Tracing star formation relations across the CO ladder and redshift space

T. R. Greve (UCL), I. Leonidaki (NOA), M. Xilouris (NOA), P. Papadopoulos (Cardiff), A. Weiss (MPIfR), P. van der Werf (Leiden)

Abstract:
We present IR–CO luminosity relations (i.e., log L_{\text{FIR}} = \alpha \log L'_{\text{CO}} + \beta) across the CO rotational ladder (continuously from J = 1 \rightarrow J = 13 \rightarrow 12) for a sample of 87 (Ultra) Luminous Infrared Galaxies observed either with Herschel SPIRE-FTS and/or with ground-based telescopes. To extend our analysis to high-redshift galaxies, we included 108 (sub)-millimetre- selected dusty star-forming galaxies from the Heracles wave at high-z. We fitted the data to the CO line luminosities in units of L_{\odot} and derived robust CO observations and well-sampled far-IR/sub-millimetre spectral energy distributions (SEDs). The derived IR–CO luminosity relations are divided into three (U)LIRG subclasses: (i) linear (i.e., α = 1), (ii) sub-linear (0 < α < 1) for the higher transitions, and (iii) super-linear (α > 1) for the lower transitions. The latter is attributed to the higher-J lines becoming sub-thermally excited, as seen in the turnover at high-J in the CO SLEDs of our sources. We provide a simple theoretical framework with which to understand the observed trends.

Galaxy samples & Data:

Low-z samples:
70 local (U)LIRGs at z=0.1 selected from the IRAS BGS (f_{\text{IRBS}} > 5.24\mu m). The IR/submm data were taken from a number of studies (see Papadopoulos et al. (2012) and references therein). The CO line data consisted of new ground-based, single-dish observations of CO J=1-0 to J=6-5, and J=5-4 for subsets of the full sample, augmented by an exhaustive compilation of literature measurements.

To extend our study to the highest CO transitions, we included data from the Herschel Comprehensive (U)LIRG Emission Survey (HerCULES; van der Werf et al. (2010)) – an open key program on the ESA Herschel Space Observatory (Fabrègues et al. (2010)) which measured CO J=4-3 to J=13-12 for 29 local (U)LIRGs using the Fourier-transform spectrograph (FTS) of the SPIRE instrument (Griffin et al. (2010)).

High-z samples:
Dusty star forming galaxies (DSFGs), selected at (sub)-millimetre wavelengths, are thought to harbour the same extreme ISM and star forming conditions as local (U)LIRGs, and were for that reason chosen as our high-z companion sample. As for the local population we carefully searched through the literature and NED and from that compiled an exhaustive data-base of CO line measurements of DSFGs at z > 1, as well as of their optical/UV/sub-mm-IR and far-IR/sub/mm-radio continuum data (see Greve, in prep. for details). The CO line data consisted of new ground-based, single-dish observations of DSFGs (e.g., The Eyeball: Sargent et al. (2010)). In total, our analysis is based on 117 CO detections towards 49 DSFGs.

SED fitting and L_{\text{FIR}} estimates

The pan-chromatic (from far-UV/optical to radio) spectral energy distributions (SEDs) of our galaxy samples were modelled using CIGALE (Code Investigating GalAXy Emission – Burgarella et al. (2005); Noll et al. (2006)). CIGALE employs dust-attenuated stellar population models to fit the far-UV/optical SED, while at the same time ensuring that the observed UV photons are re-emitted in the far-IR, thus ensuring energy-balance between the far-UV and far-IR. The far-IR/submm continuum is modeled using the templates by Dale & Helou (2002) and Charry & Elbaz (2001).

Excellent fits were obtained for all of the local galaxies due to their well-sampled SEDs. For the high-z galaxies, only sources with data points longward and shortward of (or near the) CO transition were included in the final analysis (49 sources). All SED fits used in this paper can be found at http://demogas.as.noa.gr. From the SED fits we derived the far-IR (L_{\text{FIR}}, from 50 to 300 \mu m) luminosity. The accuracy of our IR/\textit{FIR} luminosity estimates is 1-2\% dispersion of the distributions obtained through bootstrapping of the photometry errors 1000 times.

