M4.5	0.04	1.33	-9.05	1.19	2.17 $\pm$ 0.01	0.08 $\pm$ 0.01
J16053215-1933159	0.16	M4.5 ^a	0.03 ^e	1.0	-9.4 ^f	0.14	4.5 $\pm$ 0.02	< 0.05 [*]
AA Tau	0.68	M0.6	0.75	1.48	-7.64	36.0	2.21 $\pm$ 0.15	5.59 $\pm$ 0.17
BP Tau	0.49	M0.5	0.98	2.1	-7.29	25.01	< 0.33	3.32 $\pm$ 0.12
CX Tau	0.33	M2.5	0.34 ^g	1.52	-9.59 ^h	4.21	0.39 $\pm$ 0.03	0.24 $\pm$ 0.03
CY Tau	0.42	M2.3	0.36	1.08	-8.2	35.81	1.67 $\pm$ 0.04	0.55 $\pm$ 0.04
DF Tau	0.39	M2.7	0.59 ⁱ	1.21	-7.77 ⁱ	1.8	22.24 $\pm$ 1.42	13.33 $\pm$ 1.47
DL Tau	1.07	K5.5	1.49	1.13	-7.19	123.4	14.28 $\pm$ 0.13	2.58 $\pm$ 0.14
DM Tau	0.29	M3	0.24	1.41	-7.99	52.42	< 0.06 [*]	< 0.06 [*]
DN Tau	0.53	M0.3	0.7	1.26	-8.18	41.41	< 0.23 [*]	0.36 $\pm$ 0.08
DR Tau	0.83	K6	1.9	1.38	-6.71	70.44	14.21 $\pm$ 1.11	29.15 $\pm$ 1.24
FT Tau	0.3	M2.8	0.45	1.63	-8.92 ^j	42.99	1.24 $\pm$ 0.12	2.11 $\pm$ 0.12
GW Lup	0.46	M1.5	0.33	1.6	-9.03	50.06	1.36 $\pm$ 0.07	0.72 $\pm$ 0.07
IM Lup	1.09	K5	2.51	1.29	-7.85	137.22	3.04 $\pm$ 0.14	3.01 $\pm$ 0.15
LkCa15	0.7	K5.5	1.1	3.02	-7.94	88.67	< 0.09 [*]	0.25 $\pm$ 0.03
PDS 70	0.76	K7 ^k	0.38	3.82	-10.26 ^l	21.83 ^m	< 0.04 [*]	0.12 $\pm$ 0.01
RNO 90	1.5	G8 ⁿ	2.69	1.47	-7.26 ⁿ		10.19 $\pm$ 0.39	18.64 $\pm$ 0.46
RW Aur	1.5	K0	2.51	1.25	-7.07	19.72	15.41 $\pm$ 0.69	24.19 $\pm$ 0.82
SY Cha	1.12	K7	0.55	1.82	-9.18	1.33	0.66 $\pm$ 0.1	1.38 $\pm$ 0.1
Sz 50	0.25	M4	0.69	1.26	-8.79	11.96	0.57 $\pm$ 0.08	0.59 $\pm$ 0.09
Sz 98	0.55	K7	1.53	1.91	-7.44	75.85	< 0.63 [*]	4.33 $\pm$ 0.22
TW Hya	0.61	M0.5 ^o	0.23 ^o	1.96	-8.52 ^p	70.12 ^q	< 0.11	0.27 $\pm$ 0.04
V1094 Sco	0.64	K6	1.21	1.14	-7.88	135.05	1.79 $\pm$ 0.01	0.32 $\pm$ 0.01
VW Cha	0.7	K7	2.31	1.53	-7.38	16.59	< 1.73 [*]	32.57 $\pm$ 0.71
WA Oph 6	0.63	K7 ^o	0.76 ^o	1.22	-7.34 ^o	46.6 ^r	2.47 $\pm$ 0.16	1.81 $\pm$ 0.16
WX Cha	0.49	M0.5	0.86	1.78	-6.73	7.78	4.2 $\pm$ 0.32	6.91 $\pm$ 0.35
XX Cha	0.25	M3.5	0.41	1.4	-7.17	8.03	4.56 $\pm$ 0.17	2.44 $\pm$ 0.18

Notes. Upper limits are given as 3σ . Fluxes marked with an * indicates that the non-detection came from by-eye inspection of line-rich or noisy spectra. The target names for the first nine targets are the 2MASS names. Values for M_* , SpT, L_* , $\log_{10}(\dot{M})$, and M_{dust} are compiled from Manara et al. (2023) unless otherwise noted. ^a Arabhavi et al. (2025a), ^b Luhman (2007), ^c Manara et al. (2016), ^d Manjavacas et al. (2024), ^e Testi et al. (2022), ^f Franceschi et al. (2024), ^g Herczeg & Hillenbrand (2014), ^h Vlasblom et al. (2025), ⁱ Grant et al. (2024), ^j Gangi et al. (2022), ^k Pecaut & Mamajek (2016), ^l Haffert et al. (2019), ^m calculated using the 1.33 mm flux from Facchini et al. (2021) assuming $T_{\text{dust}}=20$ K and $\kappa_v=2.254$ cm $^{-2}$ g $^{-1}$, ⁿ Fang et al. (2023), ^o Pascucci et al. (2020), ^p Wendeborn et al. (2024), ^q Das et al. (2024), ^r Brown-Sevilla et al. (2021)

Q -branch. In these cases we consider these non-detections, but provide the 3σ upper limits in Table 1. Finally, while we use the 3σ threshold, confirmed by visual inspection, to determine whether the emission is detected in this work, H₂O has been detected in most of the VLMS through cross-correlation, either at shorter wavelengths or in the rotational lines that we analyze here. We refer the reader to Arabhavi et al. (2025b) for details on these H₂O detections in the VLMS sample.

2.4. 10 μm silicate feature strength

In order to investigate the connection between the gas properties and the (infrared) dust properties, we calculate the strength of the 10 μm silicate feature following the methods of e.g., van Boekel et al. (2003); Kessler-Silacci et al. (2006): $F_{9.8} = 1 + (f_{9.8,cs}/<f_c>)$, where $f_{9.8,cs}$ is the spectrum after subtracting the continuum that is determined by two anchor points, one from 6.8 to 7.5

μm and the other from 12.5 to 13.5 μm , and $<f_c>$ is the mean of the continuum. For four of the VLMS (2MASS J16053215-1933159, 2MASS J11071860-7732516, 2MASS J11082650-7715550, and 2MASS J12073346-3932539), there is either no 10 μm emission or any emission around 10 μm is coming at least partially from optically thick C₂H₄ (Arabhavi et al. 2024, 2025a), therefore for these sources we adopt a band strength of 1, representative of no silicate emission.

3. Results

3.1. Average spectrum

To explore the properties of the T Tauri and VLMS samples, we take the average spectrum of each sample to perform a spectral fit. Each spectrum is scaled to a common distance of 120 pc before the spectra are averaged in each wavelength bin. The average spectra of the T Tauri and VLMS samples are presented

