Nitrogen Fractionation in Protoplanetary Disks from the $\text{H}^{13}\text{CN}/\text{HC}^{15}\text{N}$ Ratio

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Abstract

Nitrogen fractionation is commonly used to assess the thermal history of solar system volatiles. With ALMA it is for the first time possible to directly measure $^{14}\text{N}/^{15}\text{N}$ ratios in common molecules during the assembly of planetary systems. We present ALMA observations of the $\text{H}^{13}\text{CN}$ and $\text{HC}^{15}\text{N}$ $J = 3 – 2$ lines at $0\farcs5$ angular resolution, toward a sample of six protoplanetary disks, selected to span a range of stellar and disk structure properties. Adopting a typical $^{12}\text{C}/^{13}\text{C}$ ratio of 70, we find comet-like $^{14}\text{N}/^{15}\text{N}$ ratios of 80–160 in five of the disks ($3\text{T}\text{Tauri}$ and 2 Herbig Ae disks) and lack constraints for one of the $3\text{T}\text{Tauri}$ disks (IM Lup). There are no systematic differences between $3\text{T}\text{Tauri}$ and Herbig Ae disks, or between full and transition disks within the sample. In addition, no correlation is observed between disk-averaged D/H and $^{14}\text{N}/^{15}\text{N}$ ratios in the sample. One of the disks, V4046 Sgr, presents unusually bright HCN isotopologue emission, enabling us to model the radial profiles of $\text{H}^{13}\text{CN}$ and $\text{HC}^{15}\text{N}$. We find tentative evidence of an increasing $^{14}\text{N}/^{15}\text{N}$ ratio with radius, indicating that selective photodissociation in the inner disk is important in setting the $^{14}\text{N}/^{15}\text{N}$ ratio during planet formation.

Key words: astrochemistry – ISM: molecules – protoplanetary disks – radio lines: ISM

1. Introduction

The origin of solar system organics is a fundamental and highly debated topic. It is unclear whether the organics in the different solar system bodies were inherited from the cold and dense molecular parent cloud of our Sun, or if they are the result of chemical processing within the solar nebula protoplanetary disk. The isotopic composition of present-day organics may help to shed light on their origins, since isotopic fractionation chemistry is highly environment specific and can leave a permanent imprint. Comets are especially interesting in this context, since they should preserve the isotopic compositions in different molecules during the assembly of the solar system.

Among the different methods used to trace the origin of molecules, the $^{14}\text{N}/^{15}\text{N}$ isotopic ratio is one of the most popular ones. Nitrogen isotopic ratios span at least an order of magnitude between different solar system bodies. A low nitrogen fractionation (high $^{14}\text{N}/^{15}\text{N}$) is observed toward the Sun and Jupiter ($^{14}\text{N}/^{15}\text{N} = 450$; Marty et al. 2011), while a high fractionation is observed in the rocky planets, comets, and meteorites ($^{14}\text{N}/^{15}\text{N} = 100–300$; Mumma & Charnley 2011). The origin of these $^{14}\text{N}/^{15}\text{N}$ variations is not well understood, but it suggests that different solar system bodies obtained their nitrogen from different nitrogen reservoirs (Mumma & Charnley 2011). Based on observations of the interstellar medium (ISM), comets, and chemical models, there are three major nitrogen reservoirs in dense interstellar and circumstellar media, $\text{N}_2$, $\text{NH}_3$, and $\text{HCN}$. These species have different fractionation pathways (e.g., Hily-Blant et al. 2013), and it is thus important to measure the $^{14}\text{N}/^{15}\text{N}$ ratio in molecules representative of these nitrogen reservoirs.

This study focuses on HCN. HCN is readily detected in the ISM (e.g., Liszt & Lucas 2001; Hily-Blant et al. 2013), comets (e.g., Bockelée-Morvan et al. 2008), and protoplanetary disks (e.g., Thi et al. 2004; Öberg et al. 2010, 2011; Chapillon et al. 2012). While several studies have been made toward prestellar cores and protostars, the characterization of isotopic ratios in protoplanetary disks is rather new due to the intrinsic weak line emission. Guzmán et al. (2015) presented the first detection of $\text{H}^{13}\text{CN}$ and $\text{HC}^{15}\text{N}$ in the disk around Herbig Ae star MWC 480, and provided the first measurement of the $^{14}\text{N}/^{15}\text{N}$ in a disk. They found an isotopic ratio of $200 \pm 100$, which is similar to what is observed in the cold ISM and in comets.

