Exploring the formation pathways of formamide near young O-type stars

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ABSTRACT

Context. As a building block for amino acids, formamide (NH₂CHO) is an important molecule in astrobiology and astrochemistry, but its formation path in the interstellar medium is not understood well.

Aims. We aim to find empirical evidence to support the chemical relationships of formamide to HNCO and H₂CO.

Methods. We examine high angular resolution (~ 0.2″) Atacama Large Millimeter/submillimeter Array (ALMA) maps of six sources in three high-mass star-forming regions and compare the spatial extent, integrated emission peak position, and velocity structure of HNCO and H₂CO line emission with that of NH₂CHO by using moment maps. Through spectral modeling, we compare the abundances of these three species.

Results. In these sources, the emission peak separation and velocity dispersion of formamide emission is most often similar to HNCO emission, while the velocity structure is generally just as similar to H₂CO and HNCO (within errors). From the spectral modeling, we see that the abundances between all three of our focus species are correlated, and the relationship between NH₂CHO and HNCO reproduces the previously demonstrated abundance relationship.

Conclusions. In this first interferometric study, which compares two potential parent species to NH₂CHO, we find that all moment maps for HNCO are more similar to NH₂CHO than H₂CO in one of our six sources (G24 A1). For the other five sources, the relationship between NH₂CHO, HNCO, and H₂CO is unclear as the different moment maps for each source are not consistently more similar to one species as opposed to the other.

Key words. stars: massive – ISM: individual objects: G17.64+0.16, G24.78+0.08, G345.49+1.47 – astrochemistry

1. Introduction

Formamide (NH₂CHO) is an important molecule to study for astrochemistry and astrobiology because its structure and content make it a likely precursor for glycine (NH₂CH₂COOH), the simplest amino acid and an important building block in the synthesis of prebiotic compounds. Saladino et al. (2012) argue that NH₂CHO may have played a key role in creating and sustaining life on the young Earth since it can lead to diversity in biologically relevant chemistry involving amino acids, nucleic acids, and sugars.

In recent years, two routes to forming NH₂CHO, which use common interstellar species, have been studied in depth. NH₂CHO forms either on dust grain ice mantles from the hydrogenation of isocyanic acid (HNCO) in the following reaction: HNCO + H + H → NH₂CHO (Charnley 1997). Subsequently, it sublimates into the gas, where we see it in hot cores and hot cores. The alternative is from reactions between H₂CO and NH₂ in warm gas (H₂CO + NH₂ → NH₂CHO + H) (Kahane et al. 2013). It is important to note that NH₂ is especially abundant in photon-dominated regions. Other formation pathways have been tested in the lab by Jones et al. (2011) Fedoseev et al. (2016, Skouteris et al. (2017), but we do not investigate them here as the species involved fall outside the frequency range of our dataset. Laboratory studies on these reactions show that both HNCO and H₂CO can have a chemical relationship with NH₂CHO. An early study by Raumier et al. (2004) found that vacuum ultraviolet irradiation of pure HNCO ice resulted in NH₂CHO as a product. Recent laboratory work by Kanuchová et al. (2017) shows that sufficient amounts of NH₂CHO can form in cosmic-ray-irradiated ices but the HNCO/NH₂CHO ratio does not match observations. The laboratory study by Noble et al. (2015) finds that hydrogenation of HNCO by deuterium bombardment does not lead to NH₂CHO in detectable quantities, while Barone et al. (2015) find that the H₂CO+NH₂ reaction can reproduce the abundance of NH₂CHO in IRAS16293-2422, a Sun-like protostar. Recent work by Quénard et al. (2018), which models the formation of HNCO and NH₂CHO and other peptide-bearing molecules with the N-C=O group, shows a correlation between the abundances of H₂CO and NH₂CHO as well as between HNCO and NH₂CHO without using hydrogenation. The chemical pathway studied in Fedoseev et al. (2016) indicates that NH₂ may be a key precursor to both HNCO and NH₂CHO, indicating that they are chemically related, but not in a reactant-product relationship. Recently,
Further theoretical formation pathways have been investigated through quantum chemical calculations by Darla & Sitha (2019) (NH$_3$ + CO or NH$_3$ + CO$^+$) and chemical kinetics by Vichi et al. (2019) (H$_2$O + HCN), but we do not explore those species here.

Observational evidence has been found for both chemical relationships. A tight empirical correlation has been observed using single dish observations between the abundances of HNC0 and NH$_2$CHO which spans several orders of magnitude in molecular abundance. This correlation between the abundances of these species is nearly linear, suggesting that the two molecules are chemically related. Atacama Large Millimeter/submillimeter Array (ALMA) observations by Coutens et al. (2016) of IRAS 16293-2422 show that the deuterium fractions in HNCO and NH$_2$CHO are very similar, implying a chemical link. On the other hand, Codella et al. (2017) observed a shock near L1157-B1 using interferometric observations. Through these observations and follow-up chemical modeling, they concluded that NH$_2$CHO is made efficiently in the gas phase from H$_2$CO, at least in this source. The possibility exists that different types of sources (shocked regions, outflow cavities, accretion disks, protostellar envelopes, etc.) may have different dominant formation routes, but this possibility stands to be examined. A comprehensive review of all research into the formation of interstellar formamide can be found in López-Sepulcre et al. (2019).

To make progress in the interpretation of the chemical link between these species, interferometric observations around a variety of sources are needed. We previously used ALMA to study emission extent, peaks, and velocity structure between HNCO and NH$_2$CHO in G35.20-0.74N (Allen et al. 2017). In the Keplerian disk candidate G35.20-0.74N, we found that the morphology and velocity structure of HNCO and NH$_2$CHO are almost identical, and the first moment velocity differs by less than 0.5 km s$^{-1}$. While this suggests that HNCO has a relationship to NH$_2$CHO in this source, we could not determine a relationship with H$_2$CO because those observations did not contain spectral windows with H$_2$CO lines for comparison.

In this paper, we investigate the chemical relationships between HNCO, H$_2$CO and NH$_2$CHO using high-angular resolution (≈0.2″ beam) ALMA observations to compare the emission morphology (§3.1), velocity structure (§3.2), and velocity dispersion (§3.3) of HNCO, H$_2$CO, and NH$_2$CHO emission in three high-mass star-forming regions (described in §2.1). To complement these observations, we use LTE spectral modeling to determine the column density, excitation temperature, average line width, and central velocity for each of these species in all the sources (§3.4). We discuss the results in §4 and summarize the main findings in §5.

