From Interstellar Clouds to Star-Forming Galaxies: Universal Processes?
Proceedings IAU Symposium No. 315, 2015
P. Jablonka, Ph. André & F. van der Tak, eds.

doi:10.1017/S1743921316007249

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

Thomas R. Greve

Department of Physics and Astronomy, University College London,
Gower Street, London WC1E 6BT, United Kingdom
email: t.greve@ucl.ac.uk

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

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) have 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

https://doi.org/10.1017/S1743921316007249 Published online by Cambridge University Press

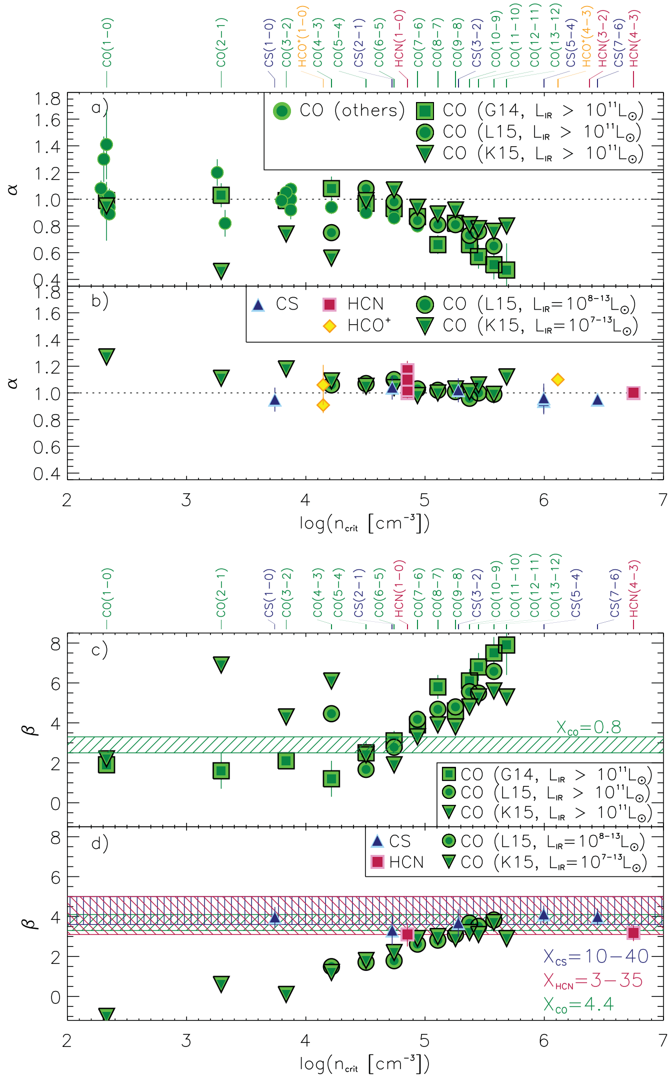

Figure 1. Observed α (top) and β (bottom) vs. critical density for the CO ladder. Panels a)+c) show (α,β)-values inferred from (U)LIRG samples only (Bayet *et al.* 2009; G14; L15; K15), and b)+d) are mainly for normal star forming galaxies (L15; K15). Also shown are (α,β)-values for transitions of the 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

https://doi.org/10.1017/S1743921316007249 Published online by Cambridge University Press

$\alpha < 1$, 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:

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

where $l_{{\rm dense}_{J,J-1}} = L'_{{\rm HCN}_{1,0}}/L'_{{\rm CO}_{J,J-1}} \sim f_{\rm dense} r^{-1}_{J,J-1}$, 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).

Acknowledgements. I am grateful to the IAU GA commitee for allocating a contributed talk, and to the DeMoGas and HerCULES teams, in particular to Ioanna Leonidaki, Manolis Xilouris, Zhiyu Zhang, Axel Weiß, Paul van der Werf, Padelis Papadopoulos, and Richard Tunnard for their valuable contribution to this work. DeMoGas is implemented under the "ARISTEIA" Action of the "Operational Programme Education and Lifelong Learning", and is co-funded by the European Social Fund and National Resources.

References

Aalto, S., Costagliola, F., González-Alfonso, E., *et al.* 2015 *A&A*, in press
Andrews, B. H. & Thompson, T. A. 2011 *ApJ*, 727, 97
Bayet, E., Gerin, M., Phillips, T. G., *et al.* 2009 *MNRAS*, 399, 264
Gao, Y. & Solomon, P. M. 2004, *ApJ*, 152, 63
García-Burillo, S., Usero, A., Alonso-Herrero, A., *et al.* 2012, *A&A*, 539, A8
Greve, T. R., Leonidaki, I., Xilouris, E. M., *et al.* 2014, *ApJ*, 794, 142
Kamenetzky, J., Rangwala, N., Glenn, J., *et al.* 2015, *ApJ*, submitted
Kepley, A. A., Leroy, A. K., Frayer, D., *et al.* 2014, *ApJ*, 780, 13
Liu D., *et al.* 2015, *ApJ*, 780, 13
Papadopoulos, P. P., van der Werf, P. P., Isaak, K., & Xilouris, E. M. 2012, *ApJ*, 715, 775
Papadopoulos, P. P., Zhang, Z.-Y., Xilouris, E. M., *et al.* 2014 *ApJ*, 788, 153
Rosenberg, M. J. F., van der Werf, P. P., Aalto, S., *et al.* 2015, *ApJ*, 801, 72
van der Werf, P. P., Isaak, K. G., Meijerink, R., *et al.* 2010, *A&A*, 518, L42
Wu, J., Evans, II, N. J., Shirley, Y. L., & Knez, C. 2010 *ApJS*, 188, 313
Zhang, Z.-Y., Gao, Y., Henkel, C., *et al.* 2014 *ApJ*, 784, L31