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PROBING THE GASEOUS DISK OF T TAU N WITH CN 5–4 LINES

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ABSTRACT

We present spectrally resolved Herschel/HIFI observations of the young multiple system T Tau in atomic and molecular lines. While CO, H2O, [C II], and SO lines trace the envelope and the outflowing gas up to velocities of 33 km s−1 with respect to systemic, the CN 5–4 hyperfine structure lines at 566.7, 566.9 GHz show a narrow double-peaked profile centered on systemic velocity, consistent with an origin in the outer region of the compact disk of T Tau N. Disk modeling of the T Tau N disk with the thermo-chemical code ProDiMo produces CN line fluxes and profiles consistent with the observed ones and constrain the size of the gaseous disk (Rout = 110+100/10 AU) and its inclination (i = 25°±5°). The model indicates that the CN lines originate in a disk upper layer at 40–110 AU from the star, which is irradiated by the stellar UV field and heated up to temperatures of 50–700 K. With respect to previously observed CN 2–1 millimeter lines, the CN 5–4 lines appear to be less affected by envelope emission, due to their larger critical density and excitation temperature. Hence, high-J CN lines are a unique confusion-free tracer of embedded disks, such as the disk of T Tau N.

Subject headings: astrochemistry - ISM: molecules - protoplanetary disks - stars: individual (T Tau)

1. INTRODUCTION

The study of the physical and chemical structure of protoplanetary disks is crucial to comprehend the formation of planetary systems. According to models disks have a stratified structure, hence different molecular species probe the physical and chemical conditions of different layers from the warm irradiated surface down to the cold midplane. Disks around non-embedded T Tauri and Herbig stars have been imaged in CO (e.g., Dutrey et al. 1997; Thi et al. 1998; Qi et al. 2004; Piétu et al. 2007), and detected in a number of other millimeter (mm) and sub-millimeter molecular lines (e.g., Dutrey et al. 1997; Thi et al. 2004). On the contrary, the study of disks around more embedded systems is obstructed by the associated envelopes and outflows which also emit strongly in the same molecular lines, hiding the fainter disk emission.

Recent studies show that CN is a good disk tracer with 88% of the T Tauri disks detected in CO 2–1 which are also observed in the CN 2–1 lines (Oberg et al. 2010, 2011; Chapillon et al. 2012). Moreover, Guilloteau et al. (2013) performed an IRAM 30 m survey of T Tauri and Herbig Ae systems located mainly in the Taurus-Auriga region and show that the CN 2–1 lines are less affected by the emission from the surrounding molecular cloud than the lines from CO isotopologues. However, CN 2–1 lines are still dominated by envelope/outflow emission in the case of actively accreting/ejecting sources, such as T Tau.

T Tau is a multiple system driving at least two bipolar jets detected in optical, near-infrared forbidden lines (Bohm & Soifer 1994; Eisloffel & Mundt 1998; Soifer & Böhm 1999; Herbst et al. 2007). The system consists of the northern component T Tau N (M∗ = 2.1 M⊙) and of the binary system T Tau Sa+Sb located 6′′7 to the south (M∗ = 2.1, 0.8 M⊙, separation Sa–Sb = 0′′13) (Köhler et al. 2008). T Tau N is optically visible and is surrounded by an almost face-on, intermediate mass disk (i < 30°, Mdisk ∼ 0.01 M⊙) and an optically thin envelope (Beckwith et al. 1996; Hogerheide et al. 1997; Akesson et al. 1998; Ratzka et al. 2003; Guilloteau et al. 2011). Both southern components, instead, are strongly obscured (Av ≈ 15, 30 mag towards T Tau Sb and Sa, respectively), possibly due to a circumbinary envelope and, for T Tau Sa, to its almost edge-on disk (i ∼ 72°, Duchêne et al. 2005; Ratzka et al. 2009). Sa and Sb are not detected at mm wavelengths suggesting that their disks are small and of low-mass (Mdisk ∼ 10−5 – 10−3 M⊙, Rout ∼ 5 AU. Hogerheide et al. 1997; Ratzka et al. 2009). While the dusty disk of T Tau N has been mapped in the mm, there are only very ten-
The achieved rms noise in bands 1–4, the [II] switch mode with fast chopping (OBSID: 1342249598, 1342249647). They were accidentally unresolved (Spinoglio et al. 2000; van Boekel et al. 2003; Podio et al. 2012). Observations of low-J CO lines (Edwards & Snell 1982; Schuster et al. 1993) as well as of less abundant molecular species, such as 13CO, C18O, o-H2O, SO lines are still strongly dominated by emission from the surrounding envelope and outflows, the CN 5–4 lines allow digging out the faint emission from the disk of T Tau. 