2. Observations and method

2.1. Source sample

We observed three high-mass star forming regions with a high luminosity ($L_{bol} = 1 - 2 \times 10^5 L_\odot$). Our sources (shown in Figure 1) are a subset of the sample studied and presented in Cesaroni et al. (2017) selected for their potential as O-type (proto)stars harboring circumstellar disks. G17.64+0.16 (hereafter G17, also known as AFGL 2136 and IRAS 18196-1331), shown in the top panel of Figure 1 is located at a distance of 2.2 kpc, has a bolometric luminosity of $1 \times 10^5 L_\odot$ and has been well studied from the infrared to the radio. G17 harbors a millimeter continuum source that is cospatial with weak H30α

![Fig. 1. Images of the 218 GHz continuum emission from Cycle 2 ALMA observations of our three regions focusing on the 218 GHz continuum emission.](image-url)
emission and a molecular plume to the west of the continuum source (Maud et al. 2018), G24.78+0.08 (hereafter G24), which is shown in the middle panel of Figure 1, is located at a distance of 6.7 kpc (Reid et al. 2019), determined by trigonometric parallax, and has a bolometric luminosity of $1.7 \times 10^4 \, \text{L}_\odot$. There are several sources associated with this star-forming region but we focus on the hot molecular cores A1 and A2. G24 A1 contains a hypercompact HII region (~1000 au) which has been determined to be expanding through methanol, water maser, and recombination line observations (Belfràn et al. 2007 [Moscadelli et al. 2018], G345.47+1.47 [hereafter G345, also known as IRAS 16562-3959], shown in the bottom panel of Figure 1) located at a distance of 2.4 kpc with a bolometric luminosity of $1.5 \times 10^6 \, \text{L}_\odot$. G345 has a continuum source associated with strong $\mathrm{H30}^\alpha$ emission (G345 Main) and a chemically rich region to the northwest of this continuum source (G345 NW spur) (Johnston et al. in prep). The other three sources from the dataset described in Cesaroni et al. (2017) could not be used in these investigations because the formamide lines were strongly blended with other species.

### 2.2. Observations

The sources were observed with ALMA in Cycle 2 in July and September 2015 (2013.1.00489.S) in Band 6 with baselines from 40 to 1500 m. The observed frequency range was between 216.9 GHz to 236.5 GHz divided into 13 spectral windows. The flux calibrators were Titan and Cerés and the phase calibrators were J1733-1304 (for G17 and G24) and J1709-3525 (for G345). The rms noise of the continuum maps ranges between 0.2 and 1.0 mJy beam$^{-1}$. The calibration and imaging were carried out using CASA. A statistical method (Sánchez-Monge et al. 2018) was used within the Python-based tool STATCONT for continuum subtraction as there were very few line free channels. The angular resolution is about 0.2 arcsec and the spectral resolution in most spectral windows is 488.3 kHz, but higher (244.1 kHz) from 220.303-220.767 GHz and lower (1953.1 kHz) in the spectral window from ~216.976-218.849 GHz. The bandwidths for all spectral windows are ~2 GHz with the largest being 1.8 GHz. For full details on observations and continuum subtraction see Cesaroni et al. (2017). The continuum intensity for subsources showing $\mathrm{H30}^\alpha$ emission were corrected for free-free emission with direct measurements for G17 from Maud et al. (2018), G24 A1 from Moscadelli et al. (2018), and calculated for G345 using the spectral index fit from Guzmán et al. (2016).

### Table 1. Source properties

| Source | $v_{\text{LSR}}$ (km s$^{-1}$) | Distance (kpc) | $L_{\text{bol}}$ (10$^3$ L$_\odot$) |
|--------|-----------------------------|----------------|----------------------------------|
| G17    | 18:22.63.70                 | 22.5           | 2.2                             |
| G24 A1 | 18:36.25.44                 | 111.0          | 6.7                             |
| G24 A2(S) | 18:36.12.465         | -12.6          | 2.4                             |

Distance and luminosity values from the RMS database Lumsden et al. (2013) except distance and $L_{\text{bol}}$ for G24.78+0.08 which is from Reid et al. (2019).

2.3. Line identification

Spectra were extracted from the positions indicated with a star in Figure 1, corresponding with the peak(s) of $\mathrm{NH}_3\mathrm{CHO}$ emission (positions listed in Table 2) from the continuum subtracted images of each sub-source (except G345 Main) using CASA. We investigate if the $\mathrm{NH}_3\mathrm{CHO}$ transitions are blended by performing simultaneous fits of the species $\mathrm{NH}_3\mathrm{CHO}$, HNCO, $\mathrm{H}_2\mathrm{CO}$, and species that were potentially blended with $\mathrm{NH}_3\mathrm{CHO}$ ($\mathrm{C}_2\mathrm{H}_5\mathrm{OH}$, $\mathrm{CH}_3\mathrm{CN}$ ($\nu_2=1$), and $\mathrm{CH}_3^+\mathrm{OH}$) via the XCLASS software (Möller et al. 2017) assuming local thermal equilibrium (LTE). This software models the data by solving the radiative transfer equation for an isothermal object in one dimension, taking into account source size and opacity. The observed spectra and the XCLASS fits are shown in Appendix B. Using this software, we determine the excitation temperature ($T_{\text{ex}}$), column density ($N_{\text{col}}$), line width (FWHM), and velocity offset ($v_{\text{LSR}}$) for each modeled species (see details in §3.4). The model parameters FWHM and $v_{\text{LSR}}$ were constrained using Gaussian fits of the observed transitions and allowed to vary ±0.5 km s$^{-1}$ from the measured central velocity. The $T_{\text{ex}}$ free parameter was allowed to vary between 50 and 300 K for HNCO and $\mathrm{NH}_3\mathrm{CHO}$ and between 70 and 400 K for $\mathrm{H}_2\mathrm{CO}$. The temperature of $\mathrm{H}_2\mathrm{CO}$ was modeled using higher temperatures and a source size smaller than the beam size (~0.15″) in order to fit the emission originating on the small scale. The range explored for $N_{\text{col}}$ for each source is equivalent to abundances between 10$^{-13}$ and 10$^{-5}$. Because G345 Main shows very strong continuum emission ($T_B$ ~90 K) and absorption features, we used spectra extracted from non-continuum subtracted images and also modeled the continuum level within XCLASS.

### Table 2. Spectral extraction points for line identification and spectromodeling with XCLASS (§3.4)

| Source | Right Ascension (J2000) | Declination (J2000) | $N_{\text{col}}$ (cm$^{-3}$) | $H30^\alpha$ |
|--------|------------------------|---------------------|-----------------------------|--------------|
| G17    | 18:22:26.370           | -13:30:12.06        | 1.09×10$^{24}$              | ✓            |
| G24 A1 | 18:36:12.544           | -07:12:11.14        | 1.3×10$^{24}$               | ✓            |
| G24 A2(S) | 18:36:12.465        | -07:12:09.61        | 9.9×10$^{23}$               | ✓            |
| G345 Main | 16:59:41.628      | -40:03:43.63        | 8.2×10$^{23}$               | ✓            |
| G345 NW spur | 16:59:41.586   | -40:03:43.15        | 2.3×10$^{25}$               | ✓            |

Notes. $N_{\text{col}}$ was determined as in Sánchez-Monge et al. (2014) using the continuum intensity at the spectral extraction point assuming a $T_{\text{ex}}$ of 100 K, a dust opacity of 1.0 cm$^2$ g$^{-1}$ (Ossenkopf & Henning 1994), and a gas-to-dust ratio of 100. Check mark (✓) symbols indicate the detection of $\mathrm{H30}^\alpha$ emission toward the sub-source. For these sources, the continuum was corrected for free-free emission.