The low $^{14}\text{N}/^{15}\text{N}$ value in the MWC 480 disk implies either inheritance of HCN from the ISM, or the presence of an active fractionation chemistry in the disk. There are two potentially active fractionation channels in disks and in the ISM. The first is through isotope exchange reactions, such as

$$\text{HC}^{14}\text{NH}^+ + ^{15}\text{N} \rightarrow \text{HC}^{15}\text{NH}^+ + ^{14}\text{N} + \text{hv},$$

which favor the incorporation of $^{15}\text{N}$ into molecules at low temperatures ($< 20$ K). $\text{HC}^{14}\text{NH}^+$ can later recombine with free electrons to produce $\text{HC}^{15}\text{N}$. Observations of HCN and HNC fractionation toward protostars present a tentative trend of the $^{14}\text{N}/^{15}\text{N}$ with temperature, supporting this scenario (Wampfler et al. 2014). The second mechanism is selective photodissociation of $^{14}\text{N}^{15}\text{N}$ over $^{14}\text{N}_2$, due to self-shielding of $^{14}\text{N}_2$ (Heays et al. 2014). In the surface layers of protoplanetary disks, which are directly illuminated by the radiation field of the central star, the dominant formation pathways leading to HCN and $\text{HC}^{15}\text{N}$ are

$$^{14}\text{N} + \text{CH}_2 \rightarrow \text{HC}^{14}\text{N}$$

$$^{15}\text{N} + \text{CH}_2 \rightarrow \text{HC}^{15}\text{N}.$$
and around stars with different radiation fields. A constant $^{14}$N/$^{15}$N ratio across disks would favor a scenario where disks inherit their organics from the natal cloud, while disk chemistry should result in a radial gradient, since the disk environment is dramatically different at different radii.

To begin to address this long-term goal, we present observations of H$^{3}$CN and HC$^{55}$N in a diverse sample of six protoplanetary disks. Because the HCN lines may be optically thick, we use the H$^{3}$CN line as a proxy of HCN to derive the $^{14}$N/$^{15}$N ratio. In Section 2 we present the observations and describe the data reduction process. The disk-averaged isotopic flux ratios derived from the observations are presented in Section 3. In Section 4, we model the disk abundance profiles of H$^{3}$CN and HC$^{55}$N in V4046 Sgr, the source with the highest signal-to-noise ratio detection. In Section 5, we discuss the results and compare with observations in our Solar System and in the cold ISM. A summary is presented in Section 6.

2. Observations and Data Reduction

The H$^{3}$CN and HC$^{55}$N $J = 3 - 2$ lines were observed with ALMA during Cycle 2 as part of project ADS/JAO. ALMA#2013.1.00226. The Band 6 observations included two spectral settings, at 1.1 and 1.4 mm. The correlator setup of the 1.1 mm and 1.4 mm settings were covered by three spectral windows in the 1.4 mm spectral setting. The CO isotopologue data was regridded to a spectral resolution of 0.5 km s$^{-1}$ for the full sample. The robust parameter was set to 1.0 for H$^{3}$CN, except for IM Lup where we used a value of 2.0. The robust parameter was set to 2.0 to improve the signal-to-noise ratio, except for V4046 Sgr and MWC 480 for which a value of 1.0 was used because of the bright line emission. For HCN isotopologue data the robust parameter was set to 0.5, and a Keplerian mask was used to help the cleaning process, created by selecting emission consistent with the expected Keplerian rotation of the disk in each channel.

The HCN isotopologue lines were covered by two spectral windows of 59 MHz bandwidth and 61 kHz channel width in the 1.1 mm spectral setting. The CO isotopologue lines were covered by three spectral windows in the 1.4 mm spectral setting, with the same bandwidth and channel width.

The data calibration was performed by the ALMA staff using standard procedures. We took advantage of the bright continuum emission of the sources to improve the signal-to-noise ratio, by further self-calibrating the HCN isotopologue data. The self-calibration solutions were derived on individual spectral windows when possible (AS 209, LkCa 15, MWC 480, and V4046 Sgr) and on averaged spectral windows for the weaker sources (IM Lup and HD 163296), and then applied to each spectral window. The continuum was then subtracted from the visibilities to produce the spectral line cubes. The clean images were obtained by deconvolving the visibilities in CASA, using the CLEAN algorithm with Briggs weighting.

3. Sample Statistics

The stellar and disk properties of the sample are summarized in Table 2. The sample includes four T Tauri stars and two Herbig Ae stars. The stellar masses range between 0.9 (AS 209) and 2.3 $M_{\odot}$ (HD 163296), corresponding to luminosities that span an order of magnitude. Two of the sources, namely LkCa 15 and V4046 Sgr, are transitional disks, with inner holes resolved at millimeter wavelengths. The sample is biased toward large disks, with a known rich molecular emission. However, given the very different physical properties, in particular the gas temperature, the source selection...
allows us to determine the disk-averaged $^{14}\text{N}/^{15}\text{N}$ ratio in HCN in a diverse sample of disks.

Figure 1 shows the observations for the full sample of disks. The dust continuum images are shown in the left column. The 1.1 mm continuum images were produced by averaging 1.1 mm line free spectral windows. The four middle panels display the $^{13}\text{CN}$ and $^{15}\text{CN}$ velocity integrated maps, for the full line (color images) and for two velocity ranges, the blue and redshifted parts of the line, to demonstrate the Keplerian rotation of the disk (blue and red contours). The right column of the figure shows the disk integrated line profiles of the $^{13}\text{CN}$ and $^{15}\text{CN}$ lines. The spectra were extracted using the same elliptical masks used to clean the data. Figures 9–14 show channels maps of the $^{13}\text{CN}$ and $^{15}\text{CN}$ lines in each source, with the elliptical masks overlaid on top.