In this letter we present Herschel/HIFI observations of the T Tau system in atomic and molecular lines with higher excitation energies than probed by Guillemit et al. (2013) in the mm range. While CO, 13CO, H2O, [C II], and SO lines are still strongly dominated by emission from the surrounding envelope and outflows, the CN 5–4 lines allow digging out the faint emission from the disk of T Tau. 

2. OBSERVATIONS AND DATA REDUCTION

We observed T Tau (α2000 = 04h 21′ 59.4′′, δ2000 = +19° 32′ 06″) with the Heterodyne Instrument for the Far Infrared (HIFI, de Graauw et al. 2010) on board the Herschel Space Observatory. We observed the target two fundamental water lines, o-H2O 110–101 and p-H2O 111–100 in the HIFI bands 1 and 4, the 12CO (hereafter CO) 10–9 line in band 5, and the [C II] 2P3/2→2P1/2 line in band 7 (OBSID: 1342249419, 1342250207, 1342249598, 1342249647). We acquired with a single on-source pointing and in dual beam switch mode with fast chopping 3′ either side of the target. The achieved rms noise in bands 1, 4, 5, 7 is of 6, 8, 75, 83 mK, respectively. The Wide Band Spectrometer (WBS) and the High Resolution Spectrometer (HRS) were used in parallel, providing a spectral resolution of 1.10 and 0.25 MHz, respectively. The Half Power Beam Width (HPBW) ranges from ~11′′ to ~38′′, depending on frequency. Hence all the three sources of the T Tau system (N, Sa, and Sb) are covered by the observations. The selected spectral settings also cover with the WBS the CN 5–4 \( J=9/2 → 7/2 \) and \( J=11/2 → 9/2 \), SO 1213–1112, 13CO 10–9, and o-H2O 312→212 lines.

The HIFI data were reduced using HIPE 10. Fits from level 2 were then created and transformed into GILDAS format for data analysis. The spectra were baseline subtracted and averaged over the horizontal and vertical polarization to increase the signal-to-noise ratio. Antenna temperatures, \( T_a \), were converted to mean beam temperature, \( T_{mb} \), using mean beam efficiency by Roelfsema et al. (2012).

The properties of the detected lines (transition, frequency, \( ν_0 \), upper level energy, \( E_u \), peak intensity, etc.) are summarized in Table 1.

3. RESULTS FROM OBSERVATIONS

The detected lines in Figure 1 show a variety of profiles indicating that they probe different gas components in the complex T Tau system. The CO and 13CO 10–9 lines show a single-peaked profile, likely dominated by cloud emission, and red-shifted and blue-shifted wings with velocities up to ~8 km s\(^{-1}\) probing outflowing gas. Assuming an average local ISM carbon isotope ratio of 68 ± 2 and a CO line ratio indicates that the CO emission is optically thin, its optical depth varying between 6.7 ± 1.5 at the peak velocity down to 2.4 ± 0.8 for gas velocities of ~5–6 km s\(^{-1}\) with respect to \( V_{peak} \). Since the 13CO 10–9 line is optically thin, it can be used to estimate the systemic velocity. The line peak indicates \( V_{sys} = +7.7 ± 0.3 \) km s\(^{-1}\), consistent with previous estimates from 13CO and C18O 1–0, 2–1 lines (Edwards & Snell 1982; Schuster et al. 1993; Guillemin et al. 2013).

The [C II] 2P3/2→2P1/2 and SO 1213–1112 lines peak at slightly blue-shifted velocity with respect to systemic (\( V_{peak} = +7.1 ± 0.2, +7.2 ± 0.5 \) km s\(^{-1}\)). As previously suggested by Guillemin et al. (2013) SO lines trace the envelope with no evidence of high-velocity wings.

\(^{16}\) Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia with important participation from NASA.

\(^{17}\) HIPE is a joint development by the Herschel Science Ground Segment Consortium, consisting of ESA, the NASA Herschel Science Center, and the HIFI, PACS and SPIRE consortia.

\(^{18}\) http://www.iram.fr/IRAMFR/GILDAS

\(^{19}\) \( F_{obs} = \frac{2K_{obs}^3}{c^2} \times \int T_{mb} dV \times \pi \left( \frac{HPBW}{2 \sqrt{\lambda}} \right)^2 \)
For CN 5–4 the rms noise is indicated by the dashed horizontal lines. The line profiles predicted by the ProDiMo disk model of T Tau N are overplotted in black, magenta, and blue (corresponding observed profiles are in grey, magenta, and blue).

