Duality in spatially resolved star formation relations in local LIRGs


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ABSTRACT

We analyse the star formation (SF) relations in a sample of 16 nearby luminous infrared galaxies (LIRGs) with more than 2800 regions defined on scales of 90 to 500 pc. We used ALMA to map the distribution of the cold molecular gas traced by the $J = 2\to 1$ line of CO and archival Paα HST/NICMOS imaging to trace the recent SF. In four objects we find two different branches in the Kennicutt-Schmidt relation at 90 pc scales, suggesting the existence of a duality in this relation. The two branches correspond to two different dynamical environments within each galaxy. One branch, which corresponds to the central region of these galaxies (90% of the regions are located at radii <0.85 kpc), shows higher gas and SF rate surface densities with higher velocity dispersion. The other branch, which shows lower molecular gas and SF rate surface densities, corresponds to the more external disk regions ($r \sim 1$ kpc). Despite the scatter, the SF efficiency of the galaxies with dual behaviour increases with increasing boundedness as measured by the $b$ parameter ($b \equiv \Sigma_{\text{H}_2}/\sigma^2 \propto \alpha^{-1/2}$). At larger spatial scales (250 and 500 pc), the duality disappears. The rest of the sample does not show evidence of this dual behaviour at any scale.

Key words. galaxies: star formation – galaxies: ISM – infrared: galaxies

1. Introduction

The relationship between the rate at which stars form and the amount of gas contained in galaxies is commonly referred to as the star formation (SF) law or the Kennicutt-Schmidt (KS) relation (Schmidt 1959; Kennicutt 1998). This relation is expressed as

$$\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^\alpha,$$

where $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$ are the star formation rate (SFR) and the molecular gas surface densities, respectively, and $\alpha$ is the power-law index. This relation was initially studied in spatially unresolved observations of galaxies, finding a power-law index of $1.4-1.5$ (Kennicutt 1998; Yao et al. 2003). The physical processes that explain the observed power-law index are not clear yet. More recently, a duality has been found in the SF laws when normal and starburst galaxies are considered (Daddi et al. 2010; Genzel et al. 2010; García-Burillo et al. 2012). In these studies normal galaxies show depletion times ($t_{\text{dep}} = M_{12}/\text{SFR}$) that are between 4 and 10 times longer than starburst. This duality introduces a discontinuity in the KS relation. In this case, when each galaxy population (normal and starburst) is treated independently, there is a linear relation ($N \sim 1$).

Spatially resolved KS relation studies (≤1 kpc) (e.g. Leroy et al. 2008; Casasola et al. 2015; Pereira-Santaella et al. 2016a; Williams et al. 2018; Vlaeem et al. 2018) found a wide range of N values ($N \approx 0.6-3$) with a considerable scatter in the relation (0.1–0.4 dex). These results suggest that there is a break-down in the star formation law at sub-kiloparsec scales (sub-kpc; ≤300 pc), although the correlation is restored at larger spatial scales (Onodera et al. 2010; Schruba et al. 2010). This break-down may be due to the different evolutionary states of individual giant molecular clouds within the galaxies when resolved at sub-kpc scales. In addition to the relation between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$, other parameters, such as the velocity dispersion ($\sigma$) or boundedness of the gas ($b \equiv \Sigma_{\text{gas}}/\sigma^2 \propto \alpha^{-1/2}$, where $\alpha_{\text{vir}}$ is the virial parameter), have been studied to characterise the local dynamical state of the gas (e.g. Leroy et al. 2017; Sun et al. 2018). These studies suggest that the dynamical environment plays an important role in the ability to form stars within a galaxy.

These previous sub-kpc studies focused on nearby normal and active galactic nuclei (AGN) galaxies. However, more intense local starburst galaxies (i.e. luminous and ultraluminous infrared galaxies; LIRGs and ULIRGs) have been barely studied at sub-kpc scales (e.g. Xu et al. 2015; Pereira-Santaella et al. 2016a; Paraficz et al. 2018; Saito et al. 2016). In this work, we present a detailed analysis of the SF relations at cloud scales (∼100 pc) in a sample of 16 local LIRGs.
Table 1. Volume limited sample of local LIRGs.

