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Probing star formation relations of mergers and normal galaxies across the CO ladder

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Abstract. We examine integrated luminosity relations between the IR continuum and the CO rotational ladder observed for local (ultra) luminous infra-red galaxies ((U)LIRGs, $L_{\rm IR} \geqslant 10^{11}\,M_\odot$) and normal star forming galaxies in the context of radiation pressure regulated star formation proposed by Andrews & Thompson (2011). This can account for the normalization and linear slopes of the luminosity relations ($\log L_{\rm IR} = \alpha \log L'_{\rm CO} + \beta$) of both low- and high-$J$ CO lines observed for normal galaxies. Super-linear slopes occur for galaxy samples with significantly different dense gas fractions. Local (U)LIRGs are observed to have sub-linear high-J ($J_{\rm up} > 6$) slopes or, equivalently, increasing $L_{\rm CO_{high-J}}/L_{\rm IR}$ with $L_{\rm IR}$. In the extreme ISM conditions of local (U)LIRGs, the high-J CO lines no longer trace individual hot spots of star formation (which gave rise to the linear slopes for normal galaxies) but a more widespread warm and dense gas phase mechanically heated by powerful supernovae-driven turbulence and shocks.

Keywords. ISM: lines and bands, ISM: molecules, galaxies: ISM, galaxies: starburst

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1. Introduction

Simple luminosity relations between the IR emission ($L_{\rm IR}$) and that of molecular transitions ($L'_{\rm mol}$ – typically low-J rotational lines of CO or of dense gas tracers like HCN, HCO^+, and CS) has seen widespread use as proxies for more fundamental relations between gas density and star formation rate, i.e., so-called Kennicutt-Schmidt 'laws' or star formation relations. However, prior to the launch of the *Herschel* Space Observatory there had been no systematic extragalactic survey of high-J CO lines (i.e., $J_{\rm up} > 7$ and above). For these lines to be strongly excited requires high densities ($n_{\rm crit} \sim 10^4 - 7\times10^5\,{\rm cm^{-3}}$) *and* (in most circumstances) high temperatures ($E_J/k_{\rm B} \sim 55 - 500\,{\rm K}$) – i.e., a hot and dense gas phase that would leave no easily discernible signature on the low-/mid-J lines (and line ratios) of CO and dense gas tracers (e.g., HCN and CS).

The first directly measured $L_{\rm IR} - L'_{\rm CO}$ correlations for $J_{\rm up} > 7$ CO transitions were presented by Greve et al. (2014) (hereafter G14), and based on SPIRE-FTS spectra (CO $J = 4-3$ to $J = 13-12$) obtained for 29 local ($z < 0.1$) (U)LIRGs as part of the *Herschel* Comprehensive (U)LIRG Emission Survey (HerCULES, see van der Werf et al. (2010) and Rosenberg et al. (2015)). G14 also included ground-based $J = 1-0$, $2-1$, and $3-2$ CO line data for a sample of 45 local (U)LIRGs (from Papadopoulos et al. (2012)). Fitting log-linear expression of the form $\log L_{\rm IR} = \alpha \log L'_{\rm CO} + \beta$ to their (U)LIRG sample, G14 found: 1) linear slopes ($\alpha \simeq 1$) for $J = 1-0$ to $6-5$, but increasingly sub-linear ($\alpha < 1$) for higher J-levels; 2) roughly constant normalizations ($\beta \simeq 2$) up to $J = 6-5$, but then increasing with higher J-levels. For $J_{\rm up} \leqslant 6$ the linear slopes are in agreement with the majority of previous studies. Sub-linear CO $J = 7-6$ slopes was also found by Bayet et al. (2009), who also predicted increasingly sub-linear slopes at higher J-lines using model extrapolations. More recently Liu et al. (2015) and Kamenetzky et al. (2015) (hereafter

