Molecular Line Emission as a Tool for Galaxy Observations (LEGO)

I. HCN as a tracer of moderate gas densities in molecular clouds and galaxies

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ABSTRACT

Trends observed in galaxies, such as the Gao & Solomon relation, suggest a linear relation between the star formation rate and the mass of dense gas available for star formation. Validation of such relations requires the establishment of reliable methods to trace the dense gas in galaxies. One frequent assumption is that the HCN (J = 1–0) transition is unambiguously associated with gas at H densities ≳ 10 cm⁻³. If so, the mass of gas at densities ≳ 10⁴ cm⁻³ could be inferred from the luminosity of this emission line, L_HCNO. Here we use observations of the Orion A molecular cloud to show that the HCN (J ≳ 1–0) line traces much lower densities 10³ cm⁻³ in cold sections of this molecular cloud, corresponding to visual extinctions A_v 6 mag. We also find that cold and dense gas in a cloud like Orion produces too little HCN emission to explain L_HCNO in star-forming galaxies, suggesting that galaxies might contain a hitherto unknown source of HCN emission. In our sample of molecules observed at frequencies near 100 GHz (also including CO, C¹⁸O, CN, and CCH), N₂H⁺ is the only species clearly associated with rather dense gas.

Key words. Stars: formation – ISM: clouds – ISM: molecules – Galaxies: evolution – Galaxies: ISM – Galaxies: star formation

1 Introduction

The relationship between star formation (SF) and the supply of dense gas is of critical importance for our understanding of cosmic SF. We must develop a detailed picture of the relation between dense gas and SF in galaxies if we wish to explain the structure and evolution of galaxies (e.g., Somerville & Davé 2014). This relation can, for example, be explored in the Milky Way. In molecular clouds within ~ 500 pc from Sun one can estimate the star formation rate, M⋆, by counting individual young stars. These nearby clouds can be resolved spatially, which also simplifies estimating the mass of gas at high density, M_dg. Recent research suggests defining M_dg as the mass residing at high visual extinctions, A_v ≥ A_v(dg) with A_v(dg) 7 mag, resulting in M⋆ ∝ M_dg (e.g., Heiderman et al. 2010; Lada et al. 2010).

It is very challenging to study M⋆ and M_dg in galaxies. One might, for example, assume that the light of young stars is absorbed and re-emitted by dust. Then the far-infrared luminosity of a galaxy (i.e., at wavelengths of 8 to 1000 µm) characterizes SF via M⋆ ∝ L_FIR. Similarly, one might assume that a certain molecular emission line requires elevated densities to be excited. Then M_dg ∝ L_g for line luminosities of a suitable transition Q. Gao & Solomon (2004b), in particular, introduced the HCN (J = 1–0) transition as a tracer of dense gas in galaxies (i.e., H₂ densities 10⁴ cm⁻³), suggesting that M_dg ∝ L_HCNO.

This raises an important question: is M_dg equal to M_dg as obtained from L_HCNO? The LEGO project Molecular Line Emission as a Tool for Galaxy Observations; led by JK) uses wide-field maps to address such questions. We here summarize key conclusions from a comprehensive study of Orion A (Kauffmann et al., in prep.; hereafter Paper II).

2 Preparation of Observational Data

Data on emission lines at ~ 100 GHz frequency (Fig. 1) were obtained with the 14m–telescope of the Five College Radio Astronomy Observatory (FCRAO). Maps of the CCH (N = 1–0, J = 1/2–1/2), HCN (J = 1–0), N₂H⁺ (J = 1–0), C¹⁸O (J = 1–0), and CN (N = 1–0, J = 3/2–1/2) transitions are taken from Melnick et al. (2011). Data on the CO (J = 1–0) and C¹³O (J = 1–0) lines are from Rippe et al. (2013). The full–width at half–maximum beam size for given frequency ν is θ_beam = 52” (ν/100 GHz)⁻¹. An efficiency η_mb = 0.47 is used for conversion to the main beam intensity scale, T_mb = T_A^ν/η_mb. This paper focuses on the integrated intensities, W = ∫ T_mb dv.

Dust–based estimates of the H₂ column density N(H₂) are derived from Herschel observations of Orion at wavelengths of 250 to 500 µm (André et al. 2010) using modified methods from Guzmán et al. (2013) described in Kauffmann et al. (2016). We assume thin ice coatings and dust coagulation for 10⁶ yr at a molecular volume density of 10⁸ cm⁻³ to select dust opacities from Ossenkopf & Henning (1994). Paper II describes how we calibrate these data against an extinction–based map from Kainulainen et al. (2011) to predict the visual extinction, A_v = N(H₂)/9.4 × 10⁻²³ cm⁻², at a resolution of 38’’.

