WARM HCN IN THE PLANET FORMATION ZONE OF GV TAU N*

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ABSTRACT

The Plateau de Bure Interferometer has been used to map the continuum emission at 3.4 mm and 1.1 mm together with the $J = 1\rightarrow0$ and $J = 3\rightarrow2$ lines of HCN and HCO$^+$ toward the binary star GV Tau. The 3.4 mm observations did not resolve the binary components, and the HCN $J = 1\rightarrow0$ and HCO$^+ J = 1\rightarrow0$ line emissions trace the circumbinary disk and the flattened envelope. However, the 1.1 mm observations resolved the individual disks of GV Tau N and GV Tau S and allowed us to study their chemistry. We detected the HCN $J = 2\rightarrow1$ line only toward the individual disk of GV Tau N, and the emission of the HCO$^+$ $J = 2\rightarrow1$ line toward GV Tau S. Simple calculations indicate that the $J = 3\rightarrow2$ line of HCN is formed in the inner $R < 12$ AU of the disk around GV Tau N where the HCN/HCO$^+$ abundance ratio is $>300$. On the contrary, this ratio is $<1.6$ in the disk around GV Tau S. The high HCN abundance measured in GV Tau N is well explained by photochemical processes in the warm (>400 K) and dense ($n > 10^3 \text{ cm}^{-3}$) disk surface.

Key words: ISM: individual objects (GV Tau N, GV Tau S) – ISM: lines and bands – radio continuum: ISM – stars: formation

Online-only material: color figures

1. INTRODUCTION

A fraction of the gas and dust in protoplanetary disks will end up in planets and may constitute the basis to form prebiotic species. A large effort has been undertaken, with the aim to detect the warm gas in the planet formation zone using Spitzer and NIR ground-based facilities. In a pioneering work, Lahuis et al. (2006) detected strong HCN and C$_2$H$_2$ absorption features toward one source, IRS 46, from a sample of more than 100 Class I and II sources located in nearby star-forming regions. Later, Gibb et al. (2007, 2008) detected the HCN and C$_2$H$_2$ absorption lines in GV Tau. Carr & Najita (2011) detected the rotational transitions of H$_2$O and OH and the rovibrational bands of simple organic molecules (CO$_2$, HCN, C$_2$H$_2$) in 11 classical T Tauri stars showing that these molecules are not uncommon in the inner region of the T Tauri disks. Thus far, only NIR spectroscopy has provided information about the chemical composition of the gas in the inner disk region. Interferometric millimeter and submillimeter observations are key to derive the kinematics and physical conditions of the gas, as well as the molecular abundance radial profiles that NIR studies cannot provide.

GV Tau (Haro 6-10) is a T Tauri binary system embedded in the L1524 molecular ($d = 140$ pc) cloud. It is one of a small number of young binaries for which the primary (GV Tau S) is optically visible and the companion (GV Tau N), located 1"2 to the north, is strongly embedded. It is associated with a parsec-scale Herbig–Haro flow which extends to 1.6 pc to the north at a position angle (P.A.) of about 222° and ∼1 pc to the south (Devine et al. 1999; see also Mousis & Magakian 1999). This region has been extensively studied in the NIR and all the studies pointed to the existence of a complex system composed of two circumstellar disks associated with GV Tau N and GV Tau S, respectively, that are themselves surrounded by a circumbinary disk and/or flattened nebula (Ménard et al. 1993; Koersko et al. 1999; Leinert et al. 2001). Doppmann et al. (2008) and more recently Wilking et al. (2012) proposed that GV Tau N and possibly GV Tau S could be binary systems themselves. The two individual disks GV Tau N and GV Tau S are misaligned and present different inclination angles. The GV Tau N disk has an edge-on geometry, while the GV Tau S disk is closer to a face-on orientation which allows the stellar radiation to escape, forming a visible nebula (Roccatagliata et al. 2011). Only the GV Tau N disk has been detected in the H$_2$ 2.12 $\mu$m rovibrational line (Herbst et al. 1995). The HCN and C$_2$H$_2$ absorption rovibrational lines are detected toward GV Tau N (Gibb et al. 2007, 2008), which proves the existence of a rich organic chemistry in the inner disk of this star. The non-detection of these lines toward GV Tau S did not allow us, however, to conclude about its disk chemistry since it could be due to the different disk inclination.