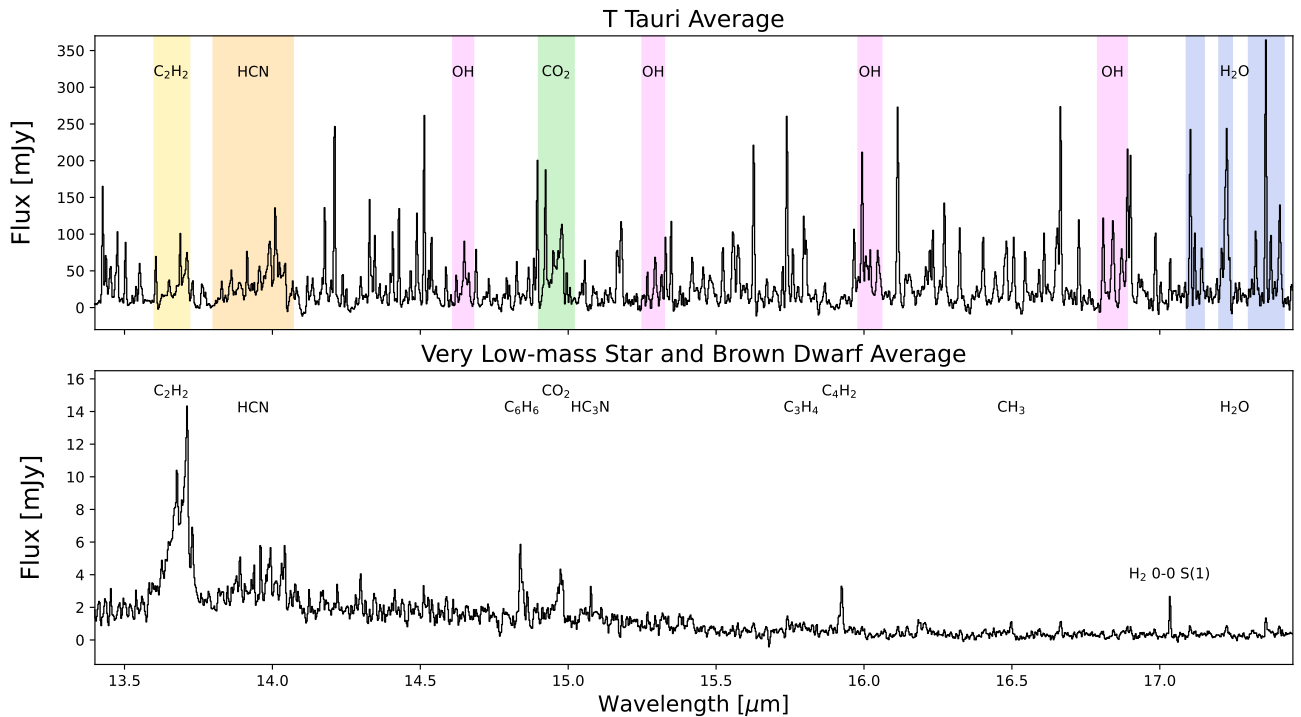


Fig. 1. The average T Tauri (top) and VLMS (bottom) sample JWST spectra. The detected molecular species are highlighted. The C_2H_2 and H_2O regions (yellow and blue, respectively) show the regions over which the fluxes are integrated. Most of the unlabeled lines in the T Tauri average are various H_2O transitions.

in Figure 1. This figure starkly highlights the difference in the molecular emission between the two samples. H_2O lines are the strongest features in the averaged T Tauri spectrum, followed by the CO_2 and HCN Q -branches, OH, and finally C_2H_2 . By comparison, the averaged VLMS spectrum is dominated by the bright C_2H_2 Q -branch, followed by C_6H_6 , HCN, CO_2 , C_4H_2 , HC_3N , $^{13}CO_2$, and finally H_2O being the weakest feature.

3.2. The flux ratio between C_2H_2 and H_2O

The anti-correlation between $F_{C_2H_2}/F_{H_2O}$ (identically $L_{C_2H_2}/L_{H_2O}$) and the stellar luminosity can be seen in Figure 2. This correlation spans over three orders of magnitude in stellar luminosity (almost two orders of magnitude in stellar mass) and over three orders of magnitude in $F_{C_2H_2}/F_{H_2O}$. We find that the absolute flux of H_2O decreases with decreasing stellar luminosity (Pearson correlation coefficient, PCC=0.84, p -value= 6×10^{-10} , but the C_2H_2 flux does not; instead, the C_2H_2 line-to-continuum ratio increases with decreasing stellar luminosity (PCC=-0.65, p -value= 2.7×10^{-5} ; see Figure A.1 in Appendix A and also Figure 8 in Arabhavi et al. 2025b). Therefore, the strong correlation that we find between $F_{C_2H_2}/F_{H_2O}$ and L_* (PCC=-0.77, p -value= 1.3×10^{-7}) is due to a combination of weak H_2O and strong C_2H_2 features in the very low-mass objects and vice versa for the T Tauri stars. While there is the overall decrease in $F_{C_2H_2}/F_{H_2O}$ with increasing stellar luminosity, even at a given stellar luminosity in the T Tauri sample, the spread in line flux ratio is around ~ 50 . We note that we do not include the accretion luminosity in the luminosity plotted in Figure 2 because the stellar luminosity is much higher ($L_{acc} \lesssim 0.1 L_*$ or even $L_{acc} \lesssim 0.01 L_*$ for the range of stellar luminosities in our sample; e.g., Mendigutía et al. 2015; Alcalá

et al. 2017; Manara et al. 2017); however, we note that this would only strengthen the correlation, if only modestly.

Additional correlations are seen with other system properties, including the stellar mass, accretion rate and disk dust mass (the latter two are presented in Figure 3). Given the correlations between stellar luminosity and mass and the correlations of the other properties with stellar mass ($M_* - \dot{M}$ as in e.g., Hillenbrand et al. 1992; Hartmann et al. 2016; Grant et al. 2022; Manara et al. 2023 and $M_* - \dot{M}_{dust}$ as in e.g., Andrews et al. 2013; Pascucci et al. 2016; Manara et al. 2023), this is not surprising. The trends seen with these system parameters are not as strong as the trend with stellar luminosity. It would also be interesting to put the JWST results into context with the outer disk information; however, high resolution (sub-)millimeter observations of the VLMS sample are currently lacking, therefore we cannot explore any potential correlations with R_{disk} (however, see Arulanantham et al. 2025 for the JWST Disk Infrared Spectral Chemistry Survey sample of T Tauri objects). We discuss the potential role of radial drift further in Section 4.

In Figure 3, we also show the relationship between $F_{C_2H_2}/F_{H_2O}$ and the strength of the $10 \mu m$ silicate feature. An overall negative correlation is observed, i.e. targets with weaker silicate features are more likely to have stronger C_2H_2 emission relative to H_2O . Interestingly, none of the sources with a $10 \mu m$ band strength of greater than 1.85 have C_2H_2 detections. The potential underlying connection is discussed in Section 4.3. Correlations between the parameters discussed above are also provided relative to the absolute fluxes and to the line-to-continuum ratios in Appendix A, where the strongest correlation is between the H_2O flux and the accretion rate, as previously found (e.g., Banzatti et al. 2020).

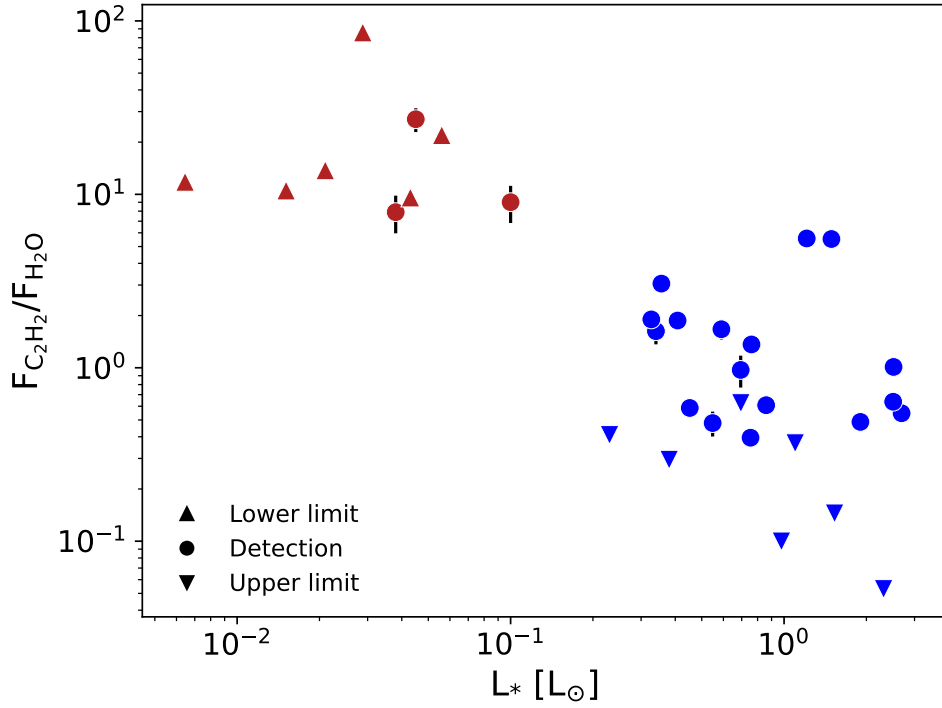


Fig. 2. The relationship between the flux ratio of C₂H₂ to H₂O as a function of stellar luminosity. Objects with $M_* > 0.2 M_\odot$ are colored in blue and represent our T Tauri sample, while those with stellar masses below $0.2 M_\odot$ are our VLMS sample and are shown in red. The two outliers around $L_* \sim 1 L_\odot$ are DL Tau and V1094 Sco, which will be analyzed in detail in Tabone et al. (in prep.). This trend is statistically significant with a p -value of 1.3×10^{-7} and a correlation coefficient of -0.77 . Upper/lower limits (downward/upward triangles) are the 3σ limits. Error bars are smaller than the points for most targets.