The lines are classified as detected if emission consistent with the expected Keplerian rotation of the disk is observed in at least three channels at a $3\sigma$ level. From the inspection of the channel maps we find that $^{13}\text{CN}$ is clearly detected toward all disks except for the T Tauri disk IM Lup. $^{13}\text{CN}$ is clearly detected toward V4046 Sgr, MWC 480, and HD 163296, weakly detected toward AS 209 and LkCa 15, and not detected toward IM Lup. We note that for the two disks with weak $^{13}\text{CN}$ line emission, while emission is detected in three or more individual channels, the emission is almost washed out in the integrated intensity maps.

The $^{13}\text{CN}$ emission is generally compact compared to the extent of the dust disk. It appears centrally peaked toward MWC 480 and V4046 Sgr, and possibly toward HD 163296, but presents clear rings toward the remaining two sources: LkCa 15 and AS 209. The latter is unexpected, since AS 209 is not a transition disk. The $^{12}\text{CN}$ line emission shows a similar behavior, although the signal-to-noise ratio is lower.

We extracted the disk integrated fluxes from the unclipped moment-zero maps using the same elliptical mask created to clean the data and extract the spectra. The uncertainty in the flux was estimated by simulating integrated flux measurements from signal free regions using the same elliptical mask but centered at random positions. The integrated disk fluxes and their associated uncertainties are listed in Table 3.

We use the extracted line flux ratios to estimate the abundance ratios of the two isotopologues. This is a reasonable first approximation when comparing HCN isotopologues, as the $^{13}\text{CN}$ and $^{15}\text{CN}$ line emission is expected to be optically thin, arise in the same region and this region is dense enough for the molecular rotational population to be in LTE (Pavlyuchenkov et al. 2007). We compute the $^{13}\text{CN}/^{15}\text{CN}$ abundance ratio in the LTE case and for $T_{\text{eq}} = 15$ K. For MWC 480, we obtain a lower $^{13}\text{CN}/^{15}\text{CN}$ ratio ($1.8 \pm 0.3$) than the value of $2.8 \pm 1.4$ reported in Guzmán et al. (2015), although both values are consistent within the errors. This is due to the different method implemented in this paper to extract the fluxes. The resulting $^{13}\text{CN}/^{15}\text{CN}$ abundance ratios span from 1.2 to 2.2 with an average of 1.8. Given the almost identical upper energies, Einstein coefficients, and the ratio $Q/\sigma_0$ (partition function over upper state degeneracy) for the $J = 3 – 2$ transition (see Table 4), the $^{13}\text{CN}/^{15}\text{CN}$ abundance ratios are almost identical to the flux ratios. We note that a higher excitation temperature of 100 K changes the inferred abundances by less than 1%.

In order to derive the nitrogen fractionation in HCN, we adopt an isotopic ratio of $^{12}\text{C}/^{13}\text{C} = 70$. Because the C isotopic ratio depends on the physical conditions of the gas (e.g., Roueff et al. 2015) we include a 30% uncertainty in this value to convert the $^{13}\text{CN}/^{15}\text{CN}$ ratio into a $^{14}\text{N}/^{15}\text{N}$ ratio. The inferred $^{14}\text{N}/^{15}\text{N}$ ratios span from 83 to 156 with an average of 124. All disks present low cometary-like $^{14}\text{N}/^{15}\text{N}$ ratios. The resulting $^{13}\text{CN}/^{15}\text{CN}$ abundance ratios and the inferred $^{14}\text{N}/^{15}\text{N}$ flux ratios are listed in Table 3. Figure 2 shows the nitrogen fractionation ratios for the full sample and compares it with DCN/HCN ratios derived by Huang et al. (2017). There is no indication of a correlation between the disk-averaged nitrogen and hydrogen fractionation in these disks, as might have been expected if both originated from a cold fractionation pathway (see also Section 5.3). We note that the spread in $^{14}\text{N}/^{15}\text{N}$ is small compared to the errors and we cannot rule out that there is a trend that is washed out by the noise.

### 4. The $^{13}\text{CN}/^{15}\text{CN}$ Profile in V4046 Sgr

HCN isotopologue emission observed toward V4046 Sgr is sufficiently bright to provide constraints on the $^{13}\text{CN}$ and $^{15}\text{CN}$ abundance profiles. In this section, we model the emission profile of the observed lines in order to retrieve the underlying $^{14}\text{N}/^{15}\text{N}$ abundance ratio across the disk.

#### 4.1. Disk Physical Structure

In order to investigate possible variations of the abundance ratio across the disk a detailed model of the line emission is needed. We build a parametric model to describe the physical structure of the disk based on the model described in Rosenfeld et al. (2013), which was constructed to reproduce the emission of the dust continuum and the CO isotopologues. We first

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**Table 2**

| Source     | Distance (pc) | Spectral type | Age (Myr) | $M_\star$/$M_\odot$ | $L_\star$/$L_\odot$ | $M_{\text{int}}$/$10^{-7}M_\odot$ yr$^{-1}$ | Disk Incl. (deg) | Disk PA (deg) | $M_{\text{disk}}$/$M_\star$ | vLSR (km s$^{-1}$) |
|------------|---------------|---------------|-----------|---------------------|---------------------|---------------------------------------------|-----------------|-----------------|---------------------|------------------|
| AS 209     | 126           | K5            | 1.6       | 0.9                 | 1.5                 | 51                                          | 38              | 86              | 0.015               | 4.6              |
| IM Lup     | 161           | M0            | 1         | 1.0                 | 0.93                | 0.01                                        | 50              | 144.5           | 0.17                | 4.4              |
| LkCa 15    | 140           | K3            | 3–5       | 0.97                | 0.74                | 1.3                                         | 52              | 60              | 0.05–0.1           | 6.3              |
| V4046 Sgr  | 72            | K5, K7        | 24        | 1.75                | 0.49, 0.33          | 0.5                                         | 33.5            | 76              | 0.028               | 2.9              |