We present 3.4 mm and 1.1 mm interferometric images of GV Tau using the IRAM Plateau de Bure Interferometer (PdBI). The highest spatial resolution observations at 1.1 mm allowed us to resolve the GV Tau N and GV Tau S individual disks and have a first glance at the chemical differences between them.

2. OBSERVATIONS

The HCN $J = 1\rightarrow0$ and HCO$^+ J = 1\rightarrow0$ lines were observed using the PdBI in its CD configuration during 2009 October–November. This configuration provided an angular resolution of 3.07 × 3.05 P.A. 17° (∼432 AU × 429 AU at the distance of Taurus). During the observations, two 40 MHz bandwidth correlator units were placed at the frequencies of the HCN $J = 1\rightarrow0$ (88631.85 MHz) and HCO$^+ J = 1\rightarrow0$ (89188.52 MHz) lines, providing a spectral resolution of 78 kHz. These lines were also observed with the 320 MHz units which provided a spectral resolution of...
correlator units were placed at the frequencies of the HCN 3→2 (265886.18 MHz) and HCO+ 3→2 lines. The spectral maps are shown in Figures 2 and 3. The phase center of our observations was \( \text{R.A.}(\text{J2000}) = 04:29:23.73 \), decl.(\text{J2000}) = 24:33:00.30. Central panel: interferometric image of the continuum emission at 1.1 mm. Contour Levels are 10 mJy beam\(^{-1}\) to 50 mJy beam\(^{-1}\) by 5 mJy beam\(^{-1}\). Left panel: interferometric spectra of the HCN 3→2 and HCO+ 3→2 lines toward GV Tau N and GV Tau S.

(A color version of this figure is available in the online journal.)

Figure 1. Right panel: interferometric image of the continuum emission at 3.4 mm. Contour Levels are 3 mJy beam\(^{-1}\) to 13 mJy beam\(^{-1}\) by 1 mJy beam\(^{-1}\). The image is centered at \( \text{R.A.}(\text{J2000}) = 04:29:23.73, \) decl.(\text{J2000}) = 24:33:00.30. Left panel: interferometric spectra of the HCN 3→2 and HCO+ 3→2 lines toward GV Tau N and GV Tau S.

In 2011 February, we performed subarcsecond imaging of this region in the HCN 3→2 and HCO+ 3→2 lines using the PdBI in its A configuration, which provides a beam of \(~0.49 \times 0.26 \, \text{P.A. 16}^{\circ} \sim (69 \, \text{AU} \times 36 \, \text{AU})\). Two 40 MHz correlator units were placed at the frequencies of the HCN 3→2 (265886.18 MHz) and HCO+ 3→2 (267557.526 MHz) lines. We used the correlator WIDEX to cover the 4 GHz bandwidth of the receivers (264.58–268.18 GHz). Only HCO+ 3→2 and HCN 3→2 were detected down to an rms of 6 mJy beam\(^{-1}\) with a spectral resolution of 2 MHz. The channels without line emission in WIDEX were used to create the continuum 1.1 mm map which was subtracted from the spectral maps. The resulting 3.4 mm and 1.1 mm continuum images are shown in Figure 1. The spectral maps are shown in Figures 2 and 3. The phase center in our observations was \( \text{R.A.}(\text{J2000}) = 04:29:23.73, \) decl.(\text{J2000}) = 24:33:00.30, in between the two stars.

3. RESULTS

3.1. Continuum

Our 3.4 mm image does not resolve the two components of the binary. An elliptical Gaussian was fit to the uv table and the parameters are shown in Table 1. The size of the emission, \(~280 \, \text{AU}\) in diameter, is slightly smaller than the size of the NIR nebula observed by Ménard et al. (1993). The 3.4 mm continuum emission peaks in the middle of the two stars, suggesting a similar contribution to the total flux from the two disks. The total flux, \(16.1 \pm 0.4 \, \text{mJy}\), is consistent with that measured by Guilloteau et al. (2011).

