HCN/HNC ratio: A new chemical thermometer at 3 mm

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Abstract. The gas kinetic temperature (T_K) determines the physical and chemical evolution of the interstellar medium (ISM). This work explores the use of HCN/HNC (J=1–0) line ratio as new probe of the gas kinetic temperature in the molecular ISM. Based on a new set of IRAM-30m observations at 30 arcsec resolution towards Orion Nebula Cluster, we find a two-part linear correlation of the observed HCN/HNC line ratio and T_K. This empirical calibration allows to obtain direct estimates of the T_K values across a wide range of column densities ($A_V \gtrsim 5$ mag) and up to scales of ~ 10 pc. Comparisons with additional studies highlight the potential use of the HCN/HNC line ratio as novel chemical thermometer at 3mm.

1 Introduction

The gas kinetic temperature (T_K) plays a key role in the most important gas properties in the Interstellar Medium (ISM). T_K determines the gas pressure ($P/k = n\ T_K$), the sound speed ($c_s = \sqrt{kT_K/\mu}$), as well as fragmentation scale ($\lambda_{frag} \propto T_K^{3/2}$) in molecular clouds. Similarly, it influences the chemical structure and molecular emission properties of the molecular gas in the ISM. The description of the thermodynamic state of the ISM gas therfore requires a detailed study of T_K.

Multiple observational techniques have been developed to investigate the gas kinetic temperature in the ISM. In dedicated molecular line studies, the gas kinetic temperature has been traditionally inferred from the study of NH_3 rotational temperures (T_{rot}, [1]) and the combination of the study of excitaton temperatures (T_{ex}) and radiative transfer calculations in multi-line observations (e.g. [10]). The wide coverage of FIR observations in the ISM has also popularized the use of dust temperatures measurements (T_{dust}) as proxies of the gas temperatures in nearby clouds ([9]). However, the above approaches require of additional assumptions such as Local Thermodynamical Equilibrium (LTE; $T_K = T_{ex} = T_{rot}$) or an effective gas-to-dust coupling ($T_K = T_{dust}$) which are difficult to justify in a wide range of physical conditions. In practical terms, these studies are typically limited in dynamic range (e.g. NH_3 at $A_V \gtrsim 10$ mag), require observations of multiple transitions as well as expensive radiative transfer modeling (e.g. CO-ladders), or become only accesible at certain frequency ranges (e.g. H_2CO at 1 mm or NH_3 at cm wavelengths). During the last years, most of the large scale observations of the local ISM, in which IRAM has been playing a leading role (e.g. [11]), are carried our at 3 mm (i.e. ALMA Band 3). Finding a versatile, reliable, easy-to-use tracer of the gas kinetic temperature at 3 mm is therefore of paramount importance for future ISM studies both in local and extragalactic contents.

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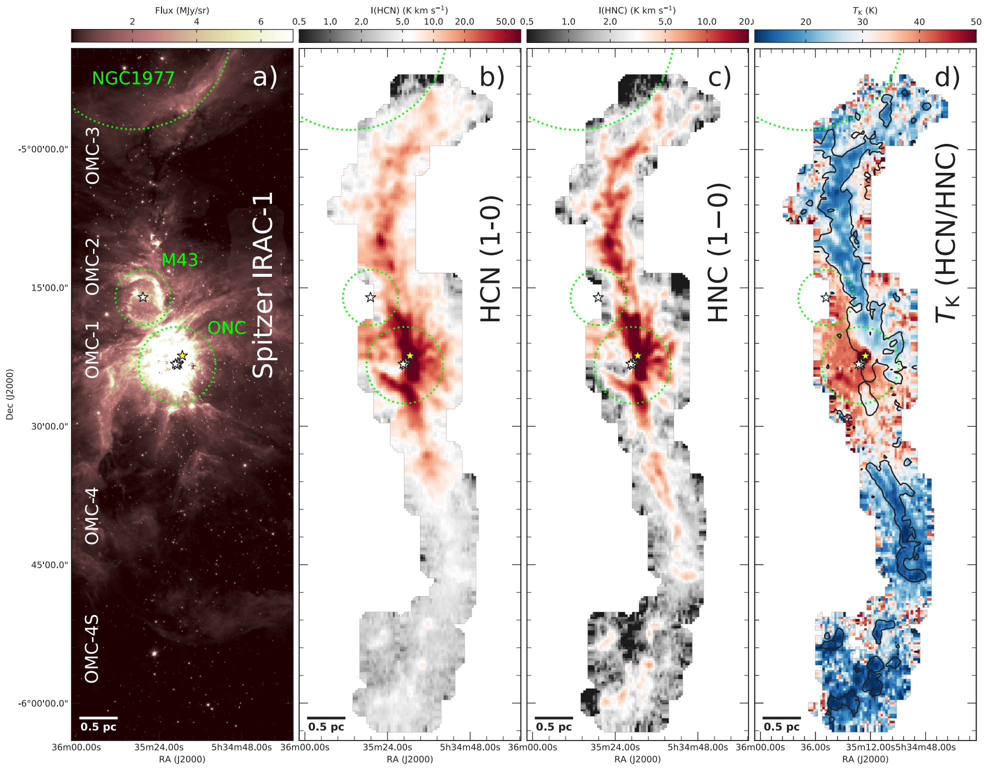