**Note.** Table reproduced from Huang et al. (2017), where a complete list of references is given.
parametrize the dust surface density as

$$\Sigma_{dust}(r) = \begin{cases} \Sigma_c \left(\frac{r}{r_c}\right)^{-\gamma} \exp\left[-\left(\frac{r}{r_c}\right)^{2-\gamma}\right] & r \geq r_{cav} \\ \Sigma_{cav} & 0.2 \text{ au} < r < r_{cav} \end{cases}$$

where $\Sigma_c$ is a normalization factor, $r_c$ is a characteristic radius, $\gamma = 1$ is the power-law index of the viscosity, and $r_{cav}$ is the radius of the inner cavity. We include two dust populations, one for the atmosphere and another for the midplane grains. The dust volume density is computed assuming a vertical Gaussian distribution of each dust grain population:

$$\rho_{dust} = \sum_{i=0,1} \frac{\Sigma_i(r)}{\sqrt{2\pi} H_i(r)} \exp\left(-\frac{z^2}{H_i(r)^2}\right).$$

The midplane grains, which are larger than the atmospheric ones, comprise the bulk of the dust mass ($\Sigma_{mid} = 0.9 \Sigma_{dust}$, $\Sigma_{atm} = 0.1 \Sigma_{dust}$). The atmospheric dust grains are vertically Gaussian distributed with a scale height:

$$H_{atm}(r) = H_{10} \left(\frac{r}{100 \text{ au}}\right)^{\delta}.$$
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Table 3

Integrated Fluxes and Inferred Abundance Ratios in the Disk Sample

| Source  | $F(\text{H}^{13}\text{CN})$ | $F(\text{HC}^{15}\text{N})$ | $N(\text{H}^{13}\text{CN}) / N(\text{HC}^{15}\text{N})$ | $^{13}\text{N}/^{15}\text{N}$ |
|---------|----------------|----------------|---------------------------------|----------------|
| AS 209  | 175 ± 25       | 79 ± 23        | 2.2 ± 0.7                       | 156 ± 71       |
| IM Lup  | <59          | <59          | -                              | -              |
| LkCa 15 | 120 ± 20       | 101 ± 18       | 1.2 ± 0.3                       | 83 ± 32        |
| V4046 Sgr | 1098 ± 35    | 670 ± 26       | 1.6 ± 0.1                       | 115 ± 35       |
| MWC 480 | 132 ± 13       | 75 ± 13        | 1.8 ± 0.3                       | 123 ± 45       |
| HD 163296 | 177 ± 23     | 87 ± 21        | 2.0 ± 0.6                       | 142 ± 59       |

Notes.
1. The uncertainties do not include absolute flux calibration errors.
2. Computed assuming LTE and $T_d = 15$ K.
3. Adopting $^{12}\text{C}/^{13}\text{C} = 70$ and an associated uncertainty of 30%.
4. 3σ upper limits.

Table 4

Spectroscopic Parameters

| Line          | Frequency (GHz) | $E_u / k$ (K) | $\lambda_{ad}$ (s$^{-1}$) | $\varphi_a$ |
|---------------|----------------|--------------|-----------------|------------|
| $\text{H}^{13}\text{CN}$ $J = 3 - 2$ | 259.0118        | 24.86        | $7.7 \times 10^{-4}$ | 21         |
| $\text{HC}^{15}\text{N}$ $J = 3 - 2$ | 258.1571        | 24.78        | $7.6 \times 10^{-4}$ | 7          |

Figure 2. N fractionation as a function of deuterium fractionation. Disks around T Tauri stars are shown in red colors, while disks around Herbig Ae stars are shown in blue colors. The DCN/HCN ratios are taken from Huang et al. (2017). Both abundance ratios are computed assuming LTE conditions and $T_d = 15$ K.

and the midplane dust grains are concentrated closer to the midplane, with a scale height that is half that of the atmospheric grains.

$$H_{\text{mid}}(r) = \frac{1}{2}H_{\text{atm}}(r).$$  (7)

With the dust density described above, the radiative transfer code RADMC-3D (Dullemond 2012) was then used to compute the dust temperature throughout the disk. The dust absorption and scattering opacities, which are needed to solve the thermal balance, were computed using the Opacity-Tool2 from the DIANA project (Woitke et al. 2016). The code assumes a mixture of amorphous laboratory silicates with amorphous carbon and 25% porosity for the grain composition. The grain size distribution follows a power law of index $-3.5$.

Figure 2. N fractionation as a function of deuterium fractionation. Disks around T Tauri stars are shown in red colors, while disks around Herbig Ae stars are shown in blue colors. The DCN/HCN ratios are taken from Huang et al. (2017). Both abundance ratios are computed assuming LTE conditions and $T_d = 15$ K.