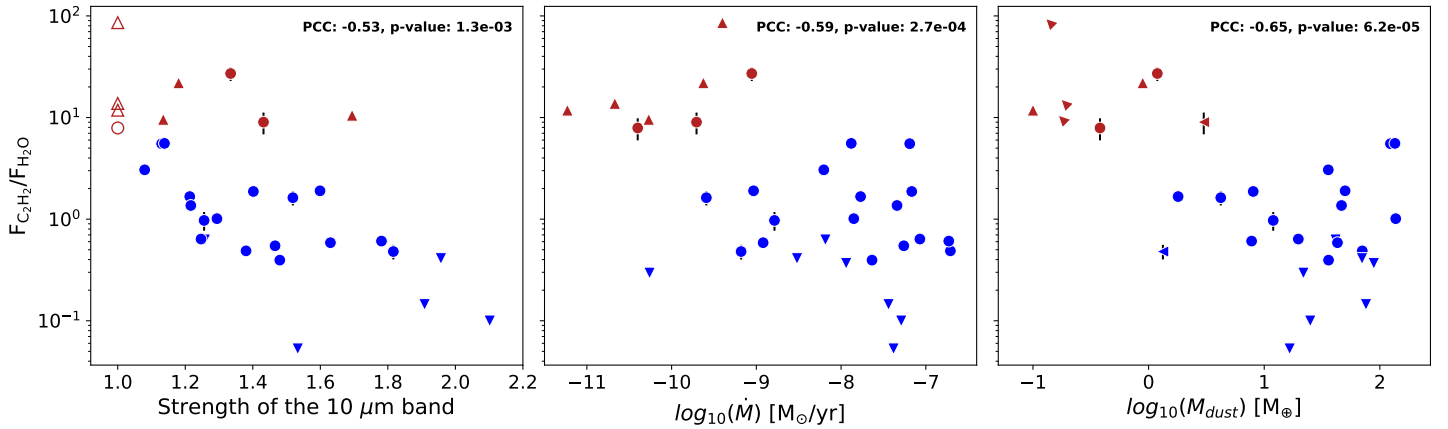


Fig. 3. Left: $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ as a function of the strength of the $10 \mu\text{m}$ silicate feature (stronger silicate features have higher values). For four of the VLMS, there is either no $10 \mu\text{m}$ emission or the emission is coming at least partially from C₂H₄, therefore we adopt feature strength of 1 for these sources (denoted by open points). Two outliers at a $10 \mu\text{m}$ band strength of 3 and 3.8 are the transitional disks LkCa 15 and PDS 70 and have been removed for clarity. Middle: The relationship between $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ and $\dot{M}$. Right: The relationship between $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ and M_{dust} . The PCCs and p -values can be found for each panel. All of the relationships are statistically significant (p -value < 0.05); however the correlations are not as strong as the $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ vs. stellar luminosity relationship. Rotated triangular markers for the VLMS sample indicate lower limits on $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ and upper limits on M_{dust} . Error bars are smaller than the points for most targets.

3.3. Fitting the average spectra

In order to interpret the average properties, we use 0D LTE slab models (see Grant et al. 2023; Tabone et al. 2023 for details) to reproduce the average spectra using only three free parameters: the column density (N), temperature (T), and the emitting area, characterized by a disk with an emitting radius (R). In order to fit each spectrum, we follow the method of Grant et al. (2023).

Briefly, the slab model spectra are calculated with a Gaussian line profile with a full width at half maximum of $\Delta V = 4.7 \text{ km s}^{-1}$ ($\sigma = 2 \text{ km s}^{-1}$) at a spectral resolving power of 2300 to match the resolution of MIRI MRS in the ~ 13 to $17 \mu\text{m}$ wavelength region. Then the model is sampled on the same wavelength grid as the data using SpectRes (Carnall 2017). A grid of models is calculated for each molecular species, with N from 10^{14} to 10^{22} cm^{-2} in steps of 0.166 in $\log_{10}$ -space, T from 100 to 1500 K in

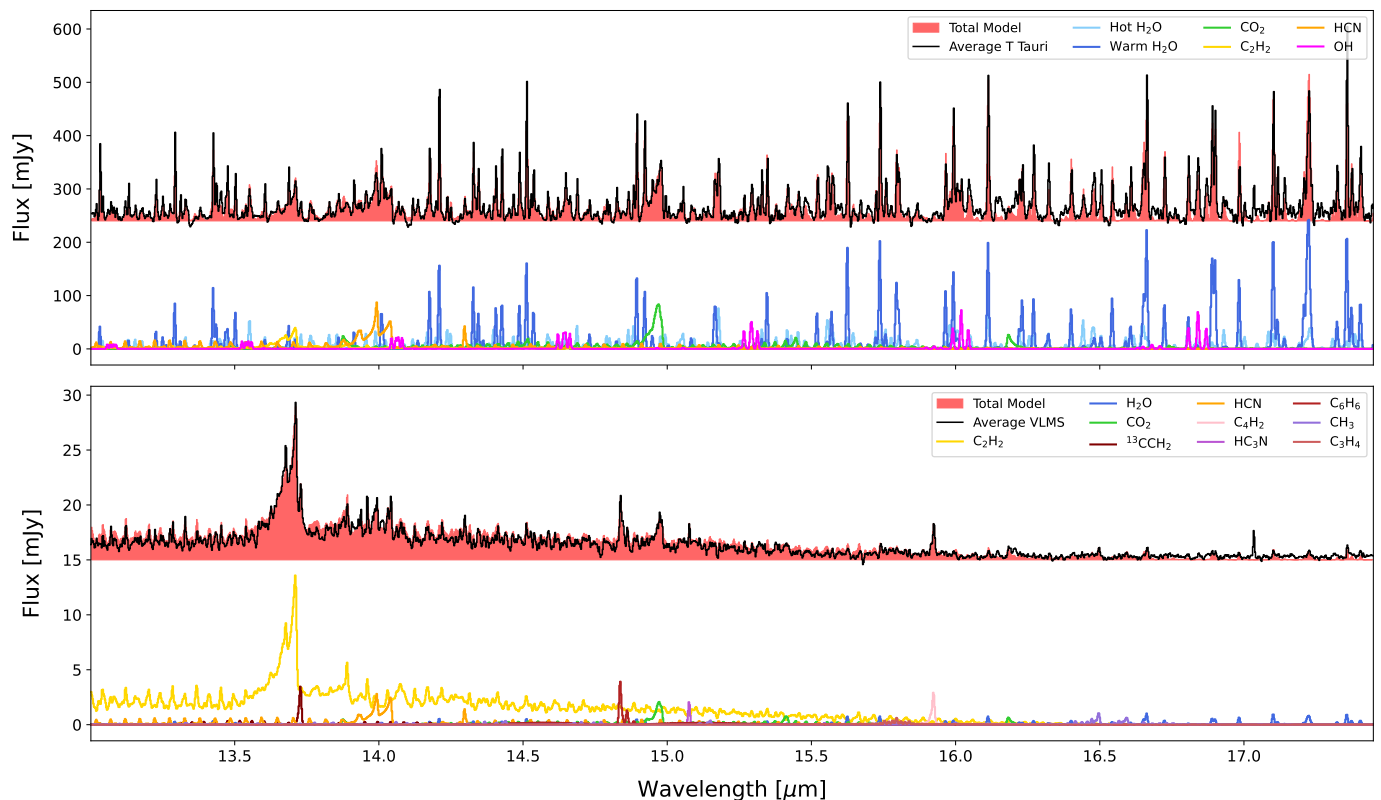


Fig. 4. The average spectra for disks in our T Tauri sample (top) and VLMS sample (bottom) in black, compared to the best-fit model in red. The model components are shown below each for reference.

steps of 25 K, and the emitting area is varied by changing the radius from 0.001 to 10 au in steps of 0.02 in $\log_{10}$ -space. One molecule is fit at a time, selecting wavelength regions that are relatively devoid of emission from other species. Then, the best-fit model is subtracted off and the next species is fit. This iterative approach has been shown to produce consistent results with analysis performed doing a simultaneous fitting of all molecular species (e.g., Grant et al. 2023 and Kaeufer et al. 2024a). Two H₂O components, one hot component with $T > 1000$ K and one intermediate component with $T \sim 600$ K, are needed to reproduce the lines in the 13–17.5 μm wavelength range for the average T Tauri spectrum, in line with works on individual sources (e.g., Grant et al. 2024; Temmink et al. 2024a; Romero-Mirza et al. 2024; Banzatti et al. 2025). Similarly, two components are needed to fit the C₂H₂ in the VLMS spectrum in order to reproduce the molecular pseudo-continuum (Tabone et al. 2023; Arabhavi et al. 2024; Kanwar et al. 2024). The best-fit model is shown in Figure 4 and the best-fit properties for the molecules that are present in both the average VLMS and T Tauri spectra are presented in Figure 5. The χ^2 maps are presented in Figure B.1 and B.2 for the T Tauri and VLMS spectra, respectively.