We also detect three water lines: the o-H$_2$O 1$_1$–1$_0$, o-H$_2$O 3$_2$–2$_1$, and p-H$_2$O 1$_1$–0$_0$ lines. The two fundamental water lines ($E_{up}$ \approx 61, 53 K) show an absorption feature at the systemic velocity, due to the cloud, and a second absorption at \approx +5.6 km s$^{-1}$, whose origin is unclear. As already observed in previous works (e.g., Kristensen et al. 2012), water lines appear to be very sensitive to high-velocity emission showing wings extending up to velocities of -12 km s$^{-1}$ and +40 km s$^{-1}$.

In contrast with previous observations of CO 6–5, 3–2, 2–1, and 1–0 lines (Edwards & Snell 1982; Schuster et al. 1993), the observed CO 10–9, H$_2$O, and [C II] lines show a red-shifted wing which is brighter and extends to higher velocities than the blue one. The lines observed with HIFI have higher upper level energies and/or critical densities than previously observed low-J CO lines ($E_{up}$ \leq 116 K), thus suggesting that the red-shifted outflowing gas is denser and more excited than the blue-shifted gas.

Our observations also cover the CN N=5–4 hyperfine structure line [Müller et al. 2001]. We detect the three brightest J=9/2–7/2 and J=11/2–9/2 lines at 566.7 GHz and 566.9 GHz, while the fainter J=9/2–9/2 components fall outside the observed range. The separation in velocity between the three detected lines is between 0.05–0.45 km s$^{-1}$, hence the lines are not resolved at the available resolution (0.5 km s$^{-1}$) and the observed profile is sensitive only to the kinematics of the emitting gas. The CN 5–4 J=9/2–7/2 lines show a narrow double-peaked profile centered at the systemic velocity with a total line width of \approx 7 km s$^{-1}$, FWHM of 4.0 \pm 0.5 km s$^{-1}$, and a peak separation $\Delta V_{sep}$ = 2.4 \pm 0.5 km s$^{-1}$. The profile of the J=11/2–9/2 blended components is also narrow and symmetric around the systemic velocity, even though the double-peak is not as clear as in the J=9/2–7/2 lines (see Table I). The blue/red-shifted wing shown by the J=9/2–7/2 and the J=11/2–9/2 components, respectively, is clearly due to the noise as it is below the noise level and is not detected in both components. Hence, the CN 5–4 profiles are consistent with emission from the outer region of the disk of T Tau N. The double-peak detected in the CN 5–4 lines is not seen in the 2–1 lines observed with the IRAM-30m by Guilloteau et al. (2013). This is due to the higher excitation energy and critical density of the CN 5–4 lines ($E_{up}$ \approx 82 K, $v_{cr}$ \approx 2 10$^8$ cm$^{-3}$), which makes them less affected by cloud emission, hence more effective to probe the disk, than CN 2–1 ($E_{up}$ \approx 16 K, $v_{cr}$ \approx 2 10$^7$ cm$^{-3}$). Emission from the disks of T Tau Sa and T Tau Sb is expected to be negligible with respect to the emission from the disk of T Tau N, as those disks are not detected in the mm continuum and are one to two orders of magnitude less massive and very small (Akeson et al. 1999; Ratzka et al. 2009; Guilloteau et al. 2011).

Assuming Keplerian rotation, a stellar mass of 2.1 $M_\odot$ and an inclination of $i \approx 20$ – 30$^\circ$ (Ratzka et al. 2009),