<table>
<thead>
<tr>
<th>Object</th>
<th>α</th>
<th>δ</th>
<th>z</th>
<th>DL [Mpc]</th>
<th>i</th>
<th>log L_{IR}</th>
<th>Morf.</th>
<th>Spectral class</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
<td>(8)</td>
<td>(9)</td>
</tr>
<tr>
<td>ESO 297-G01I</td>
<td>30.6</td>
<td>23.40</td>
<td>-37.19</td>
<td>17.6</td>
<td>0.0168</td>
<td>73.4</td>
<td>38 ± 11</td>
<td>11.13</td>
<td>1</td>
</tr>
<tr>
<td>NGC 1614</td>
<td>33.95</td>
<td>38.44</td>
<td>0.0159</td>
<td>69.7</td>
<td>48 ± 2</td>
<td>11.61</td>
<td>2</td>
<td>composite</td>
<td>3</td>
</tr>
<tr>
<td>NGC 2369</td>
<td>17.37</td>
<td>37.73</td>
<td>0.0111</td>
<td>49.7</td>
<td>66 ± 6</td>
<td>11.18</td>
<td>0</td>
<td>composite</td>
<td>4</td>
</tr>
<tr>
<td>NGC 3110</td>
<td>10.04</td>
<td>28.29</td>
<td>0.0163</td>
<td>79.8</td>
<td>57 ± 3</td>
<td>11.37</td>
<td>0</td>
<td>HII</td>
<td>2.3</td>
</tr>
<tr>
<td>NGC 3256</td>
<td>12.75</td>
<td>34.13</td>
<td>0.0093</td>
<td>45.7</td>
<td>–</td>
<td>11.72</td>
<td>2</td>
<td>HII</td>
<td>5</td>
</tr>
<tr>
<td>ESO 320-G030</td>
<td>15.11</td>
<td>11.72</td>
<td>0.0102</td>
<td>52.2</td>
<td>56 ± 4</td>
<td>11.36</td>
<td>0</td>
<td>HII</td>
<td>4.6</td>
</tr>
<tr>
<td>MCG-02-33-098 W</td>
<td>13.20</td>
<td>20.00</td>
<td>0.0152</td>
<td>75.2</td>
<td>54 ± 6</td>
<td>11.19</td>
<td>1</td>
<td>composite</td>
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</tr>
<tr>
<td>MCG-02-33-098 E</td>
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<td>75.2</td>
<td>39 ± 1</td>
<td>11.11</td>
<td>1</td>
<td>HII</td>
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</tr>
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<td>53 ± 9</td>
<td>11.39</td>
<td>0</td>
<td>Sy2</td>
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<tr>
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<td>50 ± 4</td>
<td>11.16</td>
<td>1</td>
<td>Sy2</td>
<td>2.8</td>
</tr>
<tr>
<td>IC 4518 E</td>
<td>14.57</td>
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<td>0.0154</td>
<td>71.2</td>
<td>75 ± 2</td>
<td>11.12</td>
<td>1</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>...</td>
<td>17.16</td>
<td>35.79</td>
<td>0.0172</td>
<td>76.7</td>
<td>50 ± 1</td>
<td>11.39</td>
<td>2</td>
<td>composite/HII</td>
<td>2</td>
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<td>37.74</td>
<td>0.0160</td>
<td>67.6</td>
<td>50 ± 9</td>
<td>11.33</td>
<td>2</td>
<td>Sy2</td>
<td>3,8</td>
</tr>
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<td>30.71</td>
<td>0.0112</td>
<td>46.7</td>
<td>62 ± 5</td>
<td>11.13</td>
<td>0</td>
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<td>3.7</td>
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<td>0.0160</td>
<td>66.7</td>
<td>39 ± 5</td>
<td>11.54</td>
<td>1</td>
<td>Sy1</td>
<td>8.9,10,11</td>
</tr>
</tbody>
</table>


References. Nuclear classification: 1: Kewley et al. (2001); 2: Corbett et al. (2003); 3: Yuan et al. (2010); 4: Pereira-Santaella et al. (2011); 5: Lipari et al. (2000); 6: van den Broek et al. (1991); 7: Veilleux et al. (1995); 8: Pereira-Santaella et al. (2010); 9: Alonso-Herrero et al. (2012); 10: Alonso-Herrero et al. (2009); 11: Petric et al. (2011).