In general, we compare transitions with similar $E_{\text{up}}$ values (60-100 K) except where we consider HNCO (3) which has an $E_{\text{up}}$ of 432.9 K. Additionally, where one species can have strong emission due to larger abundances, another can be undetected because the telescope is not sensitive enough to detect a much weaker signal. The transitions used in the analysis in this work are listed in Table 3. There were two different unblended transitions of $\mathrm{NH}_3\mathrm{CHO}$ used: $\mathrm{NH}_3\mathrm{CHO}$ (1) used for G17 and G345 and $\mathrm{NH}_3\mathrm{CHO}$ (2) for G24. $\mathrm{NH}_3\mathrm{CHO}$ (2) (defined in Table 3) is the best transition as it is unlikely to be blended (see the best fit spectra in Figure 2) but it only appears within the spectral windows of G24 due to its high $v_{\text{LSR}}$ (Table 1). The transitions
identified for HNCO and H$_2$CO are generally unblended, but the NH$_2$CHO (1) emission is potentially blended with ethanol (C$_2$H$_5$OH) in G345 (Figure 3). In G17, C$_2$H$_5$OH is not detected, so NH$_2$CHO (1) is considered to be unblended. For NH$_2$CHO (1) in G345, we compare the C$_2$H$_5$OH transition that can produce a blend with NH$_2$CHO (at 218461.23 MHz) with a similar transition with the same upper energy level, $E_{\text{up}}$, (23.9 K) and almost the same Einstein coefficient, $A_{ij}$, (6.54x10$^{-5}$ vs. 6.60x10$^{-5}$ s$^{-1}$) at 217803.69 MHz. We use the NH$_2$CHO (1) transition for G345 for three reasons: the emission in G345 from the isolated C$_2$H$_5$OH transition at 217803.69 MHz is much weaker than the line that is blended with NH$_2$CHO (1), the peak integrated emission of NH$_2$CHO (1) is ~8 times stronger than that of C$_2$H$_5$OH (0.24 vs. 0.03 Jy beam$^{-1}$ km s$^{-1}$), and the two have completely different morphology (see Figure A.1 in Appendix A).

3. Comparison of formamide emission to possible chemically-related species

In this section, we derive gas properties empirically from moment maps. From the integrated intensity maps (zeroth moment), we locate the peak of line emission to high accuracy with a 2D-Gaussian fit accuracy to 0.01''. We assume, then, that if two species peak in the same location, and have the same velocity and line width, then they are in the same gas and are therefore related (either they have been released from the ice around the same time or they have formed in the same gas). From the velocity maps (first moment), we measure the average central velocity for each transition at each pixel and subtract these values from each other. A small difference between these velocities for different species suggests that they are in the same gas as they are moving in the same manner. Peak positions and average velocities can be affected by optical depth, especially when dealing with the main isotope of a species (i.e. not isotopologues). Using RADEX (van der Tak et al. 2007), a one dimensional non-LTE radiative transfer code, we have determined that the optical depths for the H$_2$CO lines range from 33-430 while those for HNCO lines are much lower ranging from 0.4-69. The last quantity we derive from moment maps is the velocity dispersion (second moment) map differences. Velocity dispersion gives the average line width at each pixel which is related to the level of turbulence in the gas. A small difference between velocity dispersion values shows that the gas emitting each transition has a similar turbulence level which suggests that they are in the same gas.

| Species   | Transition | Frequency (MHz) | $E_{\text{up}}$ (K) | $A_{ij}$ (s$^{-1}$) | Sources         |
|-----------|------------|----------------|---------------------|---------------------|-----------------|
| HNCO (1)  | 10$_{1,0}$-9$_{0,0}$ | 219798.27      | 58.0                | 1.47x10$^{-4}$          | G24             |
| HNCO (2)  | 10$_{1,9}$-9$_{1,8}$ | 220584.75      | 101.5               | 1.45x10$^{-4}$          | G17, G345       |
| HNCO (3)  | 10$_{3,7}$-9$_{3,6}$ | 219656.77      | 432.9               | 2.0x10$^{-4}$           | G24, G345       |
| NH$_2$CHO (1) | 10$_{1,9}$-9$_{1,8}$ | 218459.21      | 60.8                | 7.47x10$^{-4}$          | G17, G345       |
| NH$_2$CHO (2) | 11$_{2,10}$-10$_{2,9}$ | 232273.64      | 78.9                | 8.81x10$^{-4}$          | G24             |
| H$_2$CO (1) | 3$_{0,3}$-2$_{0,2}$ | 218222.19      | 20.9                | 2.82x10$^{-4}$          | G17, G24, G345  |
| H$_2$CO (2) | 3$_{2,2}$-2$_{1,1}$ | 218475.63      | 68.1                | 1.57x10$^{-4}$          | G17, G24, G345  |
| H$_2$CO (3) | 3$_{2,1}$-2$_{2,0}$ | 218760.07      | 68.1                | 1.58x10$^{-4}$          | G17, G24, G345  |

Notes. a) The CDMS catalog can be accessed here: https://cdms.astro.uni-koeln.de/

Fig. 2. Observed and synthetic spectra of G24 A1 (left), A2(N) (middle), and A2(S) (right) with fits showing NH$_2$CHO (2) (dark blue). The continuum levels are offset for easy viewing.
Fig. 3. Spectra with fits showing NH$_2$CHO (1) toward G345 NW spur (left), G345 Main (middle) and G17 (right). NH$_2$CHO (1) is weakly blended with C$_2$H$_5$OH in the spectra of G345 NW spur but unblended in G345 Main. The continuum levels are offset for easy viewing.

Fig. 4. G17 zeroth moment maps (contours) overlaid on the dust continuum (grayscale). Left: the black contours show the H$_2$CO (2) transition ($E_{up}$=68.1 K) from 5$\sigma$ to a peak of 0.175 Jy/beam km s$^{-1}$ (contour levels 0.021, 0.052, 0.083, 0.113, and 0.144 Jy/beam km s$^{-1}$). The red contours show NH$_2$CHO (1) emission ($E_{up}$=60.8 K) from 5$\sigma$ to 0.268 Jy/beam km s$^{-1}$ (contour levels 0.022, 0.071, 0.120, 0.170, and 0.219 Jy/beam km s$^{-1}$). Right: the blue contours show the extent of the HNCO (2) emission ($E_{up}$=101.5 K) from 5$\sigma$ to 0.146 Jy/beam km s$^{-1}$ (contour levels 0.010, 0.037, 0.064, 0.092, and 0.119 Jy/beam km s$^{-1}$) with the red contours showing NH$_2$CHO (as in the left frame).

3.1. Comparison of spatial distribution

3.1.1. G17

Although G17 is not associated with strong emission of typical complex organic molecules (e.g., CH$_3$OCHO, CH$_3$CHCN) (Cesaroni et al. 2017, Maud et al. 2018), it has a clear detection of NH$_2$CHO. We see in Figure 4 that the integrated emission (moment zero) map of NH$_2$CHO is slightly more compact than that of HNCO (0.58 vs. 0.76” or 1275 vs. 1675 au). Both species are off-set from the continuum but the emission peaks of HNCO and NH$_2$CHO are separated by $\sim$0.1” (220 au). For H$_2$CO, the emission is much more extended (up to 1.6” or ~3500 au). The H$_2$CO (1), (2), and (3) (see Table 3 for line properties) zeroth moment peaks are separated from the NH$_2$CHO peak by 0.07”, 0.1”, and 0.22” respectively. The lowest energy ($E_{up}$=20.9 K) H$_2$CO (1) peak is slightly closer to the NH$_2$CHO peak than the HNCO peak (0.07” vs. 0.1”).