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20 Due to the coupling of the rigid-body angular momentum, N, with the electronic spin, S, and with the nuclear spin, I, angular momenta, the CN N=5–4 line is split into 19 hyperfine components characterised by the corresponding quantum numbers J=N+I, and F=J+1.
TABLE 2  
T TAU N disk model: star and disk parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective temperature (K)</td>
<td>5250</td>
</tr>
<tr>
<td>Stellar mass (M_☉)</td>
<td>2.1</td>
</tr>
<tr>
<td>Stellar luminosity (L_☉)</td>
<td>7.3</td>
</tr>
<tr>
<td>UV excess</td>
<td>0.1</td>
</tr>
<tr>
<td>UV power law index</td>
<td>2.10^{31}</td>
</tr>
<tr>
<td>Disk inclination</td>
<td>25</td>
</tr>
<tr>
<td>Disk inner radius (AU)</td>
<td>110</td>
</tr>
<tr>
<td>Disk dust mass (M_☉)</td>
<td>1.30^{-4}</td>
</tr>
<tr>
<td>Dust-to-gas ratio</td>
<td>0.01</td>
</tr>
<tr>
<td>Dust material mass density (g cm^{-3})</td>
<td>2.5</td>
</tr>
<tr>
<td>Minimum grain size (µm)</td>
<td>0.005</td>
</tr>
<tr>
<td>Maximum grain size (µm)</td>
<td>1000</td>
</tr>
<tr>
<td>Dust size distribution index</td>
<td>3.5</td>
</tr>
<tr>
<td>Surface density Σ ≈ r^{-x}</td>
<td>1.0</td>
</tr>
<tr>
<td>Scale height at R_in (AU)</td>
<td>0.0032</td>
</tr>
<tr>
<td>Flaring index H(r) = H_0 (R_{in}/R_{out})^β</td>
<td>1.25</td>
</tr>
<tr>
<td>Settling H(r, a) = H(r) a_{set}/a_{act}</td>
<td>0.5</td>
</tr>
<tr>
<td>Minimum grain size for settling (µm)</td>
<td>0.25</td>
</tr>
<tr>
<td>Fraction of PAHs w.r.t. ISM</td>
<td>f_PAH = 0.01</td>
</tr>
</tbody>
</table>

The peak separation of the CN lines indicates an outer disk radius R_{out} (CN) < 160 – 350 AU. This upper limit is in agreement with the size of the disk as estimated from continuum maps at 1.3, 2.7 mm (R_{out} (dust) = 67 ± 20 AU, Guilloteau et al. 2011) and from the H$_2$ ring-like structure observed by Gustafsson et al. (2008) (R_{out} (H$_2$) = 85 – 100 AU).

4. MODELING CN LINES FROM THE DISK OF T TAU N

In order to test if the CN lines originate in the disk of T Tauri N we use a parametrized disk model calculated with the thermo-chemical disk modeling code ProDiMo (Woitke et al. 2009; Kamp et al. 2010; Aresu et al. 2014).

We adopt stellar and disk parameters as inferred from previous studies, which well reproduce the source spectral energy distribution (SED) (e.g., Ratzka et al. 2009). We use stellar spectral type K0 (T_{eff} ≈ 5250 K), stellar luminosity ≈ 7.3 L_☉ and stellar mass M_* ≈ 2.1 M_☉ as determined by White & Ghez (2001). The UV spectrum (Calvet et al. 2004) is reproduced by an UV excess f_{UV} = L(910 – 2500 Å)/L_☉ = 0.1 and a power law slope L_{λ} ≈ λ^{-0.2}. The effect of X-ray radiation from the stellar corona of T Tau N (L_X = 2 10^{31} erg s^{-1}, Güdel et al. 2007) is taken into account following Aresu et al. (2011) and Meijerink et al. (2012). Following Ratzka et al. (2009) we assume a disk inner radius R_in = 0.1 AU, a dust mixture of astronomical silicates (Draine & Lee 1984) and amorphous carbon (Zubko et al. 1996) with relative abundances of 62.5% and 37.5%, and a grain size distribution n(a) ≈ a^{-q} with q = 3.5, where n(a) is the number of dust particles with radius a, and the minimum/maximum grain size are a_{min} = 0.005 µm and a_{max} = 1 mm. This implies a dust mass of 1.3 10^{-4} M_☉ to reproduce the observed mm emission (Hogerheijde et al. 1997; Akeson et al. 1998; Guilloteau et al. 2011). Using the average ISM dust-to-gas ratio of 0.01, the gas mass is 0.013 M_☉. The dust-to-gas ratio can be different from the ISM value in evolved...
disks (e.g., Thi et al. 2011; Gorti et al. 2011). However, as the CN lines are optically thick in the disk, their flux is independent on the gas mass, hence on the assumed dust-to-gas ratio. The SED is well reproduced by assuming a disk surface density $\Sigma \approx r^{-1}$ and scale height $H = 0.0032 \text{AU} (r/R_\text{in})^{1.25}$ (Ratzka et al. 2003). To obtain a dust distribution similar to the two-layers model adopted by Ratzka et al. (2009), we assume that grains larger than $a_{\text{set}} = 0.25 \mu m$ have settled to a smaller scale height than the gas, $H(r, a) = H(r) (a/a_{\text{set}})^{-r_{\text{set}}/2}$, with $r_{\text{set}} = 0.5$. As PAH emission is generally not detected in TTSs (e.g., Furlan et al. 2006), the PAH fraction, $f_{\text{PAH}}$, is set to 0.01 with respect to the ISM abundance of $10^{-6.52}$ PAH particles/H-nucleus. Lower values, $f_{\text{PAH}} = 10^{-3} - 10^{-4}$, do not affect the CN emission. The adopted stellar and disk parameters are summarized in Table 2.