Our 1.1 mm observations clearly resolve the two components which present similar intensity. Gaussian fits to the uv tables were done and the parameters are shown in Table 1. Because of our elongated beam, the disks are resolved in only one direction. Our fit gives a radius of \(~0.07 \sim (10 \, \text{AU})\) for the emission of the two disks. Guilloteau et al. (2011) observed this target using the PdBI with a larger beam of \(0.89 \times 0.56\) and derived a size twice larger than ours. After modeling the emission, they concluded that the two disks are, very likely, optically thick and the size was overestimated because of the atmospheric seeing. This could be a reason for our disagreement. Another possibility is that we have filtered out part of the disk emission. The filtering effect would be more severe toward the GV Tau S disk because of the face-on orientation. With the sizes derived from our observations, we estimate a brightness temperature of \(>69 \, \text{K}\) for the N component and \(>56 \, \text{K}\) for the S component (we give a lower limit because the emission is essentially unresolved in one direction), consistent with the emission arising from the \(R < 10 \, \text{AU}\) region of a T Tauri disk (Pinte et al. 2006).

3.2. Spectral Observations

We have detected intense emission of the HCN 1→0 and HCO+ 1→0 lines toward GV Tau. The integrated emission of the HCO+ 1→0 line is composed of a compact source centered at the phase center and an envelope elongated in the southeast–northwest direction. In Figure 2 we show the velocity map of the HCO+ 1→0 line. A clear velocity gradient is detected in the southeast–northwest direction. The direction of this gradient is close to orthogonal to the main Herbig–Haro outflow, and consistent with the existence of a rotating circumferential disk. The integrated emission of the HCN 1→0 line is composed of a compact source and an extended envelope. The compact source peaks \(~1''\) to the north of the phase center suggesting a larger contribution of GV Tau N to the total emission. The extended emission is very asymmetric, being more extended toward the southeast than toward the northwest. Moreover, the HCN 1→0 emission has an elongation in the outflow direction (see Figure 2). There is some hint of velocity gradient in the HCN 1→0 line although in this case the gradient is less clear than in the case of HCO+ 1→0.

In Figure 1, we show the spectra of the HCN 3→2 and HCO+ 3→2 lines toward GV Tau N and S. The HCN 3→2 line is only detected toward the N component. The HCO+ line is clearly detected toward the S component and tentatively detected toward the N component. The velocity-integrated intensity map of the HCN 3→2 line is well fitted with an elliptical Gaussian of \(0.32 \pm 0.04 \times 0.25 \pm 0.05\) centered at the star position, a size slightly larger than that of the 1.1 mm continuum, emission. The emission of the HCO+ 3→2 line is clearly more extended than the 1.1 mm continuum suggesting some contribution from the circumferential disk and/or the nebula. Fitting an elliptical Gaussian in the uv plane, we obtain a size of \((1.26 \pm 0.06) \times (0.73 \pm 0.09)\). The zero and first momentum maps of the HCN 3→2 and HCO+ 3→2 line emissions are...
Figure 2. Top: zero (left) and first (right) moment maps of the HCO$^+$ 1→0 line toward GV Tau. Contour levels are 0.1 to 0.5 by 0.05 Jy beam$^{-1}$ × km s$^{-1}$. The directions of the large-scale outflow defined by the giant Herbig–Haro flow (P.A. = 222$^\circ$; Devine et al. 1999) and of the Herbig–Haro jet (P.A. = 195$^\circ$; Movsessian & Magakian 1999) are indicated by two black lines through the phase center. Bottom: the same for the HCN 1→0 line.