2. The sample

We present new sub-kpc CO(2–1) observations obtained by the Atacama Large Millimeter Array (ALMA) of a representative sample of 16 local LIRGs. Our sample is drawn from the volume-limited sample of 34 local LIRGs (40 Mpc < D < 75 Mpc) defined by Alonso-Herrero et al. (2006) and contains 85% of their southern targets that can be observed with ALMA. Our sample contains six isolated galaxies, six pre-coalescence systems (interacting galaxies and pairs of galaxies), and four merger objects (Yuan et al. 2010; Rich et al. 2012; Bellocci et al. 2013). Eight objects are classified as AGN in the optical and/or show evidence of AGN activity from mid-infrared diagnostics (Alonso-Herrero et al. 2012). In Table 1 we present the main properties of the individual galaxies in the sample.

3. Observations and data reduction

3.1. CO(2–1) ALMA data

We used ALMA Band 6 CO(2–1) observations carried out between August 2014 and August 2018 from several projects (see Table 2). The observations were obtained using a combination of extended and compact antenna array configurations, except in the case of the two galaxies that are part of the volume-limited sample of 34 local LIRGs (40 Mpc < D < 75 Mpc) which only used an extended antenna array configuration. The integration time of the sources ranges between ∼7 and ∼34 min. We calibrated the data using the standard ALMA reduction software CASA

1 http://casa.nrao.edu/
evident CO(2–1) emission and with no primary beam correction. In addition to the $5\sigma_{\text{CO}}$ criterion, and to ensure that the emission of data cubes does not include noise spikes, we did not consider spatial pixels that have emission from less than three spectral channels. Finally, for each pixel meeting the above criteria, we expanded the spectral range to include a channel before and after the emission to ensure that line profile wings below $5\sigma_{\text{CO}}$ are also considered. In addition to the nominal 90 pc resolution, we smoothed the data to 240 and 500 pc resolutions to study the effect of the spatial scale on the SF laws.

### 3.2. Ancillary HST/NICMOS data

We used the continuum subtracted near-infrared narrow-band Paα 1.87 μm images taken with the NICMOS instrument on board the *Hubble Space Telescope* (HST) to map the distribution of recent star formation in the galaxies in the sample (see Alonso-Herrero et al. 2006).

We downloaded the raw data from the *Hubble Legacy Archive* (HLA)\(^2\). The individual frames were combined using the PyDrizzle package with a final pixel size (0.03″) half of the original to improve the spatial sampling. The FoV of the images is approximately 19″5 × 19″5 (~4.2–7.4 kpc). To obtain the final images, we subtracted the background emission and corrected the astrometry using stars within the NICMOS FoV in the F110W ($\lambda_{\text{eff}} = 1.13$ μm) or F160W ($\lambda_{\text{eff}} = 1.60$ μm) filters and the *Gaia* DR2 catalogue\(^3\). Three objects (ESO297-G011, MCG-02-33-098 E/W, and IC4518 E) do not have *Gaia* stars in their NICMOS image FoV. In these cases we adjusted the astrometry using likely NICMOS counterparts of the regions detected in the ALMA continuum and CO(2–1) maps. After that, the images were rotated to have the standard north-up, east-left orientation. The Paα maps (spatial resolutions of 25–50 pc) were convolved with a Gaussian kernel to match the angular resolution of the ALMA maps.

### 3.3. Region selection

We defined circular apertures centred on local maxima in the CO(2–1) moment 0 maps with a diameter of 90 pc, 240 pc, or 500 pc, depending on the spatial resolution of the maps. To do so, we first sorted the CO moment 0 pixel intensities. Then we defined circular regions using as centre the pixels in order of descending intensity to prevent any overlap between the regions. With this method we end up with independent non-overlapping regions centred on local emission maxima that cover all the CO emission in each galaxy. In total, we defined 4802 regions for the whole sample.