We fit the filamentary cloud north of ~ 5:14:00 (J2000) with a truncated cylindrical power–law density profile, n(r) = n_o (r/R)⁴, where r is the distance from the filament’s main axis. We then obtain the median density along any line of sight for an offset s from the filament main axis, n_med(s). For given s, half of the mass resides above (and half below) this density, so that n_med(s) can be considered a representative density. Further algebraic operations relate s, n_med(s), and A_v(s) (Fig. 3 see Paper II).
3. Molecules as Tracers of Cloud Material

We seek to explore molecular line emission under conditions that are representative for the Milky Way. We therefore ignore the region south of $-5:10:00$ declination (J2000). First, much of this region is subject to intense radiation emitted by young stars in the Orion Nebula. This is probably not typical for molecular clouds. Second, the well–shielded southerly regions (with dust temperatures $\leq 22$ K) are devoid of embedded stars that are characteristic of SF regions (Megeath et al. 2012). Finally, we ignore pixels where $A_V < 2$ mag because of observational uncertainties.

3.1. Line Emission per Unit Cloud Mass

The line–to–mass ratio, $h_Q = W(Q)/A_V$, indicates how the emission from transition $Q$ relates to the mass reservoir characterized by $A_V$. Given $A_V \propto N(\text{H}_2)$, the ratio $W(Q)/A_V$ essentially measures the intensity of line emission per $\text{H}_2$ molecule. It is plausible to assume that $h_Q$ is a function of $n$ and therefore $N(\text{H}_2)$. This is, for example, expected if the molecular abundance or the excitation is a function of the density. This is explored in Fig. 2. For this analysis we sort the data into logarithmically spaced bins in $A_V$, and we then derive the mean of $h_Q$ and its uncertainty from counting statistics in this bin. We see that $h_Q$ is indeed a strong function of $A_V$, which justifies our ansatz to explore the trend of $h_Q$ versus $A_V$. We normalize $h_Q$ to a maximum value of 1 in the well–detected bins of Fig. 2 in order to simplify comparisons between molecular species.

The trend of $h_Q$ vs. $A_V$ is non–trivial, and it differs between molecules. Most molecules start with a significant value of $h_Q$ at low $A_V$, their line–to–mass ratio increases towards a maximum at an $A_V$ of 5 to 20 mag, and $h_Q$ steadily decreases with increasing $A_V$ at even higher extinction. One single molecule defies this trend: the line–to–mass ratio of $\text{N}_2\text{H}^+$ begins near or at zero at low $A_V$, and $h_Q$ then begins to steadily rise at $A_V \geq 10$ mag, possibly to level out (or decrease) at $A_V \geq 100$ mag.

This is a critical result. This means that the $\text{N}_2\text{H}^+$ ($J = 1–0$) transition is the only transition among those observed here that selectively traces gas at high (column) density. All other transitions are, by contrast, most sensitive to material at $A_V \sim 10$ mag. Pety et al. (2017) conclude the same in Orion B, using an argument that relates more to our next section.

3.2. Characteristic (Column) Density traced by a Line

Figure 2 characterizes whether a given molecular emission line traces the cloud material well under given conditions. It would be desirable if this information could be collapsed into a single number. One could, for example, attempt to establish the typical $\text{H}_2$ (column) density of material that is traced by a given transition. We use the line luminosities for this purpose. Integration over the map area at column densities corresponding to $A_V \leq A_V^\text{char}$ gives the luminosity as a function of the cutoff value $A_V^\text{char}$,

$$L_Q(A_V^\text{char}) = \int_{A_V < A_V^\text{char}} W_Q \, d\Omega,$$

(1)

where $d\Omega$ is the area element measured in $\text{pc}^2$. Let $L_Q = L_Q(A_V^\text{char} \to \infty)$ be the total luminosity. We then define the characteristic column density $A_V^\text{char}$ of transition $Q$ to be the column density that contains half of the total line luminosity,

$$L_Q(A_V^\text{char}) = L_Q/2.$$

(2)

We then use the density model to define a characteristic density $n_{\text{char}} = n_{\text{med}}(A_V^\text{char})$. We also obtain the characteristic column

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**Fig. 1.** Maps of the peak intensity for transitions near 100 GHz. The left panel gives $A_V$ as inferred from Herschel data. Contours at 5 and 30 mag are drawn and repeated in all panels, and the peak intensity is stated for every transition. Line emission maps are smoothed to 1.5 resolution before filled contours are drawn at signal–to–noise ratios of 3, 5, 10, 30, 50, and 100. Panels are ordered by increasing critical density, $n_{\text{cr}}$.