The minimum grain size was set to 5 nm, and the maximum size was set to 10 μm and 1 cm, for the atmosphere and midplane grain populations, respectively.

The gas temperature is parametrized as

$$T_{\text{gas}}(r, z) = \begin{cases} T_d + (T_m - T_d) \left( \frac{z}{z_q} \right)^{25} & z < z_q \\ T_m & z \geq z_q \end{cases}$$  (8)

following Dartois et al. (2003). Here, the atmospheric temperature is given by a power law ($T_d = T_{d,0} (r/10)^{\delta_{\text{atm}}}$), and the midplane temperature is fixed to the dust temperature ($T_m = T_{\text{dust}}(z = 0)$). The fiducial scale height at which the gas temperature is allowed to vary vertically, $z_q$, is fixed to $z_q = 2H_{\text{gas}}$, where $H_{\text{gas}} = 2c_s / \Omega$ is the hydrostatic gas scale height evaluated at the midplane, $z = 0$.

Once the gas temperature is obtained, the hydrostatic equation is solved to derive the gas density across the disk. For this we assume a vertically integrated gas-to-dust ratio at each radii of 100. The adopted parameters for the model are listed in Table 5. The resulting gas density and temperature structures are shown in Figure 3. This model reproduces the main features of the $^{12}\text{CO}$, $^{13}\text{CO}$, and $^{18}\text{O}$ emission (see Figure 4) well enough for the purpose of this study, assuming standard isotopic ratios. In this model, the CO abundance is kept constant throughout the disk, except in the cold midplane ($T_{\text{gas}} < 19$ K) where the abundance is reduced by a factor of $10^3$ due to freeze-out onto dust grains, and in the disk atmosphere where the CO abundance is reduced by a factor $10^5$ due to photodissociation.

Table 5

Adopted Parameters in Disk Model

| Scale Height | $h$ | 0.4 au | 1.25 |
|-------------|-----|-------|-----|
| Dust Surface Density | $\Sigma_d$ | 0.226 g cm$^{-2}$ | |
| $\gamma$ | 1 | | |
| $r_c$ | 75 au | | |
| $\Sigma_{\text{surf}}$ | $10^{-4}$ | | |
| $r_{\text{gas}}$ | 3 au | | |
| Gas Temperature | $T_{\text{d}}$ | 200 K | |
| $q_{\text{gas}}$ | 0.8 | | |
| $\delta$ | 2 | | |

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2 https://dianaproject.wp.st-andrews.ac.uk/data-results-downloads/fortran-package/
4.2. Abundance Fitting

The molecular abundances for $^{13}$HCN and HC$^{55}$N were defined as power laws,

$$X = X_0 (r/R_0)^\alpha$$

(9)

where $X_0$ is the abundance with respect to total hydrogen at $R_0 = 100$ au and $\alpha$ is a power-law index. We also include an outer cut-off radius $R_{\text{out}}$. This parameterization is a common approach when modeling molecular abundances in disks (e.g., Qi et al. 2008, 2013).

In order to find the model that best reproduces the HCN isotopologue observations and the associated uncertainties, we use a Bayesian approach. In short, we first create a synthetic observation of the line emission for each species separately. Taking advantage of the bright HCN isotopologue emission in V4046 Sgr, we produced observed visibilities and cleaned cubes at a higher spectral resolution of 0.2 km s$^{-1}$ for the line modeling and include include 60 channels. We use the vis_sample Python package$^3$ to compute the Fourier Transform of the synthetic model and obtain visibilities that are correctly reprojected on the $u-v$ plane. The likelihood function is then computed in the $u-v$ plane, by computing the weighted difference between model and observations, for the real and imaginary parts of the complex visibility. We sample the posterior distribution with the MCMC method implemented in the emcee package by Foreman-Mackey et al. (2013).

We include two free parameters in the line modeling, that is $X_0$ and $\alpha$, which are associated with the molecular abundances of HCN and HC$^{55}$N. The outer radius, $R_{\text{out}}$, was fixed to 100 au (chosen by the extension of the emission in the moment-zero map), but we checked that a larger radius of 200 au gave the same result. The disk physical structure, that is the gas density and temperature, are fixed in the line fitting. We adopt the disk inclination, position angle, stellar mass (including both stars), and systemic velocity listed in Table 2. The level populations were computed using RADMC and assuming the gas is under LTE. We checked that non-LTE effects are not important for these lines using the non-LTE radiative transfer code LIME (Brinch & Hogerheijde 2010) to re-calculate the level populations for the best-fit model. When generating a new sample, we included a flat prior for the power-law index $-3 < \alpha < 2$, and for the molecular abundance $10^{-20} < X_0 < 10^{-8}$.

The best-fit model corresponds to $X_0 = 8.94 \pm 0.30 \times 10^{-13}$ and $\alpha = -0.69 \pm 0.03$ for HCN, and $X_0 = 3.37 \pm 0.19 \times 10^{-13}$ and $\alpha = -1.08 \pm 0.04$ for HC$^{55}$N. Our model suggests an increasing HCN/HC$^{55}$N ratio as a function of radius, i.e., higher fractionation in the inner disk compared to the outer disk. Figure 5 shows the deprojected radial profiles of the dust continuum and HCN isotopologue emission in V4046 Sgr (left panel) as well as the observed and modeled HCN/HC$^{55}$N flux ratio (right panel). We note that beyond 60 au, the ratio is highly uncertain because the signal-to-noise ratio becomes too low, in particular for HC$^{55}$N.