While some of the molecules are not well constrained, there are some interesting conclusions we can draw from the average-fit properties. Notably, the column densities for HCN, CO₂, and H₂O (the intermediate component for the T Tauri spectrum) are consistent between the VLMS and the T Tauris. While the equivalent emitting radii are largely unconstrained due to the degeneracy between radii and column density in the optically thin regime, the radii do tend to smaller values in the VLMS compared to the T Tauris. Given different snowline locations in disks around VLMS relative to T Tauri stars, we determine wa-

ter snowline location for each subsample in order to normalize the emitting radii in the bottom right panel of Figure 5. We use Equation 2 in Mulders et al. (2015) to determine the snowline location, which is based on the 3D radiative transfer models of Min et al. (2011), using the average stellar mass and accretion rate for each subsample ($M_* \sim 0.6 M_\odot$ and $\dot{M} \sim 10^{-7.75} M_\odot \text{ yr}^{-1}$ for the T Tauri sample and $M_* \sim 0.08 M_\odot$ and $\dot{M} \sim 10^{-10} M_\odot \text{ yr}^{-1}$ for the VLMS sample). This results in an H₂O snowline location of 2.25 and 0.12 au for the T Tauris and VLMS, respectively. With this normalization, the gas properties of the VLMS tend to have larger emitting radii than their higher-mass counterparts. One of the most well-constrained molecules in each case is CO₂, which is optically thick for both samples and has a cooler temperature than the other molecules. Our CO₂ and C₂H₂ temperatures are colder than what was found in the JDISCS sample of Arulanantham et al. (2025). Although it will be necessary to model each spectrum in order to get a more global picture of the diversity in the molecular properties (as was done in Arulanantham et al. 2025), the average fit already provides interesting initial clues into the similarities and differences between the two samples.

While not shown in Figure 5, the hydrocarbons besides C₂H₂ in the VLMS spectra tend to be cold (< 300 K) and in the optically thin regime with column densities $\lesssim 10^{-17.5} \text{ cm}^{-2}$ (see Figure B.2). The difference in temperature between C₂H₂ and the other hydrocarbons is likely due at least in part to the high abundances of C₂H₂. The optically thick component likely originates in the very inner disk, given its small emitting area, seen now in several sources (Tabone et al. 2023; Arabhavi et al. 2024; Kanwar et al. 2024; Long et al. 2025). Based on the 1σ contours for the equivalent emitting radius, the maximum radius for the optically thick C₂H₂ component is 2.5 times smaller than the min-

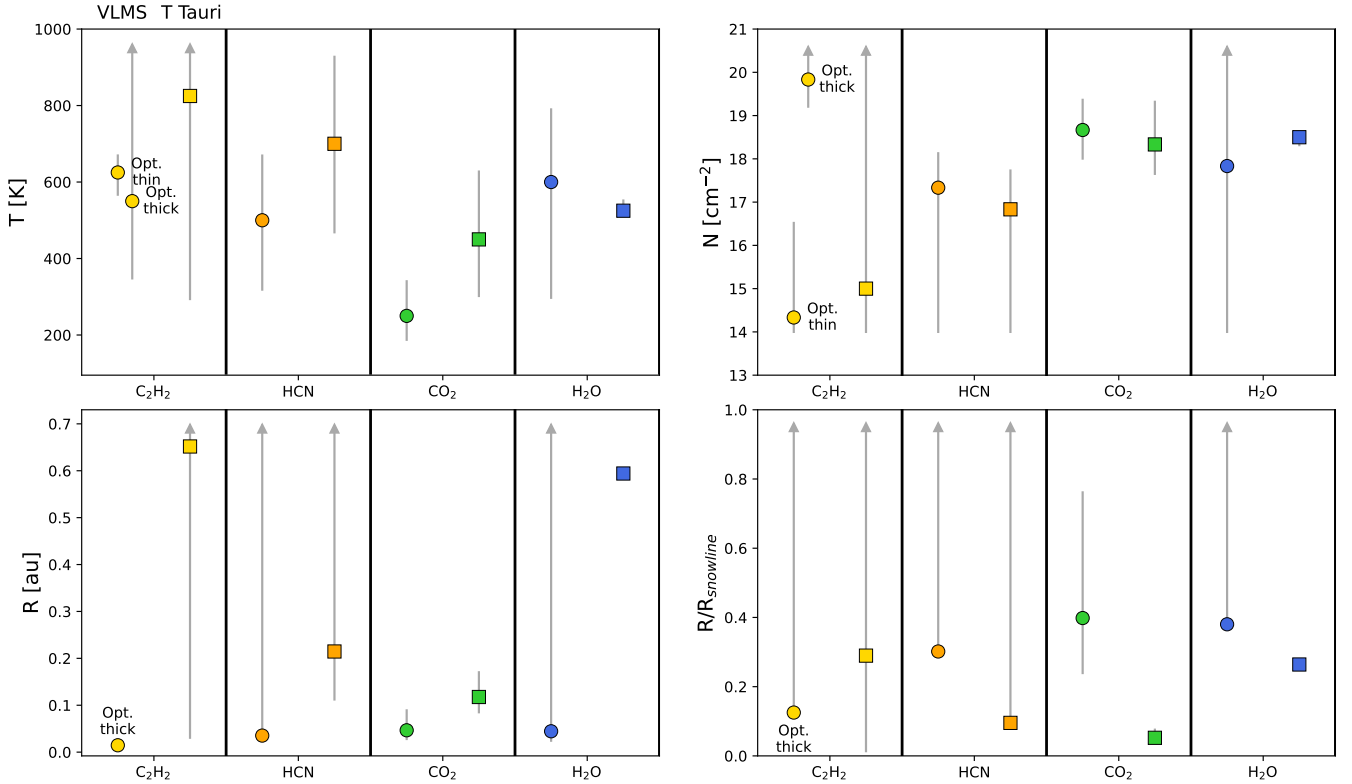


Fig. 5. The best-fit slab model parameters for the average VLMS spectrum (left circles) and T Tauri spectrum (right squares) for the different molecules. The H₂O component for the T Tauri spectrum is the intermediate ($T \sim 600$) component. Temperature and column density are shown on the top on the left and right, respectively. The equivalent emitting radius is shown on the bottom left and that radius normalized to the H₂O snowline for each subsample is shown on the bottom right. Only the optically thick C₂H₂ component is shown for the VLMS in the radii plots, as the radius is unconstrained in the optically thin case. Error bars are determined from the 1σ confidence intervals and in some cases are degenerate between parameters. For example, in the case of optically thin emission, the column density and equivalent emitting radii are degenerate. See Figures B.1 and B.2 for the χ^2 maps for the T Tauri and VLMS fits, respectively.

imum radius for the optically thin component (0.027 vs 0.067 au, respectively). Although we cannot put good constraints on the emitting area of the optically thin hydrocarbon emission (see Figure B.2), the fact that the optically thin C₂H₂ component is hotter than the other more complex hydrocarbons could come from it emitting at higher layers in the disk atmosphere (see Appendix D in Kanwar et al. 2024) or slightly closer to the star at higher temperatures. The latter could point to a radial change in the gas phase C/O ratio, wherein C₂H₂ can form at lower C/O ratios but the more complex hydrocarbons need higher values to form. Additional 2D thermochemical modeling, including non-LTE effects, will be useful to investigate the temperatures determined from the observations.

4. Discussion

We find a strong anti-correlation between the flux ratio of C₂H₂ to H₂O and the stellar luminosity. Most of the targets fall within the $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ ratio found from the T Tauri modeling work of Anderson et al. (2021) (see their Figure 11, although we note that we do not use the exact same wavelength range to determine the fluxes). T Tauri objects with an observed $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}} \leq 2$ would be most consistent with an oxygen-rich volatile content and a C/O ratio below 0.57, based on the Anderson et al. (2021) models. On the other hand, objects with host masses below $\sim 0.2 M_{\odot}$ have significantly higher $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ ratios than their higher-

mass counterparts, stemming from their decreased H₂O fluxes and increased C₂H₂ fluxes. This work builds upon trends seen with *Spitzer* observations by Pascucci et al. (2013) and initial results with JWST (see e.g., Kamp et al. 2023; Long et al. 2025; Arabhavi et al. 2025a).

Many factors can influence both the composition of disks and how much of the composition can actually be observed. Additionally, many of these factors can be related, making it non-trivial to determine what is driving the observed correlations in these samples. With this in mind, we explore the correlations that we have found and discuss what physical processes may be dominating the large difference in chemical signatures between VLMS and T Tauris.

4.1. Carbon enrichment or oxygen depletion in the VLMS disks?

The hydrocarbon-dominated average VLMS spectrum in Figure 4 highlights the rich carbon chemistry that has been found in other VLMS with JWST thus far (e.g., Tabone et al. 2023; Arabhavi et al. 2024; Kanwar et al. 2024; Long et al. 2025; Morales-Calderón et al. 2025). Long et al. (2025) use the models of Najita et al. (2011), paired with the column density ratio of C₂H₂ to CO₂, to determine the C/O ratio in their carbon-rich disk. Doing the same for the average fit spectra, the average VLMS has a C/O of ~ 1 . It is worth investigating whether the high C/O ra-

tio inferred for these disks is due to carbon enhancement and/or oxygen depletion.

The high C_2H_2 column densities derived (e.g., Tabone et al. 2023 and upper right panel of Figure 5) and the C_2H_2/HCN findings of Pascucci et al. (2009) point to carbon enhancement in the VLMS disks. Additionally, the presence of large hydrocarbon chains, including C_2H_6 , C_3H_4 , C_4H_2 , and C_6H_6 , is pointing to very abundant gas-phase carbon and a gas-phase $C/O > 1$. We note that C_2H_4 and C_2H_6 are present in a few sources, but at shorter wavelengths than we analyze here; see Arabhavi et al. (2025a) for more details.