3.1.2. G24

G24 has three subsources A1, A2(N), and A2(S). In Figure 5 we find that the H$_2$CO emission in G24 is much more extended than the NH$_2$CHO emission. In G24 A1, the extent of the H$_2$CO emission is 1.71” (~11500 au) from northeast to southwest whereas the NH$_2$CHO emission extends 0.9” (~6000 au) in the same direction. In G24 A2, the H$_2$CO emission extends 2.0” (~13400 au) whereas the NH$_2$CHO emission spans 1.1” (~7400 au). The extent of HNCO in these sources is 1.1” (~7400 au) at G24 A1.
Fig. 5. G24 zeroth moment maps (contours) overlaid on the dust continuum (grayscale). Left: the black contours show the $^{12}$CO (3) transition ($E_{\text{up}}=68.1$ K) from 5σ to a peak of 0.674 Jy/beam km s$^{-1}$ (contour levels 0.03, 0.16, 0.29, 0.42, and 0.55 Jy/beam km s$^{-1}$). The red contours show NH$_2$CHO (2) emission ($E_{\text{up}}=78.9$ K) from 5σ to 0.512 Jy/beam km s$^{-1}$ (contour levels 0.026, 0.123, 0.220, 0.318, and 0.415 Jy/beam km s$^{-1}$). Right: the blue contours show the extent of the HNCO (1) emission ($E_{\text{up}}=58.0$ K) from 5σ to 0.738 Jy/beam km s$^{-1}$ (contour levels 0.031, 0.172, 0.314, 0.455, and 0.597 Jy/beam km s$^{-1}$) with the red contours showing NH$_2$CHO (as in the left frame).

Fig. 6. G345 zeroth moment maps (contours) overlaid on the dust continuum (grayscale). Left: the black contours show the $^{12}$CO (3) transition ($E_{\text{up}}=68.1$ K) from 5σ to a peak of 0.402 Jy/beam km s$^{-1}$ (contour levels 0.027, 0.102, 0.177, 0.232, and 0.327 Jy/beam km s$^{-1}$). The red contours show NH$_2$CHO (1) emission ($E_{\text{up}}=60.8$ K) from 5σ to 0.242 Jy/beam km s$^{-1}$ (contour levels 0.020, 0.064, 0.109, 0.153, and 0.198 Jy/beam km s$^{-1}$). Right: the blue contours show the extent of the HNCO (2) emission ($E_{\text{up}}=101.5$ K) from 5σ to 0.428 Jy/beam km s$^{-1}$ (contour levels 0.014, 0.097, 0.180, 0.262, and 0.345 Jy/beam km s$^{-1}$) with the red contours showing NH$_2$CHO (as in the left frame).

and 1.5" (~10050 au) for G24 A2. The integrated emission for NH$_2$CHO and HNCO (3) breaks off between A1 (to the southeast) and A2 (to the northwest) whereas for the $^{12}$CO transitions and HNCO (1) there is some emission between the two continuum sources. In G24 A1, the separation between all HNCO or $^{12}$CO and NH$_2$CHO emission peaks are between 0.04 and 0.35".
Table 4. Peak separations between listed transitions and NH$_2$CHO (in arcseconds). The error in the peak position is $\sim 0.01''$.

| Species   | G17 | G24 | G24 | G24 | G345 | G345 |
|-----------|-----|-----|-----|-----|------|------|
|           | A1  | A2(N) | A2(S) | Main | NW spur |
| HNCO (1)  | N/A | 0.08 | 0.03 | 0.06 | N/A | N/A |
| HNCO (2)  | 0.1 | 0.04 | 0.04 | 0.03 | 0.21 | 0.03 |
| HNCO (3)  | N/A | 0.07 | 0.12 | 0.12 | 0.21 | 0.21 |
| H$_2$CO (1) | 0.1 | 0.29 | 0.25 | 0.06 | 0.25 | 0.24 |
| H$_2$CO (2) | 0.22 | 0.27 | 0.07 | 0.03 | 0.25 | 0.23 |

Notes. Transitions in column 1 are labeled as in Table 3. For G24 A2 (N) and (S) the distances are measured from the corresponding northern or southern peaks.

Fig. 7. Separations between NH$_2$CHO and each peak of HNCO and H$_2$CO. For the G24 sources HNCO (1) is used instead of HNCO (2) (see Table 3). The error in the peak position is $\sim 0.01''$.

(270-2350 au) and the closest peak to NH$_2$CHO is that of HNCO (3). In the case of G24 A1, we must remember that optical depth effects primarily affect H$_2$CO in this source.

The NH$_2$CHO, HNCO, and H$_2$CO emission in G24 A2 have two significant NH$_2$CHO integrated intensity peaks of similar strength separated by about 0.35'' ($\sim 2350$ au) that we refer to as A2(N) and A2(S) (positions of each peak indicated in Figure 1). The two emission peaks in G24 A2 complicate things slightly, as it is difficult to draw boundaries between the velocity maps of the two peaks. Nevertheless we can determine the positions of the emission peaks and analyze them separately. The more northerly H$_2$CO (2) peak was in between the NH$_2$CHO A2(N) and (S) peaks with a distance between H$_2$CO (2) A2(N) and NH$_2$CHO (2) A2(N) of 0.25'' ($\sim 1670$ au) and between H$_2$CO (2) A2(N) and NH$_2$CHO (2) A2(S) of 0.18'' ($\sim 1200$ au). The H$_2$CO (3) A2 peaks are nearer to the respective NH$_2$CHO peaks at 0.07'' ($\sim 470$ au) from A2(N) and 0.03'' ($\sim 200$ au) from A2(S).

In G24 A2(N), the closest peak to the NH$_2$CHO is the lower energy (58 K) HNCO (1) transition. In A2(S), the HNCO (3) transition and the H$_2$CO (3) peaks are equally separated from NH$_2$CHO peak at 0.03'' ($\sim 200$ au).

3.1.3. G345

The two subsources in G345 (described in Figure 1) are G345 Main and G345 NW spur. From the spectra extracted from G345 Main, we note that the chemical composition appears to be affected by a source of strong H$_3$0 emission within which is ionizing the region and destroying complex molecular species, but the closest peak to the NH$_2$CHO peak (by far) is HNCO (2). The spectra associated with G345 NW spur show that it is a very chemically diverse region – possibly an outflow cavity associated with G345 Main. The HNCO (2) and (3) emission peaks are equally the closest to the NH$_2$CHO peak in G345.49 NW spur (0.03'').

Figure 8 shows that HNCO (2) and NH$_2$CHO (1) have similar extent and velocity structure at the Main and NW spur positions. There is little high energy HNCO (3) emission at G345 Main. The H$_2$CO transitions peak at the NW spur, but there is still emission at Main, without a clear peak. We take the pixel with the highest intensity on the area designated to Main despite the emission being extended across the two parts of the source. In Main, the low energy HNCO transition peaks very close to the NH$_2$CHO peak (0.04'' away $\sim 100$ au), but the higher energy HNCO transition and all of the H$_2$CO transitions peak 0.21-0.25'' from the NH$_2$CHO peak. In the NW spur, both HNCO transitions peak very near the NH$_2$CHO peak (0.03'' $\sim 75$ au) whereas all three H$_2$CO transitions are farther at 0.21-0.24'' (500-575 au).

3.1.4. Summary of spatial distribution comparison

For our six subsources in these regions (see Table 3 and Figure 7), it is clear that the integrated emission peaks of HNCO are closer to the peaks of NH$_2$CHO than the H$_2$CO peaks. The morphology of the HNCO emission is also more similar to NH$_2$CHO, as the H$_2$CO emission tends to be much more extended and even the brightest emission (see higher intensity contours in Figures 4, 5, and 6) have a different shape to the NH$_2$CHO emission. The lack of NH$_2$CHO emission in the more extended regions indicates that it can be more efficiently made from H$_3$0 (in the gas phase) near the continuum peaks than farther out in these cases. It is clear from the H$_2$CO emission toward G24 A1 and G345 Main, that these transitions are suffering by optical depth effects.