Figure 1. IRAM-30m observations along the Orion ISF. From left to right: (a) Spitzer IRAC-1 emission map; (b) HCN (J = 1–0), (c) HNC (J = 1–0), and (d) gas kinetic temperature derived using the HCN/HNC ratio (see [6]). The black contours in panel d indicate the regions with significant N_2H^+ (J=1–0) [4], denoting those filamentary regions at high densities (> 10^5 cm^{-3}).

A large variety of astrochemical studies have investigated the variation of the HCN and HNC emission properties in the ISM (e.g. [7, 12]). This work explores the use of the HCN/HNC line ratio as a novel chemical thermometer of the molecular ISM. A detailed discussion of these results can be found in [6].

2 HCN & HNC IRAM-30m observations in Orion

We investigated the molecular emission of both HCN (88.6 GHz) and HNC (90.6 GHz) (J=1–0) lines along the Integral Shape Filament (ISF) in Orion (D∼ 415 pc; [8]). The ISF contains the most active star-forming region within solar neighbourhood (i.e., Orion Nebula Cluster; ONC) and the only one forming massive stars (Trapezium & Orion BN/KL), becoming a testbed for star-formation studies. As illustrated in Figure 1a, ISF extends over ∼ 8 pc in length, including the OMC 1/2/3/4/4S regions, and is shaped by different feedback events (e.g. ONC, M43, and NGC1977 bubbles; see Suri et al in prep.). The ISF is the most massive filament within 1 kpc ($M/L \sim 300-500$ M$_\odot$ pc^{-1}) with high emission levels in multiple molecular tracers widely studied in the literature (e.g. [5]).

We obtained On-the-Fly, Position-Switching maps of the HCN and HNC (J=1–0) emission along the ISF at 3 mm using the IRAM-30m telescope (see also [6]). Both transitions

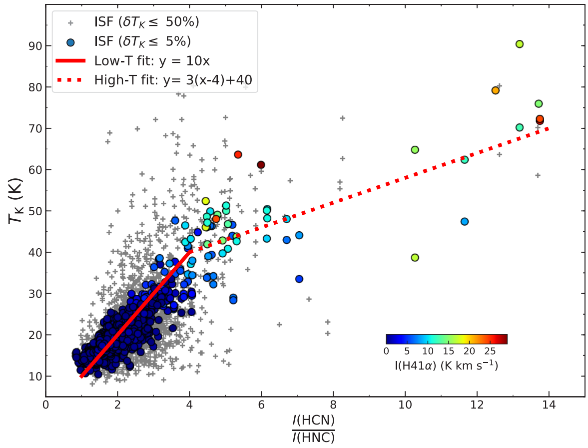

Figure 2. Empirical comparison between the I(HCN)/I(HNC) line intensity ratio and previous NH_3-based gas temperatures ($T_K(NH_3)$) estimates along the ISF. Colour filled symbols indicate those points with accurante $T_K(NH_3)$ measurements. The colour scale indicates the intensity of H41α detected in this region.

were observed simultaneously with the EMIR090 receiver in combination of the FTS backend at low spectral resolution (0.6 km s^{-1}). Figures 1b and 1c show the integrated emission of the HCN and HNC (J=1–0) lines, respectively, at a final resolution of 30 arcsec, both showing bright emission along the entire ISF down to $A_V \sim 5$ mag (limited by our map boundaries).