An interesting finding pointing away from at least some oxygen depletion being the cause of the high C/O is the common presence of CO_2 and $^{13}CO_2$ in these disks (e.g., Tabone et al. 2023; Arabhavi et al. 2024, 2025a). Additionally, it has now been found that H_2O is in fact present in these disks, albeit at very low flux levels (Arabhavi et al. 2025b), in line with the decrease in stellar luminosity (Figure A.1) and therefore emitting area, especially as the H_2O snowline is very close to the central object in these disks. This will particularly impact the hottest H_2O , mostly in the ro-vibrational lines at shorter wavelengths as the emitting area is very radially compact (see Figure 9 in Arabhavi et al. 2025b for a schematic). Another key oxygen tracer is CO , as it will lock up the bulk of the free oxygen when $C/O > 1$. Interestingly, CO – at least the high E_{up} lines of the P -branch that is covered by MIRI MRS – is not frequently detected in disks around VLMS: only two of the 10 VLMS sources in the MINDS program have CO in emission (Arabhavi et al. 2025a). It is unclear why oxygen is present in CO_2 but only weakly in H_2O or CO in these disks. Perhaps the H_2O and CO are present, but not readily observable, either due to the relative strength of the hydrocarbon Q -branches relative to the H_2O lines and/or photospheric absorption complicating the detection of disk CO emission (see Arabhavi et al. 2025a).

Here we discuss some of the factors that may be driving this difference in chemistry between the very low-mass objects and the T Tauri sample.

4.2. Stellar luminosity and the radiation field

The stellar luminosity is the main heating source for protoplanetary disks. This energy input drives chemical evolution and equilibrium in the disks. The much lower luminosities of low-mass stars and brown dwarfs ($L_* \sim 0.015$ to $0.1 L_\odot$ for the sample we explore here), mean that their disks are much colder and the snowlines are much closer to the central hosts. The flux of the H_2O lines follows the stellar luminosity, likely largely tracing a change in emitting area (Salyk et al. 2011 and Figure A.1). On the other hand, the C_2H_2 flux does not follow this trend down to the very low-mass parameter space, indicating that the C_2H_2 flux is driven by something else besides emitting area (see Appendix D in Arabhavi et al. 2025b for further discussion).

Young low-mass stars and brown dwarfs will have different UV radiation spectra than Sun-like stars. However, young M dwarfs are also known to be very active, and X-rays and EUV from flares can have a significant impact on chemical evolution (Feinstein et al. 2020). All of these differences in the radiation impinging on the protoplanetary disk will impact the disk chemistry. 2D thermochemical modeling done by Walsh et al. (2015) finds that disks around M dwarfs are more molecule rich, compared to their higher-mass counterparts. This is due at least in part to the weaker far-UV radiation for these low-mass stars. Similarly, the models of Woitke et al. (2024) find that UV fluxes correlate with the line luminosities of OH and H_2O but there is

a negative correlation with C_2H_2 and HCN due to photodissociation. Both modeling works find that X-ray-induced chemistry is important in setting the molecular complexity, in particular for C_2H_2 and HCN via the destruction of CO , N_2 , and H_2 . Therefore, the strong C_2H_2 emission in the VLMS disks may be at least partially caused by the weak UV fields of low-mass stars paired with their still moderate X-ray fluxes. Sellek & van Dishoeck (2025) explore the impact of ionization on the disk chemistry, in particular the destruction of CO by He^+ , and find that the C liberated from CO can then go into the formation of hydrocarbons. This destruction pathway, paired with rapid radial transport, can result in high C/O in the inner disks of VLMS at relatively young ages. For this scenario to work, relatively high ionization rates are needed for the VLMS, potentially due to less shielding of the disks from cosmic rays by the stellar magnetic fields and/or higher ionization from the central stars.

UV emission generated by accretion of material from the disk onto the star will also be different between the T Tauris and VLMS. While the accretion mechanism is likely the same (i.e., magnetospheric accretion), the absolute accretion rate will decrease with decreasing stellar mass, and may decrease even more rapidly below $M_* < 0.3 M_\odot$ (Manara et al. 2017). Colmenares et al. (2024) argue that the carbon-rich disk around a solar-type star studied in their work may be due to a combination of carbon grain destruction paired with an unusually low accretion rate, which allows the carbon-rich gas to persist in the disk. As we show in Figure 3, there is a relationship between $F_{C_2H_2}/F_{H_2O}$ and the accretion rate onto the star in our sample; however, while the degeneracies between the stellar mass and accretion rate make it difficult to determine what is truly driving the correlation, we do find that while F_{H_2O} decreases with decreasing accretion rate, the relationship between accretion rate and $F_{C_2H_2}$ is not as strong (see Appendix A, Figure A.2). Therefore, for the very low-mass objects, their low accretion rate may contribute to the high observed $F_{C_2H_2}/F_{H_2O}$ in two ways, by keeping the H_2O emitting area very small and by not removing all of the carbon-rich gas quickly. We note however that stars less than $0.3 M_\odot$ have been found to have a steeper L_{acc}/L_* relationship than higher mass sources, which may come from initially faster evolution (Manara et al. 2017). Thus, oxygen-rich gas may have been accreted fast at earlier ages and carbon-rich gas is accreting slowly by the age we are observing them (see discussion in 4.3.2).

4.3. Dust evolution

4.3.1. Vertical dust settling

Dust is the main opacity source in protoplanetary disks. At the earliest stages, the sub-micron sized particles will be held aloft in the disk atmosphere, but with time these grains grow from sub-micron particles into millimeter-sized grains to eventually pebbles, protoplanets, and the cores of giant planets.

Spitzer-IRS observations provided unique insights into the compositions and properties of dust in the inner disk for systems with a wide diversity of properties, including central hosts from the brown dwarf to Herbig Ae/Be regime. These works found that disks around low-mass stars and brown dwarfs show $10 \mu m$ silicate emission features, which trace micron-sized dust grains in the disk atmosphere, that are weaker than their more massive counterparts and features that show fairly high levels of crystallinity (Apai et al. 2005; Kessler-Silacci et al. 2007; Pascucci et al. 2009), now also found for objects with JWST (Kanwar et al. 2024; Kaeufer et al. 2024b). However, the radial location in the disk where the $10 \mu m$ feature will emit depends on the

stellar luminosity, such that the emitting radius for brown dwarfs will be much closer to the central object than for Herbig Ae/Be stars (≤ 0.001 - 0.1 au vs. ≥ 0.5 - 50 au; Kessler-Silacci et al. 2007). Therefore, changes in the dust vertical scale, structure, or grain size distribution may just reflect differences in the probed emitting region, rather than differences due to the stellar influence or disk evolution. In addition to the $10\ \mu\text{m}$ silicate features being generally weaker in disks around VLMS, their strength may even be overestimated in some cases. Recent JWST observations have shown that broad features from 8.5 to $12.5\ \mu\text{m}$ can in fact come at least partially from high column densities of C₂H₄ (Arabhavi et al. 2024), making it possible that some of the already weak silicate features seen in low-mass objects with *Spitzer* could in fact not even be due to dust emission. However, when present, the VLMS dust features in our sample are similar in strength to T Tauri systems with weak features, supporting that we are seeing deeper into these disks. Further investigation of the dust properties in our VLMS sample will be included in separate work (Jang et al. 2025).

If the disks around low-mass hosts have undergone more efficient dust settling, such a lack of small dust grains in the disk atmosphere means that these disks will be subject to more stellar irradiation than those around their higher-mass counterparts, where the disk atmospheres are still relatively dust rich, which may lead to additional chemical reactions. However, the biggest implication of dust settling in low-mass sources is that mid-infrared observations probe more gas before hitting the $\tau_{\text{MIR}}=1$ surface. This means that we are able to observe deeper into the disk than would otherwise be the case (see e.g., the case of J160532, Tabone et al. 2023; Franceschi et al. 2024, and the modeling work of Greenwood et al. 2019; Antonellini et al. 2023; Houge et al. 2025b). Therefore, we may be witnessing chemistry that may even be common in higher-mass systems, but which is usually hidden from view. If so, the optically thinner disks around low-mass sources may offer us a clearer picture of the midplane chemistry, where planet formation may be taking place. 2D thermochemical models find that the mid-infrared C₂H₂ emitting region is located deeper in the disk than H₂O (e.g., Woitke et al. 2018), which, paired with the high columns of carbon-rich gas we are observing, supports the idea that we are probing closer to the disk midplane in disks around lower-mass objects (see Figure 9 in Arabhavi et al. 2025a for a schematic).