5. Discussion

5.1. Disk-averaged Nitrogen Fractionation in Protoplanetary Disks

We have shown that HCN isotopologues are abundant in disks. Both H$^{13}$CN and HC$^{55}$N are detected toward five out of six disks in our sample—the one exception being the disk around T Tauri star IM Lup. The disk around IM Lup is very massive ($M_{\text{disk}} = 0.1 M_\odot$), very cold, and also very young (e.g., Cleeves et al. 2016) compared to the rest of the disks in the sample. The non-detection of H$^{13}$CN was surprising considering that IM Lup is quite bright in the main HCN isotopologue (Öberg et al. 2011). Given the observed HCN flux density of 3.5 Jy km s$^{-1}$, we could expect a H$^{13}$CN flux density of 50 mJy km s$^{-1}$ if HCN is optically thin and $^{13}$C/$^{12}$C = 70. This is consistent with the observed 3$\sigma$ upper limit of 51 mJy km s$^{-1}$.

The inferred disk-averaged nitrogen fractionation ratios range from 83 ± 37 to 156 ± 78. Despite the different physical conditions of the disks in the sample, the observed values fall along a single trend that seems to be driven by the disk mass. The inferred nitrogen fractionation is strongly correlated with the disk mass, with less fractionation in the higher mass disks. This trend is consistent with the idea that fractional condensation is an important fractionation mechanism, and the fractionation factor decreases as the fraction of the disk mass that condenses decreases.

$^3$ https://pypi.python.org/pypi/vis_sample
H$^{13}$CN/HC$^{15}$N ratios are consistent with sampling a constant disk-averaged fractionation level. In particular, we find no difference in the nitrogen fractionation level between disks around T Tauri and Herbig Ae stars, which have an order-of-magnitude difference in the stellar radiation field. No difference in the disk-averaged $^{14}$N/$^{15}$N is observed between full and transitional disks, either. The age of the star does not seem to play an important role either—we target young (∼1 Myr) and old (>10 Myr) sources—suggesting either that the $^{14}$N/$^{15}$N is inherited from the parent cloud and is not modified in the disk, or the disk chemistry sets the global, disk-averaged nitrogen fractionation level early (≤1 Myr) in the protoplanetary disk life.

Although we do not observe differences in the nitrogen fractionation ratio between the sources, the data suggest that there may be a difference in the nitrogen abundance between the disks around stars V4046 Sgr, MWC 480, and HD 163206, and the disks around T Tauri stars AS 209 and LkCa 15. The old disk around the binary T Tauri stars V4046 Sgr and the two Herbig Ae stars in the sample are enriched in HCN compared to the young T Tauri stars. Disk models have shown that dust migration and carbon and oxygen depletion (mainly due to CO and H$_2$O freeze-out) can increase the column density of cyanides by up to two orders of magnitude in the outer disk (Du et al. 2015). Future observations toward a larger sample of disks will show if this corresponds to an evolutionary trend.

5.2. Comparison between Nitrogen Fractionation in Disks, Solar System, and ISM

Figure 8 shows the observed $^{14}$N/$^{15}$N ratios in different solar system bodies, the cold ISM, and in the diffuse medium. There are large variations in the $^{14}$N/$^{15}$N ratio among different Solar system bodies, in particular between the rocky and gaseous bodies. The Sun has the highest $^{14}$N/$^{15}$N value in this comparison (441 ± 5), measured by the Genesis
mission that sampled solar wind ions, N+ among them (Marty et al. 2011). An almost identical value was found in the atmosphere of Jupiter through the NH3 observations carried out by the Cassini spacecraft (Fouchet et al. 2004). Both measurements are expected to trace the lack of nitrogen fractionation in N2, the main nitrogen reservoir of the protosolar nebula. The 15N-depleted solar value is thus considered to be representative of the conditions of the gas when the Sun formed. All the other solar system bodies are enriched in 15N compared to the Sun. A value of 14N/15N = 272 is found in the Earth’s atmosphere, measured in N2. The 14N/15N has also been measured in several comets. An isotopic ratio of ~150 was found in C/1995 O1 (Hale-Bopp) and 17P/Holmes, a value which was consistent for both HCN and CN (Bockelée-Morvan et al. 2008). Observations of 18 comets from both the Oort cloud and the Kuiper Belt all show consistently low HCN/HCN = 100–250 ratios (Mumma & Charnley 2011).

The cold ISM is also enriched in 15N. Hily-Blant et al. (2013) measured the H13CN/H15CN toward two prestellar cores, L183 and L1544, and found 14N/15N values of 140–250 and 140–360, respectively. The 14N/15N in CN was later

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**Figure 7.** Channel maps of the observed H13CN and H15CN J = 3 − 2 emission lines in V4046 Sgr (upper panels). The middle panels show the best-fit models for each line. The residuals are shown in the bottom panels. Positive (black) and negative (red) contour levels correspond to 3, 5, 7, 10, 15, 20, and 25σ.