We estimated the cold molecular gas mass using the Galactic CO-to-H$_2$ conversion factor, $\alpha_{\text{CO}} = 4.35 M_{\odot} K^{-1} (\text{km s}^{-1} \text{pc}^{-2})^{-1}$ (Bolatto et al. 2013) and the CO(2–1)/CO(1–0) ratio ($R_{21}$) of 0.7 obtained from the single-dish CO data of LIRG IC4687 (Albrecht et al. 2007). The $R_{21}$ value used is within the range found by Garay et al. (1993) in infrared galaxies and is similar to the value found by Leroy et al. (2013) in nearby spiral galaxies. We explore the variation of the CO-to-H$_2$ conversion factor in Sect. 3.5. We calculated the molecular gas mass surface density ($\Sigma_{\text{HI}}$) taking into account the area of the selected regions.

Once we had the regions in CO(2–1) emission maps, we selected the regions in the Paα maps. These regions are at the same spatial coordinates as the CO(2–1) regions. In this case we considered Paα detections when the line emission is above 3σ_{Paα}. The $\sigma_{Paα}$ in these images corresponds to the background noise.

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Table 2. CO(2–1) observations of the sample.

<table>
<thead>
<tr>
<th>Galaxy name</th>
<th>IRAS name</th>
<th>$\theta_{\text{maj}} \times \theta_{\text{min}}$</th>
<th>$\theta_{\alpha}$</th>
<th>PA</th>
<th>Sensitivity</th>
<th>Project PI</th>
<th>Mosaics</th>
<th>MRS</th>
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<td>[&quot;]</td>
<td>[&quot;]</td>
<td>[&quot;]</td>
<td>[&quot;]</td>
<td>[mJy beam$^{-1}$]</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ESO 297-G011</td>
<td>F01341–3735</td>
<td>0.21 × 0.16</td>
<td>0.19, 67</td>
<td>−72</td>
<td>0.53</td>
<td>MPS</td>
<td>9.4</td>
<td></td>
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</tr>
<tr>
<td>NGC 1614</td>
<td>F04315–0840</td>
<td>0.22 × 0.15</td>
<td>0.19, 62</td>
<td>−74</td>
<td>0.43</td>
<td>MPS</td>
<td>10.8</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>F07160–6215</td>
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<td>0.22, 53</td>
<td>88</td>
<td>0.51</td>
<td>MPS</td>
<td>8.8</td>
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<td>NGC 3110</td>
<td>F10015–0614</td>
<td>0.26 × 0.21</td>
<td>0.23, 89</td>
<td>−83</td>
<td>0.35</td>
<td>MPS</td>
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<td>F10257–4339</td>
<td>0.23 × 0.21</td>
<td>0.22, 48</td>
<td>63</td>
<td>0.43</td>
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<td>5.4</td>
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<td>ESO 320-G030</td>
<td>F11506–3851</td>
<td>0.30 × 0.24</td>
<td>0.27, 68</td>
<td>63</td>
<td>0.89</td>
<td>LC1</td>
<td>8.7</td>
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<tr>
<td>MCG-02-33-098 W</td>
<td>F12596–1529</td>
<td>0.23 × 0.17</td>
<td>0.20, 73</td>
<td>89</td>
<td>0.48</td>
<td>MPS</td>
<td>✓</td>
<td>9.4</td>
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<tr>
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<td>0.20, 72</td>
<td>89</td>
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<tr>
<td>NGC 5135</td>
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<td>0.31 × 0.22</td>
<td>0.26, 82</td>
<td>63</td>
<td>0.21</td>
<td>LC2</td>
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<tr>
<td>IC 4518 W</td>
<td>F14544–4255</td>
<td>0.23 × 0.20</td>
<td>0.21, 75</td>
<td>−86</td>
<td>0.46</td>
<td>MPS</td>
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<td>IC 4518 E</td>
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<td>0.23 × 0.20</td>
<td>0.21, 73</td>
<td>−87</td>
<td>0.47</td>
<td>MPS</td>
<td>10.3</td>
<td></td>
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<td>IC 4734</td>
<td>F18341–5732</td>
<td>0.25 × 0.21</td>
<td>0.23, 75</td>
<td>−73</td>
<td>0.77</td>
<td>TDS</td>
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<td>F21453–3511</td>
<td>0.36 × 0.29</td>
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<td>0.29</td>
<td>MPS</td>
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<td>F22132–3705</td>
<td>0.40 × 0.34</td>
<td>0.37, 82</td>
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<td>9.8</td>
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<td>0.21, 65</td>
<td>−39</td>
<td>0.29</td>
<td>TDS</td>
<td>✓</td>
<td>2.8</td>
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</table>