4.3.2. Radial dust drift

The inward drift of dust grains from the outer disk to the inner disk will impact the chemical composition in the inner disk. These dust grains begin their journey in the cold outer disk, coated in various molecular ices. As they travel inwards, they will pass snowlines of different molecular species, liberating their icy mantles as they go and enriching the gas along the way. This drift can then supply the inner disk with, for instance, an increase in H₂O vapor (Banzatti et al. 2020; Kalyaan et al. 2021; Banzatti et al. 2023); however, it should be noted that this drift will also increase the amount of dust in the inner disk that can also shield the inner disk gas (e.g., Sellek et al. 2024; Houge et al. 2025b). Banzatti et al. (2020) found an anti-correlation between $F_{\text{H}_2\text{O}}/F_{\text{C}_2\text{H}_2}$ and R_{dust} (in our formulation with C₂H₂ in the numerator this would be a positive correlation: smaller disks have less C₂H₂ relative to H₂O). In their sample of T Tauri stars, this indicates that dust drift may be shrinking the dust disks and enriching the inner regions in H₂O. Conversely, if this drift is halted, for instance via gap opening by a giant planet, this can

result in a relatively “dry” inner disk, that is lacking this extra oxygen enrichment (Najita et al. 2013).

Given this expectation that drift-dominated disks will be enriched in H₂O vapor, we might expect that disks around VLMS are rich in H₂O, due to their efficient dust drift (e.g., Pinilla et al. 2013, 2022). Mah et al. (2023) use disk evolution models to investigate this hypothesis and conclude that this enrichment might be so efficient and so rapid in low-mass systems, that this takes place very early in the disk lifetime. If this oxygen-enriched gas were to then accrete onto the central star/brown dwarf, in particular if accretion evolution happens faster in these sources (Manara et al. 2017), this would leave only carbon-rich gas to advect inward later and more slowly from the outer disk (e.g., Miotello et al. 2019; Bosman et al. 2021). This may result in a time-dependent change in the disk C/O ratio, where disks around low-mass hosts undergo a rapid decrease in C/O followed by a gradual increase in C/O (see also Sellek et al. 2024). This may also explain the 30 Myr evolved carbon-rich disk analyzed by Long et al. (2025). The modeling work of Sellek & van Dishoeck (2025) find that disks that are compact initially, as may generally be the case for disks around VLMS, high C/O in the inner disk can be reached by young ages. However, if substructures were simply to slow down but not halt radial drift, this may prolong H₂O enrichment (e.g., Kalyaan et al. 2023; Mah et al. 2024), which is the proposed explanation for the H₂O-rich spectrum of a disk around a VLMS analyzed by Xie et al. (2023). Although we cannot explore any correlations with dust radius for the VLMS sample due to the limited number of high angular resolution observations of these sources in general and in our sample particularly, we explore the relationship between $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ and the disk dust mass (Figure 3). As with the accretion rate, the trend here may be driven by the correlation between M_* and M_{disk} (Pascucci et al. 2016), and therefore with the stellar luminosity. However, the disk mass may in fact be a driving factor in setting the inner disk chemistry. More massive disks, which exist around more massive stars, will be able to form giant planets that are capable of forming traps that will halt radial drift (e.g., van der Marel & Mulders 2021). The low-mass disks around low-mass stars, on the other hand, may be (generally) incapable of forming such deep substructures, therefore allowing radial drift to happen efficiently, bringing in ice-rich material quickly.

In order to observationally test the predicted connection between drift and inner disk chemistry in disks around very low-mass hosts, two steps would be paramount: 1) observations of disks around VLMS at very young ages (≤ 0.5 Myr) to see if the gas is oxygen-rich and 2) high-resolution observations with ALMA to determine the outer radii and overall dust structure in disks around low-mass stars and brown dwarfs. The former can be done with JWST observations of younger star-forming regions, something that is currently being investigated (e.g., PID 3886, PI S. Grant), although going to even younger sources (i.e., embedded Class I sources) may be required (e.g., PID 7890, PI L. Tychoniec and PID 7135, PI K. Zhang). Exploring the latter – the connection between outer disk substructures and inner disk chemistry in VLMS disks – is challenging, given the faint nature of the disks around very low-mass stars and brown dwarfs. ALMA observations have only been done in a handful of sources at high enough angular resolution and sensitivity in the gas and dust to determine the $R_{\text{gas}}/R_{\text{dust}}$ ratio, which is expected to be high in the case of drift-dominated disks (Trapman et al. 2019; Toci et al. 2021). In shallow surveys these disks are often undetected, let alone spatially resolved. However, based on the small sample of resolved sources, it appears that drift is indeed quite efficient in disks around these objects (Kurtovic

et al. 2021). That being said, there is generally a lack of overlap between the samples with JWST data and the high-resolution ALMA data to characterize the outer disks in these exceptionally faint objects. Efforts to correct this lack of overlap will be crucial to link outer disk processes to inner disk chemistry in these systems (Xie et al. 2023) and some programs to do this are underway (e.g., 2024.1.00361.S, PI F. Long). Finally, while the focus of our discussion here has been on the early increase in C/O in low-mass systems, it should be noted that this scenario indicates that disks around T Tauri stars should show an increase in C/O at later times. Therefore, inner disk chemistry in T Tauri systems should be investigated across a range of ages to determine if such an increase in the C/O ratio is seen on timescales indicated by the models.

4.3.3. Carbon-grain destruction

Carbon-grain destruction is another viable method of increasing the gaseous C/O ratio in the inner disk (see the recent work of Houge et al. 2025a). While the sublimation temperature of refractory carbon species is debated in the literature, some estimates put the temperature as low as ~ 500 K (Li et al. 2021). If this “soot line” were present in the disks around low-mass stars, the increase in gaseous carbon would allow for the formation of the carbon-rich gas species that are now observed (Tabone et al. 2023; Arabhavi et al. 2024). While the average fit parameters of the hydrocarbons in the VLMS point to low temperatures (CO_2 , HC_3N , and C_6H_6 all have temperatures below 250 K), thus potentially pointing away from this mechanism being the dominant factor in enhancing the carbon in these disks, it may instead be that the grains are not entirely destroyed and may instead simply be eroded by high-energy radiation or H atoms. If such destruction/erosion is happening in these disks, we may not see the same effects in most T Tauri disks either due to the higher dust opacities, blocking the C-rich gas from being observed, and/or due to the difference in the level of X-ray/cosmic ray ionization. While this may be generally true, the carbon-rich spectrum of DoAr 33 has been analyzed in this context by Colmenares et al. (2024), who suggest that the low accretion rate of this object may allow the carbon-rich material to “burn and linger”, which could also explain our VLMS sources, which have low accretion rates. However, we note that the correlation with accretion rate (Figure 3) is not as strong as the correlation with stellar luminosity (see also Figure A.2).

5. Summary and conclusions

We explore the transition from H_2O -rich spectra to C_2H_2 -dominated spectra with decreasing stellar luminosity using JWST-MIRI MRS observations from the MINDS collaboration, spanning (sub-)stellar masses from 0.02 to $1.5 M_\odot$.

1. The flux of H_2O drops with decreasing stellar luminosity and accretion rate, as expected. Conversely, the C_2H_2 flux increases at the lowest host masses with an increase in the line-to-continuum ratio with decreasing L_* , driven by the strong C_2H_2 features present in the disks around low-mass stars and brown dwarfs.
2. We find a strong anti-correlation between the $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ and stellar luminosity. Anti-correlations also exist between this flux ratio and the strength of the $10 \mu\text{m}$ silicate feature, the accretion rate, and the disk mass, all of which may be due in part to strong correlations with the stellar mass and luminos-

ity, but may be related to disk evolution processes that result in the abundant carbon-bearing species observed.

3. We compute the average spectra for the very low-mass sample (VLMS, $M_* \leq 0.2 M_\odot$) and the T Tauri sample ($M_* > 0.2 M_\odot$). The average T Tauri spectrum is dominated by the forest of H_2O lines, but features from C_2H_2 , HCN, CO_2 , and OH are present. The average VLMS spectrum is dominated by the strong C_2H_2 Q -branch, with a molecular pseudo-continuum, with features from $^{13}\text{CCH}_2$, HCN, C_6H_6 , CO_2 , HC_3N , C_3H_4 , C_4H_2 , CH_3 , and finally weak H_2O lines.
4. We use slab models to fit the average spectra for the T Tauri sample and the VLMS sample. We find that one component of the H_2O emission in the T Tauri average is similar in properties to the H_2O in the average VLMS spectrum, although the VLMS H_2O has a smaller emitting area, albeit in the optically thin regime where column density and emitting area are degenerate. Two components, one optically thick and one optically thin, are needed to reproduce the C_2H_2 emission in the VLMS spectrum, similar to what has been found in individual VLMS spectra analyzed thus far. The hydrocarbon gas is generally quite cold, with CH_3 , HC_3N , C_3H_4 , C_4H_2 and C_6H_6 having temperatures below ~ 300 K.
5. We suggest that the $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ correlation is driven by an increase in the volatile C/O ratio in the disks around very low-mass stars and brown dwarfs, although more modeling work is needed to explore exactly how $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ and C/O are connected, especially in low-mass systems and utilizing extended carbon chemistry networks. If the high $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}$ ratios for VLMS are due to a high gas phase C/O in the inner disk, this is likely driven by an enhancement in carbon-rich gas, rather than oxygen depletion alone. This carbon enrichment may be due to the weaker UV radiation and/or X-ray/cosmic ray ionization from very low-mass objects or due to the different evolutionary timescales of their disks, in particular the fast dust evolution that takes place in disks around VLMS, or some combination of multiple processes acting in concert. The latter can both alter the chemistry, via radial drift and/or by vertical dust settling, the latter of which allows for stellar radiation to penetrate closer to the disk mid-plane and means that our infrared observations probe deeper into the disk due to the decreased opacity. Some of these potential processes are tightly linked to the age of the systems, necessitating further exploration across a range of ages and evolutionary states in both stellar mass regimes.