Fig.1: log L_{\text{FIR}} vs. log L_{\text{CO}} across the CO rotational ladder (from J=1-0 to J=13-12). The low-z (z < 0.1) data include the (U)LIRG sample from Papadopoulos et al. (2012) (dark-grey symbols) with CO observations from J=1-0 to J=6-5, and (U)LIRGs from HerCULES (van der Werf et al. (2010)) (pink symbols). The high-z (z > 1) sources are un lensed, or weakly lensed, DSFGs (yellow symbols) and strongly lensed DSFG (blue symbols) recovered from various (sub-)millimetre surveys. The dashed lines with the best fit of the functional form log L_{\text{FIR}} = \alpha \log L'_{\text{CO}} + \beta to the data, with the optimum parameter (\alpha, \beta) values and their errors indicated in each panel. The scatter (\sigma) of the data around the best fit alters along with the correlation coefficient (r) given in each panel.

Analysis & Discussion

The FIR-CO relations derived here are shown in Fig. 1. This is the first time that FIR-CO relations have been directly inferred from observations up to such high J-transitions. Statistically significant correlations are seen across the board and normalizations of the form L_{\text{FIR}} = \alpha L'_{\text{CO}} + \beta are fitted to the data (dashed lines in Fig.1).

For the low- to mid-z J-transitions (up to J=5-4) we find FIR-CO slopes of unity. This is in agreement with some previous studies, although super-linear slopes have also been found in fact predicted by models (Krumholz & Thompson (2007); Narayanan et al. (2008)). See Fig. 2. A slope of 1.5 is expected for CO transitions that trace the bulk of the star forming ISM in galaxies, provided that a fixed fraction of the gas mass (\text{M}_{\text{gas}} \rightarrow \text{M}_{\text{gas}}^{\text{f}}) turns into stars every free-fall time (t_{\text{ff}} \rightarrow t_{\text{ff}}^{\text{f}}).

For CO transitions J=6-5 and beyond we find statistically significant sub-linear FIR-CO relations for the CO line luminosities, with the slopes becoming shallower with increasing J (Fig. 2). The sub-linear slopes are explained by the fact that the high-J CO lines not only require high densities but also high kinetic temperatures to be excited. In fact, from Fig. 3 we see that the lines become significantly redshifted, meaning that the lines no longer trace the cold, dense gas. Although, the models qualitatively agree with these findings, the predicted sub-linearly set in at much lower transitions (J=3-2) than what is observed.

Finally, we note that for the true high density gas tracers like HCN and CS, the observations strongly favour linear slopes (i.e., slopes, \alpha, consistent with unity for J=6-5 to J=6-4 (corresponding to gas densities of \sim 10^2-10^3 \text{cm}^-3), and becomes increasingly sub-linear (\alpha < 1) for the higher transitions. The latter is attributed to the higher-J lines becoming sub-thermally excited, as seen in the turnover at high-J in the CO SLEDs of our sources. We provide a simple theoretical framework with which to understand the observed trends.

where \text{a}_{\text{H2}} is the slope of the FIR-CHN1-0 relation which has been shown to be unity for the bulk of the gas mass (\text{M}_{\text{gas}} \rightarrow \text{M}_{\text{gas}}^{\text{f}}), and \text{a}_{\text{H2}} \rightarrow \text{H}_{2}^{\text{f}} can be expressed as:

\text{a}_{\text{H2}} = \frac{\text{d} \log L_{\text{HCN}}}{\text{d} \log L'_{\text{CO}}} = \frac{\text{d} \log L'_{\text{CO}}}{\text{d} \log L_{\text{HCN}}} \alpha_{\text{H2}} \left( 1 + \frac{\text{d} \log L_{\text{HCN}}}{\text{d} \log L_{\text{CO}}} \right)

Fig.2: Slope (\alpha) (d)eterminations for CO (Yao et al. 2003; Narayanan et al. 2005; Baan et al. 2006; Jenee et al. 2009; Iono et al. 2009; Bayet et al. 2009; Genzel et al. 2010; Mao et al. 2010), HCN (Genzel & Solomon 2004b; Bussmann et al. 2008; Garcia-Gómez et al. 2008a; Iono et al. 2009; Zhang et al., in prep.;) and CS (Wu et al. 2010, Zhang et al., in prep.) for the first two CO transitions, a-estimates are slightly offset horizontally in order to ease the comparison. The grey-shaded regions show the CO and HCN slopes (and the 1-sigma scatter) predicted by galaxy radiative transfer models by Narayanan et al. (2008).

Fig.3: The CO spectral energy distributions – here given as the CO line luminosities in L_{\odot} units, normalised by the FIR luminosity of the local (U)LIRG+HerCULES sample (red), the un lensed (green) and strongly lensed (blue) high-J DSFGs. The f_{\text{lim}} bars indicate the full range of L_{\text{CO}}/\text{L}_{\text{FIR}} values, while the brackets mark the variation of the individual sources.