**Figure 8.** 14N/15N isotopic ratios observed toward different solar system bodies (Bockelée-Morvan et al. 2008; Marty et al. 2011), the ISM (Ikeda et al. 2002; Lucas & Liszt 1998; Hily-Blant et al. 2013), and protoplanetary disks (this work). The solar and Earth values were measured for N+ and N2, respectively, and the rest of the sources all correspond to isotopic ratios measured for HCN.
measured toward L1544 resulting in a surprisingly high CN/C\textsuperscript{15}N ratio of 500 ± 75 (Hily-Blant et al. 2013b). The authors were able to reproduce the observed difference in CN and HCN with chemical models of cold gas. The fact that CN and HCN present similar fractionation levels in comets, could be explained if CN is produced in the coma from photodissociation of HCN (Hily-Blant et al. 2013b). Ikeda et al. (2002) also found a low HCN/H\textsubscript{2}C\textsubscript{15}N ratio of 151 ± 16 toward the prestellar core L1521E.

Finally, the averaged \textsuperscript{15}N enrichment observed for HCN in protoplanetary disks is similar to comets and the cold ISM. While the similar nitrogen fractionation ratios found in the cold ISM, comets, and disks are consistent with an inheritance scenario for the origin of organics in the solar system, as we discuss in the next section, the increasing \textsuperscript{14}N/\textsuperscript{15}N ratio in the disk of V4046 Sgr suggests that in situ disk chemistry also contributes to the observed fractionation patterns.

5.3. Resolved Nitrogen Fractionation Chemistry in Disks

The bright emission of the HCN isotopologues in V4046 Sgr allows us to trace the \textsuperscript{14}N/\textsuperscript{15}N profile across a disk for the first time. In general, there are three possibilities for what could be observed: a flat, decreasing or increasing \textsuperscript{14}N/\textsuperscript{15}N as a function of disk radius. If H\textsubscript{2}^13CN and HC\textsubscript{15}N are inherited from the prestellar gas and no further chemical processing occurs in the disk, then a constant \textsuperscript{14}N/\textsuperscript{15}N ratio is expected across the disk. On the other hand, if the nitrogen chemistry is altered by in situ chemical fractionation in the disk then a varying \textsuperscript{14}N/\textsuperscript{15}N is expected. In this case, if chemical fractionation dominates the nitrogen fractionation then a low \textsuperscript{14}N/\textsuperscript{15}N is expected to occur in the outer disk, where the gas temperature is low (i.e., a decreasing \textsuperscript{14}N/\textsuperscript{15}N with radius). In contrast, if selective photodissociation is the dominant pathway to fractionate HCN, then an increasing \textsuperscript{14}N/\textsuperscript{15}N profile would be observed because this pathway is most important in regions exposed to UV photons, i.e., the inner disk, which is illuminated by the central star.

The observations toward V4046 Sgr show that both H\textsubscript{2}^13CN and HC\textsubscript{15}N are best reproduced by a decreasing abundance profile. However, the inferred HC\textsubscript{15}N emission profile is slightly steeper than that of H\textsubscript{2}^13CN, pointing to a higher fractionation in the inner disk than in the outer disk. The varying \textsuperscript{14}N/\textsuperscript{15}N observed in V4046 Sgr shows that there is an active nitrogen fractionation in the disk, which changes the original fractionation pattern. The fact that \textsuperscript{13}N/\textsuperscript{15}N is lower in the inner disk suggests that selective photodissociation is indeed an important pathway to fractionate HCN in the inner disk. Higher signal-to-noise ratio observations are needed to determine if there is also an active N fractionation chemistry in the outer disk.

There is additional evidence that cold ion–molecule fractionation does not alone regulate the H\textsubscript{2}^13CN/H\textsubscript{2}C\textsubscript{15}N ratio in disks. Huang et al. (2017) measured the D/H isotopic ratio in DCO\textsuperscript{+} and HCN toward the same sample of disks. They found enhanced D/H ratios compared to the elemental ratio in the local ISM (∼2 × 10\textsuperscript{-7}) in all disks, with DCN/HCN ratios ranging from 0.005 to 0.08. If the cold pathway dominates the fractionation for both species in these disks we could expect a correlation between the D/H and \textsuperscript{14}N/\textsuperscript{15}N ratios. However, we do not see such correlation in the sample (see Figure 2).

5.4. Future Directions

We have shown that the \textsuperscript{14}N/\textsuperscript{15}N ratio increases with radius in the disk around T Tauri stars V4046 Sgr. However, the angular resolution of the current data (0\textdegree5 corresponding to ∼36 au at 73 pc) prevents us from resolving \textsuperscript{14}N/\textsuperscript{15}N variations at smaller scales and the low signal-to-noise ratio prevents us from constraining the chemistry beyond 60 au. Future observations at larger angular resolution should allow us to measure the radial dependence of \textsuperscript{14}N/\textsuperscript{15}N at solar system scales, and determine how the fractionation ratio changes from the inner (<15 au) to the outer (>30 au) disk.