By analyzing large samples of disks with a wide range of parameter space, we are able to investigate trends with system properties. However, given that many physical and chemical processes are correlated and, in some cases, interconnected, it is crucial to scrutinize the samples over multiple axes, to collect complementary data, and to compare the observations to models in order to determine the driving processes.

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Appendix A: $F_{\text{C}_2\text{H}_2}$, $F_{\text{H}_2\text{O}}$, and the line-to-continuum ratio

The relationships between the absolute flux values of C₂H₂ and H₂O and the line-to-continuum ratios for those molecules as a function of stellar luminosity are presented in Figure A.1. The $F_{\text{H}_2\text{O}}-L_*$ relationship is largely as expected: the lower luminosity of the host, the lower the line luminosity, although we may be limited by sensitivity for the H₂O lines in the VLMS sample. By contrast, there is no clear $F_{\text{C}_2\text{H}_2}-L_*$ relationship; however, there is a correlation between the line-to-continuum ratio for C₂H₂ and the stellar luminosity. The relationships between the absolute fluxes and the strength of the 10 μm silicate feature, stellar accretion rate, and the disk dust mass are presented in Figure A.2. The strongest correlation there is between the H₂O flux and the stellar accretion rate, found similarly between $L_{\text{H}_2\text{O}}$ and the accretion luminosity by Banzatti et al. (2020). However, the trend between the C₂H₂ line flux and the accretion rate, while present, is not very strong. This may be due to the bright C₂H₂ fluxes of the VLMS, as correlations have been seen between C₂H₂ and $\dot{M}$ in T Tauri samples by Banzatti et al. (2020) and Arulanantham et al. (2025).

Woitke et al. (2024) find that the flux of C₂H₂ reacts more strongly to an increase in accretion rate than H₂O does, which is not what we find in our sample. Given the relationship between accretion rate and stellar luminosity (see e.g., Manara et al. 2023 and references therein), we also check $F_{\text{H}_2\text{O}}$ vs. $\dot{M}/M_*$, which are correlated, but with a weaker correlation than $F_{\text{H}_2\text{O}}-\dot{M}$ and than $F_{\text{C}_2\text{H}_2}/F_{\text{H}_2\text{O}}-L_*$.

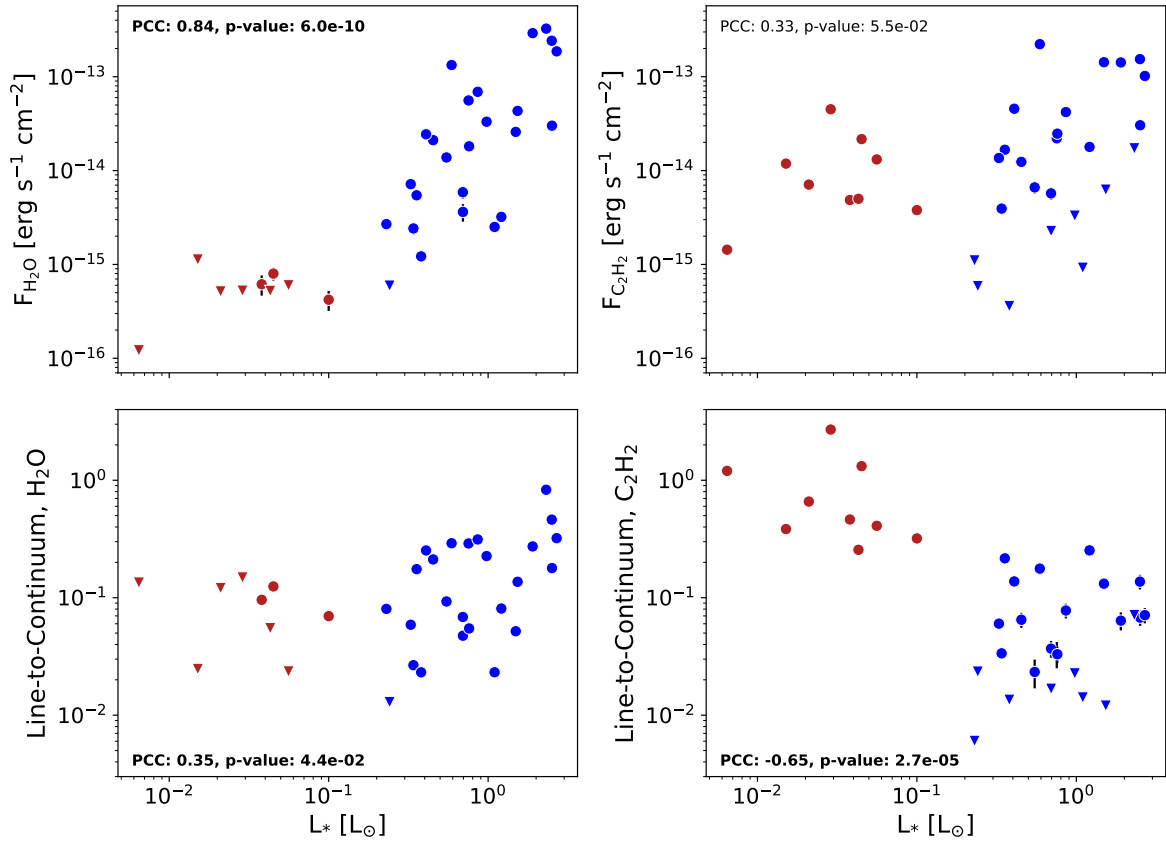


Fig. A.1. The absolute fluxes of H₂O (top left) and C₂H₂ (top right) as a function of stellar luminosity. The fluxes are determined after normalizing the spectra to a distance of 120 pc. The line-to-continuum ratio for H₂O and C₂H₂ as a function of stellar luminosity are shown in the bottom left and right, respectively. Upper limits (downward triangles) are the 3 σ fluxes. Error bars are smaller than the points for most targets. The blue points are the T Tauri sample and the red points are the VLMS targets. The PCCs and p -values can be found for each panel. Significant correlations (p -value < 0.05) are provided in bold. $F_{\text{H}_2\text{O}}$ vs. L_* (top left) and C₂H₂ line-to-continuum ratio vs. L_* (bottom right) have the strongest correlations.

Appendix B: χ^2 maps

The reduced χ^2 maps for the molecules detected in the average T Tauri and VLMS spectra are shown in Figures B.1 and B.2, respectively. The contours are the 1 σ , 2 σ , and 3 σ levels determined as $\chi^2_{\text{min}} + 2.3$, $\chi^2_{\text{min}} + 6.2$, and $\chi^2_{\text{min}} + 11.8$, respectively (see Appendix C of Grant et al. 2023 for details).