Table 1
Gaussian Fits to the Continuum and Spectral Data

| Source | $\lambda$ | HPBW ("') | Flux (mJy) | Major ("') | Minor ("') | P.A. |
|--------|----------|-----------|------------|------------|------------|------|
| GV Tau N+S | 04:29:23.733 | 24:33:00.56 | 3.4 mm$^a$ | 3'07 × 3'05 | 16.1(0.4) | 2.02(0.08) | 1.06(0.13) | −14(3) |
| GV Tau N | 04:29:23.731 | 24:33:01.30 | 1.1 mm$^a$ | 0'09 × 0'07 | 49.8(1.1) | 0.14(0.03) | 0.03(0.04) | 52(1) |
| | | | 1.3 mm$^b$ | 0'09 × 0'07 | 43.8(3.1) | 0.24(0.11) | 0.09(0.06) | 53(16) |
| | | | HCN 3→2$^c$ | 0'05 × 0'04 | 3.64(0.21) | 0.32(0.04) | 0.25(0.05) | −41(20) |
| GV Tau S | 04:29:23.743 | 24:32:59.99 | 1.1 mm$^a$ | 0'09 × 0'07 | 38.0(1.1) | 0.12(0.02) | 0.03(0.05) | −34(1) |
| | | | 1.3 mm$^b$ | 0'09 × 0'07 | 46.7(3.2) | 0.37(0.05) | 0.11(0.07) | −2(8) |
| | | | HCO$^+$ 3→2$^c$ | 0'09 × 0'07 | 9.24(1.1) | 1.26(0.06) | 0.73(0.09) | −74(5) |

Notes.
$^a$ This work.
$^b$ Guilloteau et al. (2011).
$^c$ Total flux in Jy × km s$^{-1}$.

shown in Figure 3. A clear velocity gradient is detected in GV Tau N. The velocity gradient defines a rotation axis that is in between that of the main Herbig–Haro outflow and the Herbig jet (Devine et al. 1999; Movsessian & Magakian 1999). In GV Tau S, we detect a velocity gradient in the north–south direction but it cannot be interpreted as a disk rotation. The kinematics of the HCO$^+$ 3→2 line is very likely affected by the outflow motion.
3.3. HCN and HCO\(^+\) Column Densities

Gibb et al. (2007, see also erratum 2008) detected absorption due to the HCN \(\nu_3\) toward GV Tau N. The estimated column density and rotational temperature were \(3.7 \pm 0.3 \times 10^{16}\) cm\(^{-2}\) and \(115 \pm 10\) K for HCN assuming a line width of 12 km s\(^{-1}\). With these physical conditions the HCN \(3\rightarrow 2\) line is optically thick and the expected brightness temperature is \(\sim 110\) K. We measured a peak intensity of 192 mJy beam\(^{-1}\) (\(\sim 26\) K) toward GV Tau N which implies that the size of the emitting region is \(< 24\) AU, so that the warm HCN is present in the inner \(R < 12\) AU from the star. The HCN \(3\rightarrow 2/\text{HCO}^+\ 3\rightarrow 2\) flux ratio toward GV Tau N is \(< 10\). Large velocity gradient (LVG) calculations show that assuming that both molecules arise in the same region with the physical conditions derived by Gibb et al. (2007), the HCN/\text{HCO}^+ column density ratio is \(< 300\) (see Figure 4(a)). The HCN \(1\rightarrow 0\) line would then be optically thin with a brightness temperature of \(< 94\) K in this small region which diluted in the 3.4 mm beam would give a main beam brightness temperature of \(< 0.28\) K. The main beam brightness temperature we measure is larger, \(0.85\) K, consistent with the fact that the emission is extended and mostly arises from the outer part of the disk and the circumbinary disk/nebula.

Toward GV Tau S, only the HCO\(^+\) \(3\rightarrow 2\) line is well detected and the HCN \(3\rightarrow 2/\text{HCO}^+\ 3\rightarrow 2\) flux ratio is \(< 0.3\). Assuming \(n(H_2) = 10^7\) cm\(^{-3}\) and a kinetic temperature of 18 K, we derive a beam averaged column density of \(N(\text{HCO}^+) = 1.0 \times 10^{14}\) cm\(^{-2}\) in a linewidth of 8.6 km s\(^{-1}\) and the HCN/\text{HCO}^+ column density ratio would be \(< 0.6\) (see Figure 4(a)). Other possibility is that the emission arises in the lower density and warmer disk surface.
In Figure 4(a), we explored this possibility \((n(H_2) = 10^5 \text{ cm}^{-3}, T_2 = 115 \text{ K})\) and conclude that in this case we would obtain \(N(\text{HCN})/N(\text{HCO}^+)<1.6\). We use the 3.4 mm lines of HCN and HCO\(^+\) to have an estimate of the HCN/HCO\(^+\) column density ratio in the nebula surrounding the binary. Using the integrated line intensity of the weakest satellite component of the HCN 1→0 line, assuming local thermodynamic equilibrium and \(T_{\text{rot}} = 15 \text{ K}\), we estimate a beam averaged column density of \(1.5 \times 10^{13} \text{ cm}^{-2}\). With the same assumptions, we derive a HCO\(^+\) column density of \(\approx 1 \times 10^{13}\). Therefore, the average HCN/HCO\(^+\) column density in this region is \(\approx 1.7\). This ratio is not dependent on the assumed rotation temperature as long as it is the same for the two molecules, which is a reasonable assumption taking into account their similar dipole moment.