3.2. Comparison of the velocity field

The velocity field of each molecule was investigated by creating the first order moment map for each transition listed in Table 3. These maps were then subtracted from each other to determine the difference between the gas velocities for each species. Where possible, two transitions from the same species were also compared to determine the "internal error", as the velocity difference of transitions within the same gas implies a lower limit for accuracy. Histograms were made for the absolute values of each velocity difference map showing the number of pixels within each bin (see Appendix C). The average value and standard deviation of these histograms were used to determine which species was most similar to NH$_2$CHO. Results are detailed per source below and summarized in Table 5 and Figure 11.

3.2.1. G17

Figure 8 shows that the velocity differences between HNCO and NH$_2$CHO and H$_2$CO and NH$_2$CHO are not significantly differ-
Fig. 8. Velocity difference (from first moment maps) at each pixel in G17 between (left) H$_2$CO (2) and NH$_2$CHO (1) and (right) HNCO (2) and NH$_2$CHO (1). The contours show the integrated intensity maps for H$_2$CO (2) and HNCO (2) as in Figure 4. The velocity scale is the same for both panels.

Fig. 9. Velocity difference (from first moment maps) at each pixel in G24 between (left) H$_2$CO (3) and NH$_2$CHO (2) and (right) HNCO (1) and NH$_2$CHO (2). The contours show the integrated intensity maps for H$_2$CO (3) and HNCO (1) as in Figure 5. The velocity scale is the same for both panels.

ent. The average velocity difference for HNCO (2) is 0.78 km s$^{-1}$, whereas the differences for H$_2$CO (2) and (3) are 0.72 and 0.67 km s$^{-1}$, respectively. For G17 overall the H$_2$CO transitions are on average more similar to NH$_2$CHO. HNCO (3) is not detected toward G17.

3.2.2. G24

Figure 9 shows that the range of velocity differences in G24 A2(N) and A2(S) (to the northwest) are greater between HNCO and NH$_2$CHO than H$_2$CO and NH$_2$CHO with the smallest average difference between H$_2$CO (3) and NH$_2$CHO for A2(N) and between H$_2$CO (2) and NH$_2$CHO for A2(S) at 0.53 and 1.13 km s$^{-1}$, respectively. It is less obvious visually for G24 A1 (to the southeast), but we can see from the average values listed in Table 5 that the average difference closest to zero is between HNCO (3) and NH$_2$CHO at 1.01 km s$^{-1}$.

3.2.3. G345

Figure 10 shows the velocity differences in G345 Main (to the southeast) and NW spur (to the northwest). The range of values

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Fig. 10. Velocity difference (from first moment maps) at each pixel in G345 between (left) H$_2$CO (2) and NH$_2$CHO (1) and (right) HNCO (2) and NH$_2$CHO (1). The contours show the integrated intensity maps for H$_2$CO (2) and HNCO (2) as in Figure 6. The velocity scale is the same for both panels.

Fig. 11. Average velocity difference between NH$_2$CHO and transitions HNCO (2) and (3) and H$_2$CO (2) and (3). For the G24 sources HNCO (1) is used instead of HNCO (2) (see Table 3).

3.2.4. Summary of the velocity field comparison

We see in the Table 5 and Figure 11 that there are an equal number of subsources where the average velocity difference is closest to zero for each of our related species. For a few sources, the range of average differences between different transitions is very small. For G17 in particular, the averages are 0.67, 0.72, and 0.78 km s$^{-1}$ for H$_2$CO (3), H$_2$CO (2) and HNCO (2), respectively. For G24 A2(N) the difference is clearer with average velocity differences of 0.53, 0.58, 0.81, and 1.45 km s$^{-1}$ for H$_2$CO (3), H$_2$CO (2), HNCO (3) and HNCO (1), respectively. In the cases of G24 A1 and G24 A2(N), the internal error for HNCO is much larger than that of H$_2$CO (0.73 and 0.74 vs. 0.27 and 0.22 km s$^{-1}$). This indicates that, in terms of errors, the difference between NH$_2$CHO and H$_2$CO is stronger than the difference between NH$_2$CHO and HNCO in these sources.

3.3. Comparison of the velocity dispersion

Second order moment maps were made for each of the transitions studied for each star-forming region. These maps were then subtracted from each other to determine the difference between the velocity dispersion for each species. Though it may be affected by optical depth, similar line widths between species can suggest that they are in the same gas. As in §3.2, transitions from the same species were compared to determine internal error. Histograms were made of the absolute values of each dispersion difference map showing the number of pixels within each velocity bin. The average value and standard deviation of these histograms were used to determine which species was most similar to NH$_2$CHO. Results are detailed per source in the text and summarized in Table 6 and Figure 15. The histograms for this analysis are shown in Appendix C.
Table 5. Average values (with the standard deviation in parentheses) of the histograms (see Appendix C) of each velocity (first moment) difference map. All units are km/s.

| Transitions                  | G17  | G24 A1 | G24 A2(N) | G24 A2(S) | G345 NW spur | G345 Main |
|-----------------------------|------|--------|-----------|-----------|--------------|-----------|
| $\text{H}_2\text{CO} (2)$ – $\text{H}_2\text{CO} (3)$ | 0.42 (0.58) | 0.27 (0.54) | 0.22 (0.50) | 0.34 (0.61) | 0.27 (0.39) | 0.43 (0.43) |
| HNCO (2) – HNCO (3)         | N/A  | 0.73 (0.44) | 0.74 (0.48) | 0.44 (0.56) | 0.25 (0.18) | N/A       |
| $\text{H}_2\text{CO} (2)$ – NH$_2$CHO | 0.72 (0.54) | 1.14 (1.14) | 0.58 (0.46) | 1.13 (1.06) | 0.97 (0.90) | 0.76 (0.62) |
| HNCO (2) – NH$_2$CHO         | 0.67 (0.38) | 1.15 (1.11) | 0.53 (0.38) | 1.16 (1.10) | 0.91 (0.89) | 0.84 (0.73) |
| HNCO (3) – NH$_2$CHO         | 0.78 (0.74) | 1.30 (0.92) | 1.45 (0.75) | 1.23 (0.82) | 1.18 (1.07) | 0.51 (0.38) |
| N/A                         | 1.01 (0.49) | 0.81 (0.28) | 1.26 (0.85) | 0.86 (0.35) | N/A          |           |

Notes. For G24, HNCO (1) is used instead of HNCO (2). G17 and G345 Main have only one HNCO transition, so the internal error for HNCO transitions cannot be determined.

3.3.1. G17

Figure 12 shows the difference at each pixel between the second order moment maps of $\text{H}_2\text{CO}$ and NH$_2$CHO and HNCO and NH$_2$CHO toward G17. It is clear that the difference between HNCO and NH$_2$CHO is smaller and we determine that the average difference is 0.52 km s$^{-1}$ for HNCO (2), whereas for $\text{H}_2\text{CO}$ (2) and (3) the average differences are 0.68 and 0.86 km s$^{-1}$, respectively. HNCO (3) is not detected toward G17.