As the CN line fluxes and profiles are very sensitive to the assumed disk outer radius, $R_\text{out}$, and inclination, $i$, we proceed through two steps. First, we run a grid of models at low resolution (50×50 grid points) adopting $R_\text{out}$ and $i$ values which cover the range of estimates from previous studies ($R_\text{out} = 67, 90, 100, 110, 120 \text{AU}$, $i = 20, 25, 30, 35, 40, 45 \text{AU}$, Stapelfeldt et al. 1998, Gustafsson et al. 2008, Ratzka et al. 2009, Guilloteau et al. 2011, Harris et al. 2012). Then, we run a high resolution model (100×100 grid points) for $R_\text{out}$ and $i$ which best fit the observations, to better resolve the chemical and temperature gradients and the vertical extent of the line forming region in the disk. The predicted FWHM and peak separation do not depend on the model resolution while the line fluxes are lower by up to $\sim 30\%$ when increasing the resolution.

The line profiles and fluxes are obtained by first solving the statistical equilibrium with 2D escape probability to obtain the level populations, and then using 2D ray-tracing. As the three brightest lines of each CN J=11/2–9/2 lines originate according to our model. The best fit of the CN line fluxes is obtained using the high resolution model. Figure 3 shows the region in the disk where 50% of the CN N=5–4 J=9/2–7/2 and J=11/2–9/2 lines originate according to our model. This is obtained using vertical escape probability and without accounting for disk inclination. The model indicates that the CN lines are excited in a disk upper layer located at 40–110 AU distance from the star, which is irradiated by the stellar UV field. This heats the gas up to temperatures of $\sim 50 – 700$ K, while the gas density is $\sim 3 \times 10^3 – 3 \times 10^6$ cm$^{-3}$, thus the CN lines are almost thermalized and optically thick ($\tau \sim 10^2 – 10^3$) in the line emitting region. In this disk layer, CN is produced by H + CN, and C + NO reactions, and photo-dissociation of HCN, while the main destruction route is photo-dissociation of CN.

In Figure 1 and Table 1 the model-predicted line profiles and fluxes are compared with the observed ones. For CN lines, the model predicts a FWHM of 3.9 km s$^{-1}$ and peak separation of 2.6 km s$^{-1}$, in agreement with observations (FWHM= 4.0, 4.2 ± 0.5 km s$^{-1}$, $\Delta \text{V}_{\text{sep}} = 2.4, 2.1 \pm 0.5$ km s$^{-1}$). Also the line fluxes agree with observations within a factor $\sim 0.9, 1.2$. The sum of the fluxes of the N=2–1 components, instead, is about an order of magnitude lower than what observed by Guilloteau et al. (2013), who suggest that the line is dominated by envelope emission. The CO, $^{13}$CO, H$_2$O, and SO line fluxes predicted by the disk model are from a factor four to two orders of magnitude smaller than observed, as well as for the high-J CO, H$_2$O, OH, and atomic [O I], [C II] lines previously observed with PACS (see Table 4 by Padojio et al. 2012). This is a further evidence that these lines are dominated by envelope and outflow emission, as already suggested by the fact that [O I] [C II] emission is spatially extended with PACS ($\geq 9\prime$) and by the broad profiles of CO, H$_2$O, SO, and [C II] obtained with HIFI.

5. CONCLUSIONS

The Herschel/HIFI observations of the T Tau system show emission in a number of molecular and atomic lines. The origin of the emission lines in embedded, accreting/ejecting sources is highly debated, being crucial to identify a tracer to dig out the faint disk emission (e.g., Padojio et al. 2012, 2013). In the case of T Tau, the CO, H$_2$O, and [C II] lines clearly trace high-velocity outflowing gas. By contrast with those lines and with previously observed CN 2–1 lines (Guilloteau et al. 2013), the CN 5–4 lines show narrow double-peaked profiles centered at the systemic velocity, suggesting an origin in the outer disk of T Tau N. Disk modeling predicts CN line fluxes and profiles in agreement with observed ones and constrains the size of the gaseous disk of T Tau N ($R_\text{out} = 110^{+10}_{-20}$ AU) and its inclination ($i = 25^\circ \pm 5^\circ$). This study demonstrates that high-J CN lines are a unique tool to probe the gaseous disk of strongly accreting/ejecting sources and paves the way for future observations of embedded disks with ALMA.

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