**Fig. 2.** Normalized line–to–mass ratio, $h_Q$, for the reference region. Shading indicates the uncertainty at a confidence level $\sim 68\%$, while gray dashes indicate the limits of bins. $N_2H^+$ is a good tracer of dense gas since $h_Q$ increases with increasing $A_V$. Pety et al. (2017) conclude the same in Orion B, using an argument that relates more to our next section.
4. Tracing the Dense Gas in Star–Forming Galaxies

4.1. HCN as a Tracer of Moderately Dense Gas

The constraints on \( h_Q \approx W(Q)/A_V \) and \( A_{V_{\text{char}}}^Q \) are of critical importance for the study of star-forming galaxies. For example, Gao & Solomon (2004) speculate that gas at densities \( \geq 3 \times 10^3 \text{ cm}^{-3} \) is traced by emission in the HCN (\( J = 1-0 \)) transition. More recently, Usero et al. (2015) assumed threshold densities as large as \( 3 \times 10^5 \text{ cm}^{-3} \) (they deem \( 10^{4.5} \text{ cm}^{-3} \) likely), while Jimenez-Donaire et al. (2016) estimate threshold densities \( \geq 5 \times 10^3 \text{ cm}^{-3} \) from H\(^2\)CN–to–H\(^2\)CN line ratios in galaxies. More generally, it is often argued that the high critical density of the HCN (\( J = 1-0 \)) line, \( n_{\text{cr}} = 1 \times 10^6 \text{ cm}^{-3} \), implies that this transition traces gas of very high density. However, the analysis presented here shows that \( A_{V_{\text{char}}}^Q \approx 6.1 \pm 1.2 \text{ mag} \), which suggests that \( n_{\text{cr}}^Q \approx 870 \pm 550 \text{ cm}^{-3} \). This does not fundamentally question the interpretation of trends like the Gao & Solomon relation, but it critically affects the detailed analysis of data.

The low value of \( n_{\text{char}}^Q \) is not entirely surprising. Evans (1999) and Shirley (2015) also see Linke et al. (1977) point out that HCN should become detectable at “effective” densities \( n_{\text{eff}} \approx (1 \text{ to } 3) \times 10^5 \text{ cm}^{-3} \) for gas at 10 K and regular abundances, for which \( n_{\text{eff}} \ll n_{\text{cr}} \). Further, HCN can be excited by electrons at H\(_2\) densities \( \ll n_{\text{cr}} \) if fractional electron abundances \( X_e(-) > 10^{-5} \) prevail (Goldsmith & Kauffmann 2017 following a suggestion by S. Glover). Here we provide solid observational evidence supporting such work.

Critical densities simply do not control how line emission couples to dense gas. This is already evident from Fig. 1.

The low characteristic density \( \approx 870 \text{ cm}^{-3} \) for the HCN (\( J = 0-1 \)) line has important implications for modeling. Theoretical studies often relate \( M_* \) and \( M_{\text{dust}} \) via the free–fall time at density \( n_{\text{char}}^Q \approx 10^5 \text{ yr} \cdot (0.1 \text{ cm}^{-3})^{1/2} \), and a star formation efficiency, \( \xi_{\text{SF}} \approx 1 \), via \( M_* = \xi_{\text{SF}} \cdot M_{\text{dust}}/\tau_{\text{ff}} \). A landmark paper by Krumholz & Tan (2007), for example, assumes \( n_{\text{char}}^Q \approx 6 \times 10^5 \text{ cm}^{-3} \), infers \( \xi_{\text{SF}} \approx 0.01 \), and concludes that SF is “slow” in regions sampled by HCN (\( J = 1-0 \)). Our measurements indicate that \( n_{\text{char}}^Q \approx 70 \text{ cm}^{-3} \) is a factor \( \approx 70 \) smaller, \( \tau_{\text{ff}} \) a factor \( \approx 70^{1/2} \approx 8 \) larger, and SF thus by a similar factor more efficient and “faster”. Determinations of \( n_{\text{char}}^Q \) for HCN and other molecules are thus of essential importance for SF theory.

4.2. Galactic vs. Extragalactic Star Formation Relations

We initially set out to investigate whether \( M_{\text{dust}} \) as derived from \( A_V \) is equal to \( M_\ast \) as obtained from \( L_{\text{HCN}(1-0)} \). We now return to this question. Lada et al. (2010) argue that \( M_\ast \approx M_{\text{dust}} \) if \( M_{\text{dust}} \) is calculated as the cloud mass residing at \( A_V \approx A_V^\text{med} = 7 \text{ mag} \).
Fig. 4. Star formation in the Milky Way and galaxies. The reference relation for the Milky Way does not describe galaxies. This might hint at unknown reservoirs of HCN emission.