The regions that are below 3σ correspond to the upper limits. Paα emission is detected in 2783 regions (58% of the total). Then we estimated the SFR surface density (Σ_{SFR}) of the regions. We used the Ha Kennicutt & Evans (2012) calibration, which assumes a Kroupa (2001) initial mass function, and a Ha/Paα ratio of 8.6 (case B at T_e = 10,000 K and n_e = 10^5 cm^{-3}, Osterbrock & Ferland 2006). The variation in this ratio is ∼15% due to changes in the physical properties of the ionised gas (i.e. T_e = 5-20×1000 K and n_e = 10^5-10^6 cm^{-3}). We took into account the area of the selected regions, obtaining the SFR surface density. All these Σ_{H2} and Σ_{SFR} values are corrected for the inclination of each galaxy (see Table 1).

Both the SFR and the cold molecular gas surface density estimates are affected by flux calibration errors. We assume an uncertainty of about 10% in the ALMA data (see ALMA Technical Handbook4), and ∼15-20% in the NICMOS data (Alonso-Herrero et al. 2006; Böker et al. 1999).

3.4. Extinction correction

To correct the Paα emission for extinction, we used the Brγ and Brγ line maps observed at 240 pc scales with the SINFONI instrument on the Very Large Telescope (VLT) in eight objects from our sample (effective FoV between 8″ × 8″ and 12″×12″; Piqueras López et al. 2013) to derive A_k (see Table 2). We calculated the Brγ/Brγ ratio in circular regions with a diameter of 240 pc. We assumed an intrinsic Brγ/Brγ ratio of 1.52 (Hummer & Storey 1987) and the Fitzpatrick (1999) extinction law. In each 240 pc region, we determined A_k (A_k = 0.11 × A_V) and the column density of the CO(2–1) 240 pc maps (N_{HI}).

The N_{HI} values were divided into five equally spaced ranges between log N_{HI}/cm^{-2} = 22.55 and 23.88. For each range we estimated the mean and standard deviation of A_k: obtaining slightly increasing values with N_{HI} between 0.95 ± 0.6 and 1.98 ± 1.29 mag. To obtain an estimation of the extinction, we measured N_{HI} in the circular apertures with a diameter of 90 (110), 240, and 500 pc in our entire sample and assigned them the mean A_k corresponding to their N_{HI} range. We assume that the galaxies without SINFONI data (half of the sample) follow the same trend found between A_k and N_{HI} in the other eight galaxies.

3.5. Effects of the CO-to-H_{2} conversion factor

The obtained cold molecular gas masses depend on the conversion factor (α_{CO}) used. In this paper we assume a Galactic α_{CO} conversion factor to derive molecular gas masses. As argued in the following, we do not expect that a lower conversion factor, typical of ULIRGs (Papadopoulos et al. 2012) is appropriate for our targets.

Our sample does not contain strongly interacting objects or compact mergers like most local ULIRGs. The galaxies in our sample have a mean infrared luminosity of log(L_{IR}/L_{⊙}) = 11.30. In addition, galaxies in our sample show a mean effective radius of the molecular component (R_{eff}^{CO} of ULIRGs show a mean value of R_{eff}^{CO} = 340 pc (Pereira-Santaella et al. 2021). Therefore, it is likely that the α_{CO} of our sample differs from that of local ULIRGs.