3.3.2. G24

Figure 13 shows the difference at each pixel between the second order moment maps of $\text{H}_2\text{CO}$ and NH$_2$CHO and HNCO and NH$_2$CHO toward G24 A1 (to the southeast) and G24 A2(N) and A2(S) (to the northwest). HNCO (3)-NH$_2$CHO has the smallest average velocity dispersion difference for all three subsources of G24 at 0.41 km s$^{-1}$ for A1, 0.21 km s$^{-1}$ for A2(N), and 0.47 km s$^{-1}$ for A2(S).

3.3.3. G345

Figure 14 shows the difference at each pixel between the second order moment maps of $\text{H}_2\text{CO}$ and NH$_2$CHO and HNCO and NH$_2$CHO toward G345 Main (to the southeast) and G345 NW spur (to the northwest). For G345 Main, it is clear from the figure and Table 5 that HNCO (2) has the smallest average difference between velocity dispersion values at 0.53 km s$^{-1}$. The average second order moment map differences for $\text{H}_2\text{CO}$ (2) and (3) are 0.80 and 0.77 km s$^{-1}$, respectively, and there is no HNCO (3) emission toward G345 Main. The average difference between $\text{H}_2\text{CO}$ (3) and NH$_2$CHO in G345 NW spur is smallest at 0.80 km s$^{-1}$, but the average difference for HNCO (2)-NH$_2$CHO is 0.81 km s$^{-1}$, so these two maps are equally similar within errors.

3.3.4. Summary of velocity dispersion comparison

As a measure of the similarity between the motions of the gas containing each species, the line width test comes out in favor of HNCO for five out of six subsources. In the sixth (G345 NW spur), the difference between $\text{H}_2\text{CO}$ (3)-NH$_2$CHO and HNCO (2)-NH$_2$CHO is only 0.01 km s$^{-1}$. In the five subsources that show the velocity dispersion of HNCO as definitively closest to NH$_2$CHO, the average values are also consistent with zero if we consider the difference between $\text{H}_2\text{CO}$ (2) and (3) as the error for these measurements.
Fig. 13. Velocity dispersion difference (from second moment maps) at each pixel in G24 between (left) H$_2$CO (3) and NH$_2$CHO (2) and (right) HNCO (1) and NH$_2$CHO (2). The contours show the integrated intensity maps for H$_2$CO (3) and HNCO (1) as in Figure 5. The velocity scale is the same for both panels.

Fig. 14. Velocity dispersion difference (from second moment maps) at each pixel in G345 between (left) H$_2$CO (2) and NH$_2$CHO (1) and (right) HNCO (2) and NH$_2$CHO (1). The contours show the integrated intensity maps for H$_2$CO (2) and HNCO (2) as in Figure 6. The velocity scale is the same for both panels.

3.4. Comparison of column densities and excitation temperatures

Using the XCLASS LTE spectral modeling software described in §2.3, we determine excitation temperature ($T_{\text{ex}}$), column densities ($N_{\text{col}}$), line width (FWHM), and velocity ($v_{\text{LSR}}$) for spectra extracted from single pixels (indicated in Figure 1). Modeled $N_{\text{col}}$ values were divided by the H$_2$ column densities listed in Table 2 to obtain abundances for comparison, and output $v_{\text{LSR}}$ were subtracted from the $v_{\text{LSR}}$ of the sources listed in Table 1 to obtain velocity offsets. The full modeling results are presented in Tables 8, 9, and 10. The errors shown were determined using the errorestim_ins algorithm using the Markov chain Monte Carlo (MCMC) method built into the XCLASS software. A detailed description of this method is included in the XCLASS manual.

Figure 15 shows the modeled abundance values ($X$) for NH$_2$CHO, H$_2$CO, and HNCO plotted against each other for all subsources. The relationships between each of the species pairs hold.

5 Manual downloadable from: https://xclass.astro.uni-koeln.de/sites/xclass/files/pdfs/XCLASS-Interface_Manual.pdf
Table 6. Average values (with the standard deviation in parentheses) of the histograms of each dispersion (second moment) difference map. All units are km s\(^{-1}\).

| Transitions | G17 | G24 A1 | G24 A2(N) | G24 A2(S) | G345 NW spur | G345 Main |
|-------------|-----|--------|-----------|-----------|-------------|-----------|
| H\(_2\)CO (2) – H\(_2\)CO (3) | 0.08 (0.60) | 0.12 (0.58) | 0.17 (0.61) | 0.13 (0.67) | 0.17 (0.58) | 0.07 (0.56) |
| HNCO (2) – HNCO (3) | N/A | 0.99 (0.53) | 1.11 (0.58) | 0.98 (0.67) | 0.67 (0.23) | N/A |
| H\(_2\)CO (2) – NH\(_2\)CHO | 0.68 (0.68) | 0.75 (0.55) | 0.79 (0.48) | 1.59 (0.86) | 0.92 (0.44) | 0.80 (0.73) |
| HNCO (2) – NH\(_2\)CHO | 0.86 (0.69) | 0.62 (0.51) | 0.65 (0.47) | 1.63 (0.91) | 0.80 (0.50) | 0.77 (0.70) |
| H\(_2\)CO (3) – NH\(_2\)CHO | 0.52 (0.39) | 0.67 (0.62) | 0.95 (0.59) | 0.81 (0.68) | 0.81 (0.41) | 0.53 (0.45) |
| HNCO (3) – NH\(_2\)CHO | N/A | 0.41 (0.41) | 0.21 (0.19) | 0.47 (0.47) | 1.32 (0.49) | N/A |

Notes. For G24, HNCO (1) is used instead of HNCO (2). G17 and G345 Main have only one HNCO transition, so the internal error for HNCO transitions cannot be determined.

Table 7. Summary of results from map analyses. The check symbol (✓) indicates the species with the emission peak closest to the NH\(_2\)CHO peak, correlation between NH\(_2\)CHO velocity-diagram centers nearest to zero, or dispersion-diagram center nearest to zero. Equals signs (=) indicate that the parameters were equal for both HNCO and H\(_2\)CO within errors.

| Source                 | Peak    | HNCO     | H\(_2\)CO |
|------------------------|---------|----------|-----------|
|                        | Velocity | Dispersion| Velocity  |
|                        |         |          | Dispersion|
| G17                    | ✓       | ✓        | ✓         |
| G24 A1                 | ✓       | ✓        | ✓         |
| G24 A2(N)              | ✓       | ✓        | ✓         |
| G24 A2(S)              | =       | =        | ✓         |
| G345 Main              | ✓       | =        | =         |
| G345 NW spur           | ✓       | =        | =         |

Fig. 15. Average velocity dispersion difference between NH\(_2\)CHO and transitions HNCO (2) and (3) and H\(_2\)CO (2) and (3). For the G24 sources HNCO (1) is used instead of HNCO (2).

The \(T_{ex}\) and FWHM values do not show any correlation between any of the pairs of species, but both of these parameters have a very narrow range of results for NH\(_2\)CHO. The \(T_{ex}\) range for NH\(_2\)CHO is 50-150 K, whereas for HNCO it is 75-200 K and for H\(_2\)CO it is 70-375 K. The largest errors in \(T_{ex}\) are for HNCO around G345 Main at 63 K, but the average error in \(T_{ex}\) is 12.7 K. The FWHM for NH\(_2\)CHO range from ~2.3-5.7 km s\(^{-1}\), while for the other two the range is 2.8-6.5 km s\(^{-1}\). The errors associated with the FWHM fits are very small with an average of 0.2 km s\(^{-1}\) with the largest error being 0.7 km s\(^{-1}\).