High-angular-resolution observations toward more disks are needed to determine whether an increasing \textsuperscript{14}N/\textsuperscript{15}N is a general characteristic of disks or unique to V4046 Sgr. A larger sample is also needed to draw more general conclusions on the dominant fractionation pathways in disks, and how the \textsuperscript{14}N/\textsuperscript{15}N pattern depends on the physical conditions of the disk. In this respect, new chemical models that include all nitrogen fractionation pathways (selective photodissociation and cold isotope exchange reactions) as well as inheritance from the parent cloud are key to interpret the observations. In addition, it is desirable to include the fractionation of both carbon and nitrogen in the models, since most \textsuperscript{14}N/\textsuperscript{15}N measurements in both disks and cold ISM rely on observations of the \textsuperscript{13}C isotopologues to measure the contribution of the main isotopologues.

In contrast to HCN, hydrides (e.g., N\textsubscript{2}H\textsuperscript{+} and NH\textsubscript{3}) are found to be \textsuperscript{15}N-depleted in the ISM. Toward L1544, Bizzocchi et al. (2013) found a nitrogen isotopic ratio in N\textsubscript{2}H\textsuperscript{+} of 1000. Toward the class 0 protostar B1b, Daniel et al. (2013) found \textsuperscript{14}N/\textsuperscript{15}N ratios of 260–355 for NH\textsubscript{3} and an upper limit of >600 for N\textsubscript{2}H\textsuperscript{+}. Hily-Blant et al. (2013) proposed that the difference in nitrogen fractionation between cyanides and hydrides in the cold ISM is the result of their different chemical origins: HCN derives from atomic N, while NH\textsubscript{3} and N\textsubscript{2}H\textsuperscript{+} derive from molecular nitrogen. This hypothesis, however, is challenged by the recent measurement of the \textsuperscript{14}N/\textsuperscript{15}N ratio in NH\textsubscript{2}, a photodissociation product of NH\textsubscript{3} in cometary coma, toward comet C/2012 S1 (ISON), where a fractionation ratio of 139 ± 38 was found (Shinnaka et al. 2014). A similarly low value (~130) was found previously by Rousselet et al. (2014) based on the averaged spectrum of 12 comets. Toward comet ISON, CN and HCN were also found to be highly enriched in \textsuperscript{15}N (\textsuperscript{14}N/\textsuperscript{15}N ~ 150). As explained by Shinnaka et al. (2014), one possibility to obtain similar HCN and NH\textsubscript{3} fractionation levels in comets, despite very different fractionation levels in the cold ISM, is through grain surface chemistry. Indeed, the ISM values represent the \textsuperscript{14}N/\textsuperscript{15}N in the gas phase, while cometary values represent the \textsuperscript{14}N/\textsuperscript{15}N in the ices. It is also possible that the measured cometary values is not representative of the composition of the nucleus. Measurements of the isotopic ratio in NH\textsubscript{3} and N\textsubscript{2}H\textsuperscript{+} in disks would provide additional clues to answer these questions. In particular, if the cyanide/hydrde dichotomy observed in the cold ISM holds for disks as well.

Finally, more observations toward comets targeting different molecular parent species (i.e., species tracing the cometary nucleus and not daughter species that are produced in the coma) will be important to compare with observations in the ISM and disks, and to elucidate the origins of \textsuperscript{15}N enhancements, and ultimately the origins of organics, across the solar system.
6. Conclusions

We have presented ALMA observations at \( \sim 0.5 \) angular resolution of the HCN isotopologues in a diverse sample of six protoplanetary disks. The sample contains four T Tauri and two Herbig Ae stars, which sample an order of magnitude in radiation fields. Both H\(^{13}\)CN and HCN\(^{15}\) are detected toward all the sources, except for IM Lup, which is the most massive and coldest disk, and likely the youngest, in the sample. Adopting a standard C\(^{12}/C\(^{13}\) ratio of 70 (with a 30\% uncertainty), we infer disk-averaged \(^{14}N/^{15}N\) ratios of 80–160 for the sources. Despite the different physical conditions of the disks, \(^{14}N/^{15}N\) in HCN is similar for all sources. No differences are observed between T Tauri and Herbig Ae stars, or between the full disks and the transitional disks, which feature large dust cavities. Also, no correlation is observed between disk-averaged \(D/H\) and \(^{14}N/^{15}N\) ratios in the sample. The observed disk-averaged \(^{14}N/^{15}N\) ratios are similar to what is observed in comets and in the cold ISM, which is consistent with the inheritance scenario for the origin of organics in the solar system. However, chemical processing within the protoplanetary disk phase based on these ratios alone cannot be ruled out. Indeed, in the one disk where we could resolve the H\(^{13}\)CN/HCN\(^{15}\) ratio as a function of radius we find a slightly steeper profile for HCN\(^{15}\), i.e., an increasing \(^{14}N/^{15}N\) ratio with radius. The higher nitrogen fractionation level in the inner disk compared to the outer disk suggest that selective photodissociation is an important fractionation pathway in the inner disk.

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Appendix

Channel Maps

Figures 9–14 show channel maps of the observed H\(^{13}\)CN and HCN\(^{15}\) J = 3–2 emission lines in the disk sample.

![Channel Maps](image-url)
**Figure 10.** Same as in Figure 9 but for IM Lup.

**Figure 11.** Same as in Figure 9 but for LkCa 15.
Figure 12. Same as in Figure 9 but for V4046 Sgr.
Figure 13. Same as in Figure 9 but for MWC 480.
Figure 14. Same as in Figure 9 but for HD 163296.
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