L15 and K15, respectively) have delineated the $L_{\rm IR} - L'_{\rm CO}$ relations up to $J = 13-12$ for much larger samples of local galaxies than that of G14 (spanning a range of $10^7 - 10^{13}\,L_\odot$ in $L_{\rm IR}$). Both studies find increasingly sub-linear α for $J_{\rm up} > 6$, *when fitting only to the (U)LIRG population*, in broad agreement with G14 (Fig. 1a). The three studies also find similar β-values for $J_{\rm up} > 6$ (Fig. 1b). However, L15 and K15 find *linear* slopes for all transitions up to $J = 13 - 12$ (Fig. 1b) when fitting to their full samples, which are dominated by normal star forming galaxies. Finally, most surveys of HCN, HCO^+, and CS towards nearby star forming galaxies ($L_{\rm IR} \sim 10^9 - 10^{12}\,L_\odot$) have established linear slopes for the low-/mid-J transitions (Fig. 1a and b) (e.g., Gao & Solomon 2004; Zhang et al. 2014; cf. García-Burillo et al. 2012).

2. α and β for low-J CO and HCN/CS/HCO^+ lines

Stars form in dense, highly dust-obscured regions, and the radiation pressure exerted by the strong absorption and scattering of UV light by dust grains is likely to be an important SF-regulating feedback mechanism. Andrews & Thompson (2011) derived the $L_{\rm IR} - L'_{\rm CO_{low-J}}$ relations in the case of Eddington-limited SF and found the maximal possible luminosity is given by $L_{\rm Edd} = 4\pi G c \kappa^{-1} X_{\rm CO} L'_{\rm CO}$, where κ is the Rosseland-mean opacity, and $X_{\rm CO}$ is the $L'_{\rm CO}$-to-$M_{\rm H_2}$ conversion factors. This not only accounts for the linear slopes observed for the $L_{\rm IR} - L'_{\rm CO_{low-J}}$ relations, but also constrains the overall normalization. Adopting $\kappa = 5-30\,{\rm cm^2\,g^{-1}}$ and $X_{\rm CO} \simeq 0.8\,M_\odot\ ({\rm K\,km\,s^{-1}\,pc^2})^{-1}$, which are plausible (albeit poorly constrained) values for (U)LIRGs, $\beta_{\rm Edd} = \log(4\pi G c \kappa^{-1} X_{\rm CO}) = 2.5-3.3$ (Fig. 1c). For normal star forming galaxies, where $X_{\rm CO} \simeq 4.4\,M_\odot\ ({\rm K\,km\,s^{-1}\,pc^2})^{-1}$, $\beta_{\rm Edd} \simeq 3.3 - 4.1$ (Fig. 1d).

As expected, $\beta_{\rm Edd}$ sets an upper limit on the observed β-values, and (U)LIRGs – having a larger fraction of the ISM being dense and actively forming stars – are significantly closer to this maximal limit than normal star forming galaxies. This 'intermittency' (Andrews & Thompson 2011), i.e., the fraction of the ISM actively forming stars (effectively the dense gas fraction, $f_{\rm dense}$), sets the $L_{\rm IR} - L'_{\rm CO_{low-J}}$ normalization for a given galaxy population. By the same token, two galaxy samples with significantly different dense gas fractions ($f_{\rm dense,1}$ and $f_{\rm dense,2}$, say) will have $L_{\rm IR} - L'_{\rm CO}$ relations offset by $\Delta\beta \sim \log(f_{\rm dense,2}/f_{\rm dense,1})$. Thus, an increasing $f_{\rm dense}(L_{\rm IR})$ function (or, equivalently, $\beta(L_{\rm IR})$) can explain the super-linear ($\alpha \simeq 1.1 - 1.3$) $L_{\rm IR} - L'_{\rm CO_{low-J}}$ relations derived by some studies of 'mixed' galaxy samples (Fig. 1b).