3 HCN/HNC: A new chemical thermometer for the ISM

We compare the observed I(HCN)/I(HNC) intensity ratio with previous T_K estimates previously obtained using NH_3 observations in the ISF ([3]) in Figure 2. Our results show a positive and strong correlation between these quantities in different parts of the cloud. Outside the Orion Nebula, indicated by low intensities of the H41α emission (see color scale), the I(HCN)/I(HNC) shows a tight and steep dependence on T_K. A shallower correlation tentatively continues inside the nebula showing higher H41α values. A two-part linear fit to the data in Fig.2 allows to empirically calibrate the observed I(HCN)/I(HNC) line ratio into a direct proxy of the T_K following:

$$T_K[K] = 10 \times \left(\frac{I(HCN)}{I(HNC)}\right) \quad \text{when} \quad \frac{I(HCN)}{I(HNC)} \leq 4 \tag{1}$$

$$T_K[K] = 3 \times \left(\frac{I(HCN)}{I(HNC)} - 4\right) + 40 \quad \text{when} \quad \frac{I(HCN)}{I(HNC)} > 4 \tag{2}$$

These equations describe two physically distinguished regimes: (a) Eq.1 describes a low-temperature regime between $T_K < 40$ K characteristic of the typical cloud conditions, while (b) Eq.2 can be applied of the more extreme gas conditions found in the Orion Nebula.

The observed dependence of the HCN/HNC line ratio with temperature appears to be controlled by a combination of chemical and emission properties of both HCN and HNC tracers. Similar temperature-dependent abundance variations are produced by the combination of the selective destruction of $HNC + O \rightarrow CO + NH$ (reaction 1) at low-temperatures and the effective isomerization of $HNC + H \rightarrow HCN + H$ (reaction 2) at higher temperatures. Previous studies assumed high activation energies (> 1200 K) inhibiting reaction 1. Tests using different chemical models, however, indicate that the observed dependence can be reproduced using a low-energy barrier ($\Delta E \sim$ 15-25 K) in addition to the temperature dependence excitation and opacity changes of HCN and HNC (see [6] for a full discussion).

Independent of its origin, the I(HCN)/I(HNC) line ratio provides an empirical measurement of the gas kinetic temperature in the ISM. The parameterization obtained in Eqs.1 and 2 allows to obtain estimates of the T_K based on two direct observables, namely, the integrated intensities of I(HCN) and I(HNC) (J=1–0) lines at 3 mm. This method simplifies previous estimates based on more time-consuming calculations (radiative transfer calculations) and observationally expensive techniques (e.g. CO-ladders that require multiple observations).

We have tested our new temperature estimates along the ISF. Figure 1d shows the gas kinetic temperature map obtained after converting the integrated intensity maps of HCN and HNC (Figs.1b & 1c) into T_K(HCN/HNC) according to Eqs.1 and 2. Despite its complexity, our temperature estimates reproduce the expected thermal gas behaviour in this region. Overall, the coldest part of the cloud down to 15-20 K correspond with the densents filamentary regions identified in N_2H^+ (black contours). Outside, the Interstellar Radiation Field (ISRF) increases the gas tempeartures up to lukewarm temperatures of 30-40 K. Additionally, the effects of the different feedback mechanisms (e.g. Orion Nebula) are clearly seen in our maps by their enhanced gas temperatures above 40-50 K. Particularly within the optimal range of this method (i.e. $T_K \sim [15, 40]$ K, see Eq.1), the HCN/HNC line ratio therefore acts as an effective observational probe of the gas kinetic temperature in this cluod.

Additional comparisons with previous results shows the a similar behaviour of this HCN/HNC line ratio tracing the thermal properties of molecular clouds. The use of Herschel column density maps [9] indicate that the HCN/HNC line ratio provides information of the gas temperatures over a large range of column densities down to $A_V \sim 5$ mag compared to NH_3-based temperature measurements limited to $A_V \sim 10$mag. Temperature variations of the HCN/HNC ratio are seen in gas surveys across the galactic plane (e.g. MOPRA survey, [2]). Additional application of this technique show positive results in other star-forming regions in Orion (Hacar et al, in prep). As primary advantage for (extra-)galactic studies, both HCN and HNC (J=1–0) integrated intensities can be easily measured in 3mm-band surveys using broadband receivers such as EMIR. With a robust behaviour, the observed HCN/HNC line ratio could in principle be used as chemical thermometer of the molecular ISM.

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