4. DISCUSSION AND CONCLUSIONS

Our millimeter data allow us for the first time to sample the planet formation zone of the disks GV Tau N and GV Tau S and evidence a dramatic chemical differentiation in the molecular gas associated with GV Tau N and GV Tau S. Previous NIR observations did not allow to conclude because the absorption lines are strongly dependent on the disk orientation. Our observations show that the HCN/HCO\(^+\) ratio must be \(> 300\) in the planet formation zone of GV Tau N. In contrast, the HCN/HCO\(^+\) must be \(< 1.6\) in GV Tau S. The huge HCN column density found in the inner \(R < 12 \text{ AU}\) disk of GV Tau N is consistent with the chemical calculations by Agúndez et al. (2008). They predicted an HCN abundance as large as \(5 \times 10^{-5}\) in the inner \(R < 3 \text{ AU}\) of circumstellar disks (see Figure 4(b)). The HCN does not arise from the disk midplane but from the photon-dominated region in the disk surface. The high densities and temperatures in this region are essential to achieve a huge HCN abundance (Cernicharo 2004). The synthesis of organic molecules in the gas requires that atomic carbon, produced by the dissociation of CO, incorporates into C-bearing species faster than reverting to CO. For example, \(\text{C}_2\text{H}_2\) and HCN reach low abundances at 100 K because the reactions of \(\text{C}_2\text{H}\) and CN with \(\text{H}_2\) have activation barriers (Cernicharo 2004).

At temperatures above \(\sim 400 \text{ K}\), atomic oxygen is efficiently converted into OH, which may react with C to form CO but reacts faster with \(\text{H}_2\) to form water. Thus, most of the oxygen forms \(\text{H}_2\text{O}\), and CO does not reach its maximum abundance allowing atomic carbon to form C-bearing molecules. The key reactions for the HCN formation such that \(\text{C}+\text{NO} \rightarrow \text{CN}+\text{O}\), or \(\text{H}_2+\text{CN} \rightarrow \text{HCN}+\text{H}\), proceed very rapidly at these large gas densities \(>10^7 \text{ cm}^{-3}\) and temperatures (Cernicharo 2004). This mechanism also works for any dense photodissociation region (PDR) such as those found around protoplanetary nebulae where the photodissociation of CO and HCN allows a fast photopolymerization toward longer carbon chains (Cernicharo 2004). This same result was found by Walsh et al. (2010) in their disk chemical model which included a grain–surface network. In that model, the \([\text{HCN}]/[\text{HCO}^+]\) ratio was \(\sim 1000\) at \(R \sim 1 \text{ AU}\) and always \(>10\) for \(R < 10 \text{ AU}\). Although not essential, accretion shocks could contribute to enhance the density and gas kinetic temperature and make the HCN formation more efficient.

One puzzling question then is the non-detection of HCN in GV Tau S. This can only be explained by a different disk morphology (flatter disk, an inner gap), different dust properties, and/or a different gas/dust ratio in the inner disk. Higher spatial resolution interferometric observations are required to unveil the hidden structure of this interesting binary.

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REFERENCES

Agúndez, M., Cernicharo, J., & Goicoechea, J. 2008, A&A, 483, 831
Carr, J. S., & Najita, J. R. 2011, ApJ, 733, 102