For HCN and CS, $\beta_{\rm Edd} \sim 3.1 - 5$ and $\sim 3.6 - 5$, respectively, assuming $X_{\rm HCN} = 3 - 35\,M_\odot\ ({\rm K\,km\,s^{-1}\,pc^2})^{-1}$ and $X_{\rm CS} = 10 - 40\,M_\odot\ ({\rm K\,km\,s^{-1}\,pc^2})^{-1}$. Being superior tracers of the dense, actively star forming gas, the observed β-values for HCN and CS are much closer to (but still enveloped by) the Eddington limit than was the case for (low-/mid-J) CO (Fig. 1d). The issue of 'intermittency' is thereby also all but removed for these tracers, resulting in their approximately linear $L_{\rm IR} - L'_{\rm mol}$ relations across a vast $L_{\rm IR}$ range (e.g., Wu et al. 2010).

3. α for high-J CO lines: linear or sub-linear?

Three independent studies (G14; L15; K15) have shown that local (U)LIRGs exhibit sub-linear high-J $L_{\rm IR} - L'_{\rm CO}$ relations, and two of those (L15 and K15) further showed that the slopes are linear for samples dominated by normal star forming galaxies. In the latter case, the high-J CO lines are tracing SF 'hot spots' of warm dense gas being heated either 'calorimetrically' by UV-photons from nearby OB-associations, and/or mechanically by

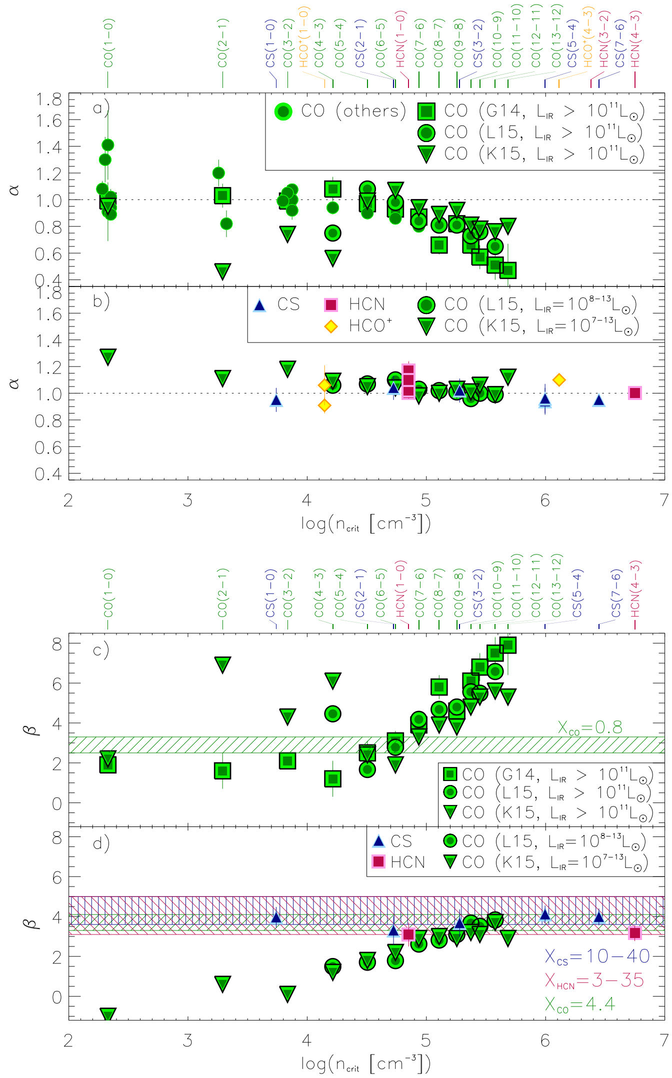

Figure 1. Observed α (top) and β (bottom) vs. critical density for the CO ladder. Panels a)+c) show (α,β)-values inferred from (U)LIRG samples only (Bayet et al. 2009; G14; L15; K15), and b)+d) are mainly for normal star forming galaxies (L15; K15). Also shown are (α,β)-values for transitions of the dense gas tracer molecules HCN, CS, and HCO^+. The shaded horizontal regions indicate $\beta_{\rm Edd}$ ($= \log(4\pi G c \kappa X_{\rm mol})$) for CO, HCN, and CS expected for Eddington-limited SF, assuming optically thick FIR opacities in the range $\kappa = 5-30\,{\rm cm^2\,g^{-1}}$ and conversion factors ($X_{\rm mol}$, in units of $M_\odot\ ({\rm K\,km\,s^{-1}\,pc^2})^{-1}$) as indicated in panels c)+d).