Figure 17 shows the velocity offset values for NH\(_2\)CHO, HNCO, and H\(_2\)CO plotted against each other for all subsources. The scatter of velocity offset values for NH\(_2\)CHO is smaller with HNCO than with H\(_2\)CO (R\(^2\) of 0.95 vs. 0.48). The slope of the NH\(_2\)CHO vs. HNCO velocity offset plot is nearly 1, but the intercept is not zero (V\(_{ex}\) = 1.31 V\(_{HNCO}\) - 0.68) whereas the slope of NH\(_2\)CHO vs. H\(_2\)CO is closer to 0.7 but the intercept is nearer to zero (V\(_{ex}\) = 0.69 V\(_{H_2CO}\) + 0.39). The errors on the model fit of velocity offset are also small where the largest is 0.9 km s\(^{-1}\) but the average error for all sources and species is 0.3 km s\(^{-1}\).

4. Discussion

4.1. Overall map trends

We see from the summary of map analysis results in Table 2 that the peak positions and dispersion maps favor HNCO slightly over H\(_2\)CO in similarity with NH\(_2\)CHO and the velocity dispersion maps for HNCO are almost always most similar to NH\(_2\)CHO. There are two sources which favor HNCO over H\(_2\)CO in all three moment map tests: G24 A1 and G345 Main. While the integrated emission peaks of HNCO are generally much closer to NH\(_2\)CHO (by 0.1-0.3\('\)) differences of less than 0.2\('\) are smaller than the beam. We measure the 2D-Gaussian peaks of the lines with an error of 0.01\('\) so the similarity between HNCO and NH\(_2\)CHO peaks is significant. The gas velocity structure of NH\(_2\)CHO is similar to HNCO in half of the sources
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4.2. XCLASS analysis

The result of our XCLASS analysis shows no relationship between the widths of lines of different species or between the gas temperatures ($T_{ex}$) of any of the species. The velocity offset relationship is strongest between HNCO and NH$_2$CHO with a nearly linear fit and a small scatter. There is a correlation between abundances for all three pairs of species but the best fit is between H$_2$CO and NH$_2$CHO. Most interesting is the relationship between the abundances of HNCO and NH$_2$CHO in this work is almost exactly the same as that reported in López-Sepulcre et al. (2015). In their paper, the best power-law fit was $X(NH_2CHO) = 0.04 X(HNCO)^{0.93}$ and the best fit in this work is $X(NH_2CHO) = (0.06 \pm 0.03) X(HNCO)^{0.95(\pm0.05)}$. The correlation between abundances of all three pairs of species suggests that such a correlation is not a good indicator of a direct chemical relationship.

5. Conclusions

We present an observational study of two species potentially chemically related (HNCO and H$_2$CO) to NH$_2$CHO. Our study improves upon previous studies using single dish observations by including map analysis made possible using highly-sensitive interferometric observations. The different moment maps that we employ indicate whether the gas containing NH$_2$CHO has the same properties as the gas containing its potential precursors. The spectral analysis performed in López-Sepulcre et al. (2015) and Bisschop et al. (2007) used significantly more transitions and the rotational diagram method in order to determine abundances. While we had fewer unblended transitions available to us, the XCLASS LTE spectral modeling method is more rigorous and does not require the assumption of optically thin transitions as that would be incorrect. A few interferometric studies involving NH$_2$CHO have been done (e.g., Codella et al. (2017) - L1157-B1, Coutens et al. (2016) - IRAS 16293-2422), but only involving one of its precursors, so we also improve upon that method by investigating the three species together in several star forming regions.
HNCO and HNH2 relationship between the abundances of HNCO and NH2CHO as chemically related to NH2CHO. The abundance correlation between H2CO and NH2CHO is slightly stronger than the correlation between HNCO and NH2CHO but both are very well correlated. It is possible that both formation processes are important in creating this species, or that different environments favor one process over the other. Dedicated studies using more transitions and isotopologues in a more diverse selection of sources (high- and low-mass protostars, young stellar objects with disks, outflow regions, etc.) would shed light on this relationship.

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Fig. 17. XCLASS determined velocity offset comparison between NH2CHO and HNCO (top left), NH2CHO and H2CO (top right), and HNCO and H2CO (bottom). The symbols are as in Figure 16.

In our spectral modeling, we confirm the single dish relationship between the abundances of HNCO and NH2CHO demonstrated in Bisschop et al. (2007) and López-Sepulcre et al. (2015) using interferometric observations. Our map analyses favor HNCO as chemically related to NH2CHO.
### Table 8. XCLASS LTE spectral modeling results for formamide (NH$_2$CHO). Columns show modeled excitation temperature ($T_{\text{ex}}$), column density ($N_{\text{col}}$), line width ($\Delta v$), and line velocity ($v_{\text{LSR}}$) for each of our key species. The columns indicated by a minus sign (-) indicate the error to the left of the result and those indicated by a plus sign (+) indicate the error to the right.

| Source     | $T_{\text{ex}}$ | - | + | $N_{\text{col}}$ lower limit | $N_{\text{col}}$ upper limit | $\Delta v$ | - | + | $v_{\text{LSR}}$ | - | + |
|------------|-----------------|---|---|-----------------------------|-----------------------------|------------|---|---|-----------------|---|---|
| G17        | 56.23           | 0.29 | 0.44 | 2.09×10$^{15}$ | 1.78×10$^{15}$ | 2.88×10$^{15}$ | 5.7 | 0.3 | 0.2 | 23.3 | 0.5 | 0.65 |
| G24 A1     | 65              | 14 | 26 | 2.77×10$^{16}$ | 6.49×10$^{15}$ | 8.96×10$^{16}$ | 3.1 | 0.2 | 0.2 | 108.4 | 0.7 | 0.7 |
| G24 A2(N)  | 79              | 13 | 15 | 1.45×10$^{16}$ | 6.06×10$^{15}$ | 2.97×10$^{16}$ | 3.3 | 0.1 | 0.1 | 110.5 | 0.4 | 0.9 |
| G24 A2(S)  | 89              | 20 | 2  | 2.42×10$^{15}$ | 1.41×10$^{15}$ | 5.75×10$^{15}$ | 2.5 | 0.1 | 0.3 | 110.3 | 0.1 | 0.5 |
| G24 A2(N)  | 152             | 33 | 27 | 5.13×10$^{16}$ | 3.31×10$^{16}$ | 1.41×10$^{16}$ | 2.4 | 0.6 | 0.5 | 117.8 | 0.6 | 0.6 |
| G345 NW spur | 93           | 4  | 10 | 9.68×10$^{14}$ | 7.69×10$^{14}$ | 1.22×10$^{15}$ | 3.3 | 0.2 | 0.2 | -12.03 | 0.06 | 0.03 |