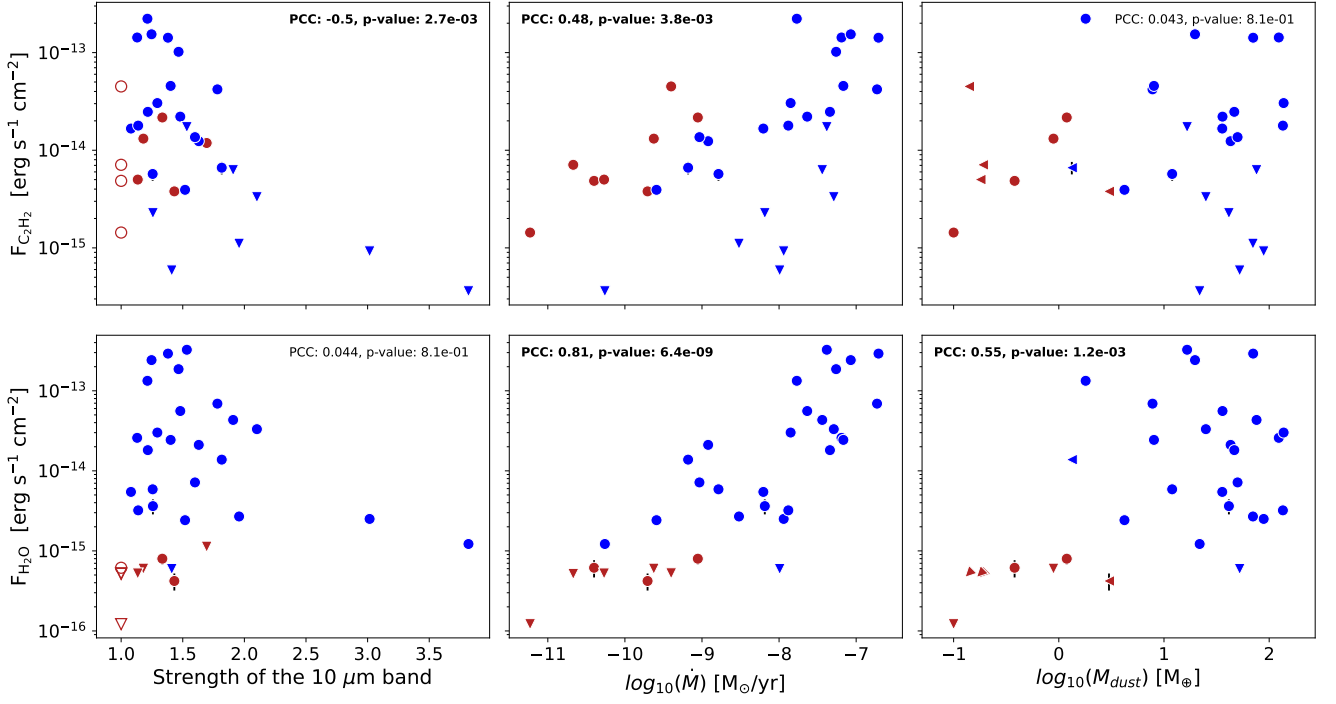


Fig. A.2. The absolute fluxes of C_2H_2 (top) and H_2O (bottom) as a function of the strength of the $10 \mu\text{m}$ silicate feature (left), stellar accretion rate (middle), and dust disk mass (right). The fluxes are normalized to a distance of 120 pc. Upper limits (downward triangles) are the 3σ fluxes; objects with M_{dust} upper limits are either leftward facing triangles if the molecular species is detected, or rotated triangular markers if both the flux and dust mass are upper limits. Error bars are smaller than the points for most targets. The blue points are the T Tauri sample and the red points are the VLMS targets. The PCCs and p -values can be found for each panel. Significant correlations (p -value < 0.05) are provided in bold.

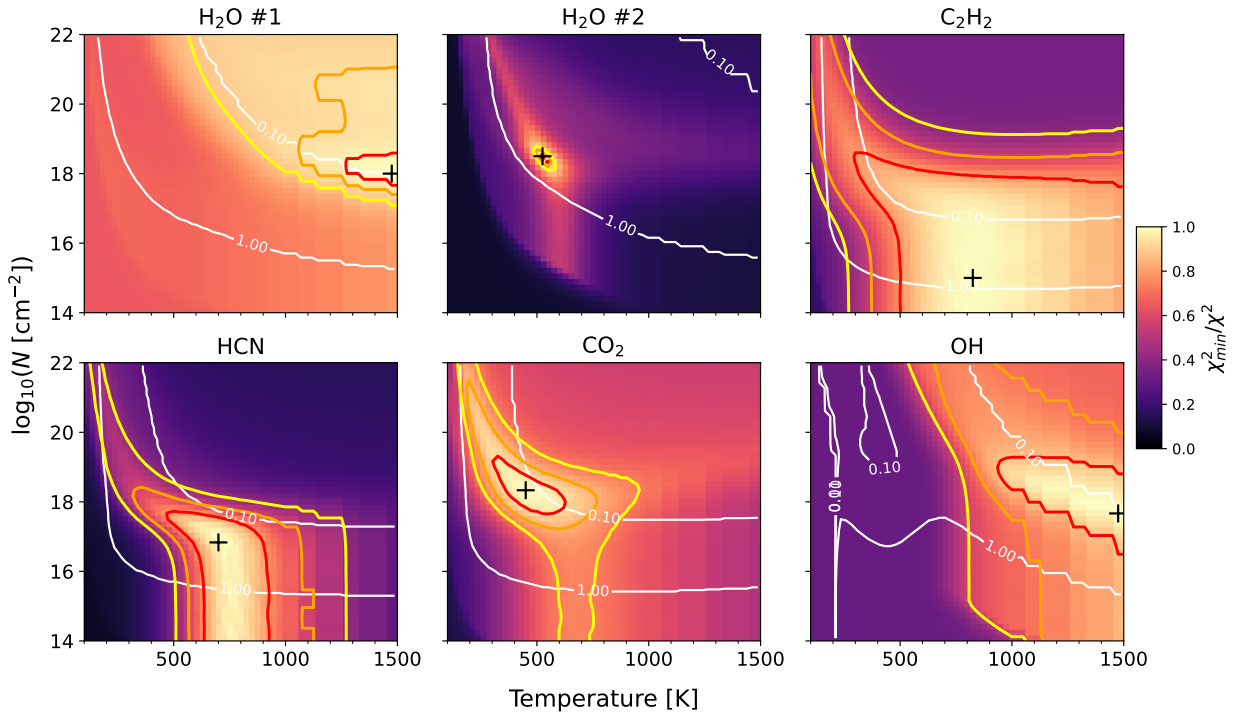


Fig. B.1. The χ^2 maps for the molecules fitted in the average T Tauri spectrum. The color-scale shows $\chi^2_{\text{min}}/\chi^2$ and the red, orange, and yellow contours correspond to the 1σ , 2σ , and 3σ levels. White contours show the emitting radii in au, as given by the labels. The best-fit model is represented by the black plus.

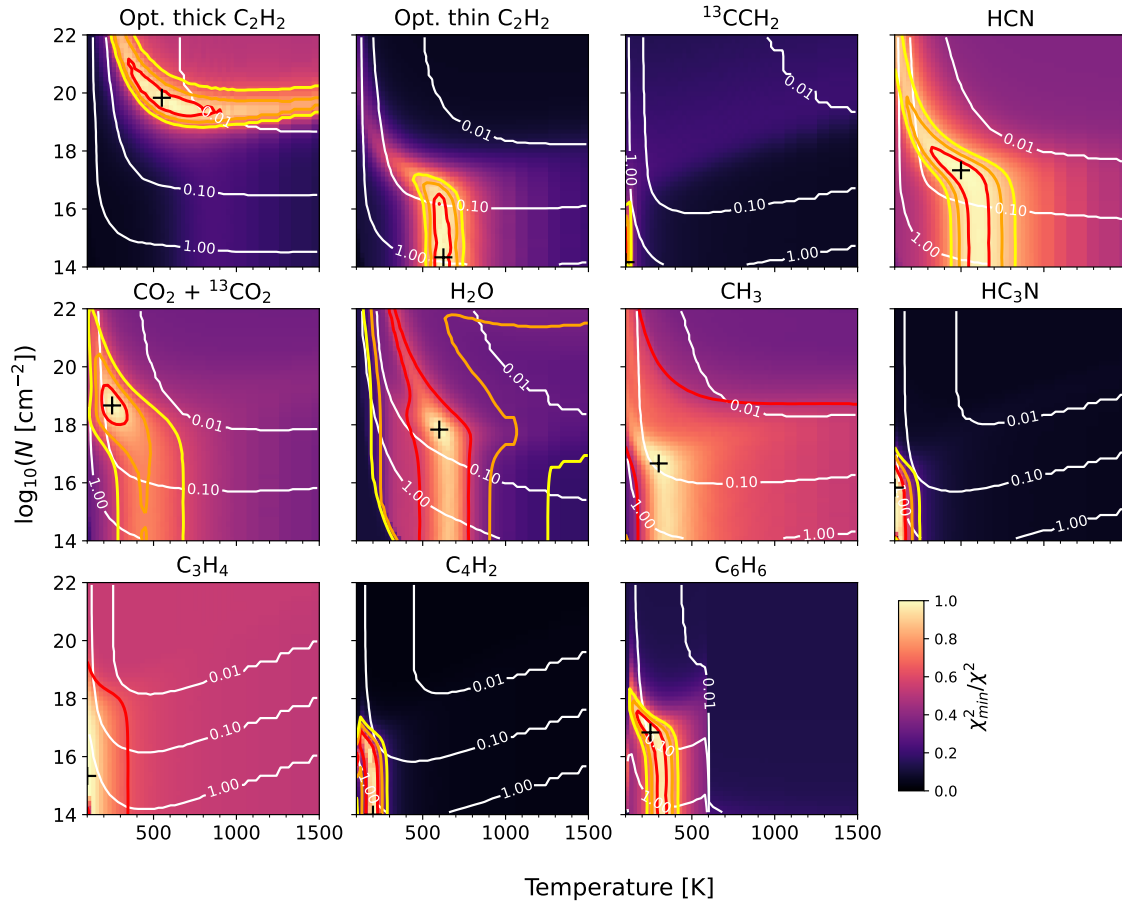


Fig. B.2. Same as Figure B.1, but now for the molecules in the average VLMS spectrum.