SN-driven shocks and outflows from young stellar objects. Just as the HCN/CS lines have β-values close to the Eddington limit, so do the high-J CO lines (Fig. 1d), which may reflect this more direct link with the SF-sites than the lower-J CO lines.

Clearly, local (U)LIRGs (having $\alpha_{\rm CO_{high-J}} < 1$ and $\beta_{\rm CO_{high-J}} > \beta_{\rm Edd}$) do not adhere to this picture, which is not surprising given their extreme ISM conditions. In fact, high-J CO lines are observed to be more strongly excited in local (U)LIRGs than in normal galaxies (e.g., Papadopoulos et al. 2014; G14) and, on average, $L_{\rm CO_{high-J}}/L_{\rm IR}$ increases with $L_{\rm IR}$ for LIRG-like luminosities and above (K15). The latter is compatible only with

$\alpha < 1$, since a linear α would imply $L_{\rm CO}/L_{\rm IR} \propto L_{\rm IR}^{1/\alpha-1} \times 10^{-\beta/\alpha} = 10^{-\beta} = constant$. In a similar vein, G14 noted that $\alpha_{{\rm CO}_{J,J-1}}$ can be expressed as:

$$\alpha_{{\rm CO}_{J,J-1}} = \alpha_{{\rm HCN}_{1,0}} \left(1 + \frac{d\log l_{{\rm dense}_{J,J-1}}}{d\log L'_{{\rm CO}_{J,J-1}}}\right) \simeq 1 + \frac{d\log l_{{\rm dense}_{J,J-1}}}{d\log L'_{{\rm CO}_{J,J-1}}}, \qquad (3.1)$$

where $l_{{\rm dense}_{J,J-1}} = L'_{{\rm HCN}_{1,0}}/L'_{{\rm CO}_{J,J-1}} \sim f_{\rm dense} r_{J,J-1}^{-1}$, parametrizes deviations in $\alpha_{{\rm CO}_{J,J-1}}$ from unity, and depends on both the dense gas content ($f_{\rm dense} \sim L'_{{\rm HCN}_{1,0}}/L'_{{\rm CO}_{1,0}}$) and the global CO line excitation ($r_{J,J-1} = L'_{{\rm CO}_{J,J-1}}/L'_{{\rm CO}_{1,0}}$). The sub-linear slopes for higher J lines observed in (U)LIRGs is due to an increase in the excitation of these lines – and thereby in the warm and dense gas fraction – with increasing high-J CO luminosity. The presence of a significant warm and dense molecular gas component has been suggested as a general feature of the ISM in extreme merger/starbursts such as local (U)LIRGs by Papadopoulos et al. (2012), who argued that high CR energy densities and/or the dissipation of shocks due to strong SN-driven supersonic turbulence can volumetrically heat and maintain significant amounts of high-density gas at temperatures $\gtrsim 100\,$K more efficiently than UV radiation, and without being attenuated by dust or readily dissociating CO as UV radiation does.

We end on a few cautionary notes regarding the $L_{\rm IR} - L'_{\rm mol}$ relations. They: 1) are only of use in a statistical sense, and individual sources may show significant departures; 2) do not necessarily apply to high-z dusty star forming galaxies, which are a heterogeneous population and in general *not* scaled-up versions of local ULIRGs; 3) are galaxy-integrated relations. Resolved HCN observations of nearby galaxies have shown significant scatter in the IR/HCN luminosity ratio (Kepley et al. 2014); 4) may not have a straightforward interpretation in the case of local (U)LIRGs, where an obscured hot mid-IR core may cause strong self- and continuum-absorption of HCN and CO lines (Aalto et al. 2015).

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