### Table 9. XCLASS best fit results as in Table 8 but for HNCO.

| Source     | $T_{\text{ex}}$ | - | + | $N_{\text{col}}$ lower limit | $N_{\text{col}}$ upper limit | $\Delta v$ | - | + | $v_{\text{LSR}}$ | - | + |
|------------|-----------------|---|---|-----------------------------|-----------------------------|------------|---|---|-----------------|---|---|
| G17        | 86              | 4  | 1 | 9.12×10$^{15}$ | 8.32×10$^{15}$ | 9.33×10$^{15}$ | 6.17 | 0.03 | 0.19 | 22.67 | 0.14 | 0.02 |
| G24 A1     | 192.0           | 0  | 1 | 5.01×10$^{16}$ | 4.79×10$^{16}$ | 5.37×10$^{16}$ | 6.43 | 0.06 | 0.31 | 108.4 | 0.08 | 0.06 |
| G24 A2(N)  | 177.0           | 18 | 27 | 1.66×10$^{17}$ | 6.77×10$^{16}$ | 2.46×10$^{17}$ | 3.28 | 0.05 | 0.13 | 110.7 | 0.4  | 0.5 |
| G24 A2(S)  | 114.9           | 0.7 | 3.7 | 5.02×10$^{17}$ | 4.08×10$^{17}$ | 7.46×10$^{17}$ | 3.63 | 0.01 | 0.1 | 110.1 | 0.03 | 0.06 |
| G345 Main  | 173.0           | 27 | 63 | 2.19×10$^{16}$ | 1.38×10$^{16}$ | 6.61×10$^{16}$ | 5.0 | 0.7 | 0.3 | -18.4 | 0.3  | 0.2 |
| G345 NW spur | 198.7         | 0.4 | 0.5 | 1.78×10$^{16}$ | 8.00×10$^{14}$ | 2.17×10$^{15}$ | 4.3 | 0.2 | 0.1 | -13.3 | 0.3  | 0.2 |

### Table 10. XCLASS best fit results as in Table 8 but for H$_2$CO.

| Source     | $T_{\text{ex}}$ | - | + | $N_{\text{col}}$ lower limit | $N_{\text{col}}$ upper limit | $\Delta v$ | - | + | $v_{\text{LSR}}$ | - | + |
|------------|-----------------|---|---|-----------------------------|-----------------------------|------------|---|---|-----------------|---|---|
| G17        | 110             | 1  | 3 | 3.58×10$^{16}$ | 3.51×10$^{16}$ | 3.59×10$^{16}$ | 4.26 | 0.06 | 0.23 | 22.78 | 0.08 | 0.92 |
| G24 A1     | 374             | 5  | 6 | 1.51×10$^{17}$ | 1.47×10$^{17}$ | 1.55×10$^{17}$ | 6.4 | 0.1 | 0.3 | 108.4 | 0.3  | 0.4 |
| G24 A2(N)  | 76              | 4  | 9 | 5.49×10$^{16}$ | 2.34×10$^{16}$ | 1.29×10$^{17}$ | 5.1 | 0.1 | 0.2 | 112.2 | 0.2  | 0.4 |
| G24 A2(S)  | 138             | 30 | 46 | 5.33×10$^{17}$ | 4.42×10$^{17}$ | 5.89×10$^{17}$ | 4.6 | 0.3 | 0.2 | 112.38 | 0.03 | 0.75 |
| G345 Main  | 188             | 4  | 33 | 3.86×10$^{16}$ | 2.81×10$^{16}$ | 4.77×10$^{16}$ | 2.9 | 0.6 | 0.7 | -17.29 | 0.21 | 0.09 |
| G345 NW spur | 70            | 2  | 4 | 3.52×10$^{16}$ | 3.19×10$^{16}$ | 3.76×10$^{16}$ | 4.00 | 0.01 | 0.31 | -12.5 | 0.3  | 0.3 |
Appendix A: Formamide and ethanol in G345 NWspur

Fig. A.1. Right: Spectrum of G345 NW spur showing a C$_2$H$_5$OH transition (5$_{3,2}$-4$_{2,1}$) at 217803 MHz with the same $E_u$ and nearly equal $A_{ij}$ as the C$_2$H$_5$OH transition (5$_{2,1}$-4$_{2,1}$) that is blended with the NH$_2$CHO (1) transition (at 218461 MHz). Left: Contours of the integrated intensity map of this C$_2$H$_5$OH line is overlaid on the map of the NH$_2$CHO (1) transition to show that the strength and spatial extent is different.
Appendix B: XCLASS fits

Fig. B.1. Spectral window from 218.1-218.8 GHz for G17 containing NH$_2$CHO (1) and H$_2$CO (1), (2), and (3).

Fig. B.2. Spectral window from 219.5-219.8 GHz for G17 containing HNCO (3).
Fig. B.3. Spectral window from 220.5-220.75 GHz for G17 containing HNCO (2). We modeled two components for the CH$_3$CN emission (green) toward this source.

Fig. B.4. Spectral window from 217.7-218.7 GHz for G24 A1 containing NH$_2$CHO (1) and H$_2$CO (1), (2), and (3). NH$_2$CHO (1) is blended with a transition of C$_2$H$_5$OH.
Fig. B.5. Spectral window from 231.8-232.3 GHz for G24 A1 containing NH$_2$CHO (2).

Fig. B.6. Spectral window from 217.7-218.7 GHz for G24 A2(N) containing NH$_2$CHO (1) and H$_2$CO (1), (2), and (3). NH$_2$CHO (1) is blended with a transition of C$_2$H$_5$OH.
**Fig. B.7.** Spectral window from 231.8-232.3 GHz for G24 A2(N) containing NH$_2$CHO (2).

**Fig. B.8.** Spectral window from 217.7-218.7 GHz for G24 A2(S) containing NH$_2$CHO (1) and H$_2$CO (1), (2), and (3). NH$_2$CHO (1) is blended with a transition of C$_3$H$_5$OH.
Fig. B.9. Spectral window from 231.8-232.3 GHz for G24 A2(S) containing NH$_2$CHO (2).

Fig. B.10. Spectral window from 217.8-218.8 GHz for G345 NW containing NH$_2$CHO (1) and H$_2$CO (1), (2), and (3).
**Fig. B.11.** Spectral window from 219.5-219.8 GHz for G345 NW containing HNCO (3). The additional transitions shown in the total XCLASS fit are HC$_3$N (219675 MHz), C$_2$H$_3$CN (219699 MHz), and CH$_3$CHO (219756 MHz).

**Fig. B.12.** Spectral window from 220.3-220.8 GHz for G345 NW containing HNCO (2).
Fig. B.13. Spectral window from 217.8-218.8 GHz for G345 Main containing NH$_2$CHO (1) and H$_2$CO (1), (2), and (3).

Fig. B.14. Spectral window from 219.5-219.8 GHz for G345 Main containing HNCO (3).
Fig. B.15. Spectral window from 220.3-220.8 GHz for G345 Main containing HNCO (2).
Appendix C: Histograms

**$H_2CO(2)$ - $H_2CO(3)$**

**$H_2CO(2)$ - NH$_2$CHO**

**HNCO(2) - NH$_2$CHO**

**$H_2CO(3)$ - NH$_2$CHO**

Fig. C.1. G17 first moment difference histogram.
Fig. C.2. G24A1 first moment difference histogram.
Fig. C.3. G24A2(N) first moment difference histogram.
Fig. C.4. G24A2(S) first moment difference histogram.
H_2CO(2) - H_2CO(3)

H_2CO(2) - NH_2CHO

HNCO(2) - NH_2CHO

H_2CO(3) - NH_2CHO

Fig. C.5. G345 Main first moment difference histogram.
Fig. C.6. G345 NW spur first moment difference histogram.
Fig. C.7. G17 second moment difference histogram.
Fig. C.8. G24A1 second moment difference histogram
Fig. C.9. G24A2(N) second moment difference histogram.
Fig. C.10. G24A2(S) second moment difference histogram.
Fig. C.11. G345 Main second moment difference histogram.
Fig. C.12. G345 NW spur second moment difference histogram.