In Sec. 3.2 we have shown that $A_V^0 \approx 6$ mag for the HCN (1–0) transition is similar to $A_{Vdg}$. This suggests that about half of $L_{HCN}(1–0)$ originates directly in the dense star-forming gas of galaxies. The remaining fraction of $L_{HCN}(1–0)$ does not directly trace $M_{dg}$. Still, this emission might be a decent probe of the gas surrounding and shaping $M_{dg}$. From this perspective one might postulate

$$M_{dg} = \alpha_{HCN}(1–0) \cdot L_{HCN}(1–0),$$

(3)

where $\alpha_{HCN}(1–0)$ is a constant ($Gao$ & $Solomon$ 2004b), for example, suggested that $\alpha_{HCN}(1–0) \approx 10 M_\odot/(K\text{ km s}^{-1}\text{ pc})$, based on simple models. But $\alpha_{HCN}(1–0)$ has never been estimated using observations, in particular not down to densities $\lesssim 10^3 \text{ cm}^{-3}$ that we suggest are traced by the HCN (1–0) line.

We estimate $L_{HCN}(1–0) \approx 8 \times 10^{40} \text{ K km s}^{-1}\text{ pc}^2$, following the procedure described in Sec. 3.2. Recall that this is a lower limit since we cannot predict $W_{16}$ for $A_V < 2$ mag (Sec. 3). We further derive $M_{dg} \approx 1.6 \times 10^{5} M_\odot$ by evaluating the mass of material residing at $A_V \approx 7$ mag in the $K$-band extinction map. We thus find $\alpha_{HCN}(1–0) \lesssim 20 M_\odot/(K\text{ km s}^{-1}\text{ pc}).$

This is in good agreement with modeling by $Gao$ & $Solomon$ (2004b) — for the wrong reasons, given their models essentially assume $p_{char} \approx 3 \times 10^4 \text{ cm}^{-3}$, which exceeds the true value by a factor $\approx 30$. $Shimajiri$ et al. (2017) estimate $\alpha_{HCN}(1–0) \approx 10 M_\odot/(K\text{ km s}^{-1}\text{ pc})$ from observations of Aquila, Ophiuchus, and Orion B. Their work assumes a scaling factor to include gas at $A_V < 8$ mag. Our work differs from theirs in that we actually measure this factor (Fig. 3) while $Shimajiri$ et al. implemented a sophisticated treatment of interstellar radiation fields.

In Fig. 4 we use our new observational determination of $\alpha_{HCN}(1–0)$ to compare SF in the $Gao$ & $Solomon$ (2004a) galaxies to SF in molecular clouds near the Sun ($Lada$ et al. 2010) and in the Galactic Center (GC; $Longmore$ et al. 2013; $Kauffmann$ et al. 2016). For the galaxies we adopt $\dot{M}_* = \beta_{IR} \cdot L_{IR}$ with $\beta_{IR} \approx 3 \times 10^{-10} M_\odot \text{ yr}^{-1} \text{ L}_\odot^{-1}$ (Eq. [4] and the offset from Fig. 3 of $Murphy$ et al. 2011). $Lada$ et al. (2010) suggest a reference relation describing SF rates in clouds within $\sim 500$ pc from Sun, $M_{*\odot} = (4.6 \pm 2.6) \times 10^{-8} M_\odot \text{ yr}^{-1} \cdot (M_{dg}/M_\odot)$, from which GC clouds appear to deviate by a factor $\approx 10$.

Figure 4 shows that also galaxies deviate from $M_{*\odot}$ by an average factor $\langle M_{*\odot}/M_\odot \rangle \approx 4.5$. Given that $\langle M_{*\odot}/M_\odot \rangle \approx \alpha_{HCN}(1–0)$ could $\alpha_{HCN}(1–0)$ in galaxies be smaller than estimated here? Significant contributions to $L_{HCN}(1–0)$ from reservoirs outside those considered here, for example from diffuse cloud envelopes, could indeed reduce $\alpha_{HCN}(1–0) = M_{dg}/L_{HCN}(1–0)$.

5. Summary

We study the relationship between various emission lines and dense gas. This analysis is based on observations of various molecules at frequencies near 100 GHz ($^{12}$CO, $^{13}$CO, C$^3$O, CN, CCH, HCN, and N$_2$H$^+$). We focus on the HCN (1–0) transition, for which we find that it typically traces gas at $A_V \approx 6.1^{+1.2}_{-1.0}$ mag, corresponding to a characteristic H$_2$ density $\approx 870 \text{ cm}^{-3}$ (Sec. 3.2). The only major transition clearly connected to dense gas is the N$_2$H$^+$ (1–0) transition, characteristic of $A_V \approx 16$ mag and densities $\approx 4,000 \text{ cm}^{-3}$. The low characteristic densities derived for the HCN (1–0) line are about two orders of magnitude below values commonly adopted in extragalactic research (Sec. 4.1). This impacts theoretical discussions of SF trends in galaxies. We use this new knowledge on the emission from HCN to compare SF in galaxies to SF in the Milky Way (Sec. 4.2). The comparisons indicate that galaxies either deviate from SF relations holding in the Milky Way, or hitherto unknown reservoirs of emission contribute to $L_{HCN}(1–0)$.

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