The CO-to-H_{2} conversion factor can be affected by the metallicity of the galaxies, showing higher values with decreasing metallicity (α_{CO} = 4.35 (Z/Z_{⊙})^{-1.6} M_{⊙} pc^{-2}(K km s^{-1})^{-1}, Accurso et al. 2017). Rich et al. (2012) studied the metallicity in some local (U)LIRGs, showing a decrease in the abundance with increasing radius. In the case of the metallicity in local disks, Sánchez et al. (2014) observed a similar behaviour. Based on these works, the expected variation in the conversion factor due to metallicity gradients at r < 4 kpc is small, 20–30%.

4. Results and discussion

4.1. Star formation relation for individual galaxies

We studied the molecular KS relation for each LIRG at scales of 90 (110) pc. As an example, Fig. 1 shows the SFR surface density as a function of molecular gas surface density for NGC 7130 (similar figures for the rest of the sample are presented in Appendix A.1). The KS diagram suggests that the regions follow two different power laws. These two branches were identified using the Multivariate Adaptive Regression Splines (MARS) fit (Friedman 1991) in log Σ_{SFR} and log Σ_{H2}, which gives the position of the breaking points (cut points) for a linear regression with multiple slopes. We obtained the adjusted coefficient of determination, the cut points, and their errors using MARS fit in 100 realisations of the data based on the uncertainties in both axes.

We consider that the MARS breaking point is significant when the adjusted coefficient of determination found by MARS (R^2_{MARS}) is larger than that of the linear fit (R^2_{linear}). The adjusted coefficient of determination is used to compare the linear and MARS fits since it takes into account both the number of terms in the model and the number of data points. In this galaxy the break of a linear regression occurs at log Σ_{H2}/(M_{⊙} yr^{-1} kpc^{-2}) = 3.35 (for cut on Σ_{SFR}, see Fig. A.1).

We fit the two branches using the orthogonal distance regression (ODR) method. This fit gives power-law indices of N = 4.19 ± 0.46 and N = 0.68 ± 0.07. The right panel of Fig. 1 shows that the branch with higher gas and SFR densities (left panel) is located in the central region of the galaxy (at radii up to 0.85 kpc), while the other branch with lower gas and SFR densities is located in the more external disk regions. The duality is reinforced if we consider a factor α_{CO} = 0.8 (Downes & Solomon 1998) typical of ULIRGs in the central regions of our galaxies.

We do not include in our analysis the upper limits. Pessa et al. (2021) studied the influence of the non-detections in several resolved scaling relations. In general, the non-detections could artificially flatten the relations at small spatial scales, resulting in a steepening when the analysis is carried out at larger spatial scales. This occurs because the pixels with signal are averaged with the non-detection pixels at larger scales. However, they found that ignoring the non-detections in the star formation relation has a small impact on the measured slope.

4.2. Star formation relation across the sample

We repeated the same analysis for the rest of the sample finding two different regimes (branches) in the KS relations in four galaxies (25% of the sample, hereafter referred to as dual galaxies; see Table 3 and Fig. A.2).

The remaining 12 galaxies (75% of the sample) can be modelled with a single power law (hereafter referred to as non-dual galaxies; see Table 4 and Fig. A.3) at 90 pc scales. For the four dual galaxies the cut points on both the Σ_{H2} and Σ_{SFR} axes are similar (log Σ_{H2}/(M_{⊙} pc^{-2}) ∼ 3.25 and log Σ_{SFR}/(M_{⊙} yr^{-1} kpc^{-2}) ∼ 0.91).
Therefore, in the top left and top middle panels of Fig. 2 we combine all the regions of the dual galaxies with a cut on both axes obtained in each individual dual galaxy. We find that the power law for the regions above the cut points (hereafter referred to as high-N regions) is steeper than for the regions below them (hereafter referred to as low-N regions). The indices of the best power-law fits are \( N = 4.12 \pm 0.22 \) (high-N regions) and \( N = 0.91 \pm 0.04 \) (low-N regions) when using the \( \Sigma_{HI} \) cut point (Fig. 2 top left), and \( N = 1.89 \pm 0.15 \) (high-N regions) and \( N = 0.89 \pm 0.03 \) (low-N regions) when we consider the \( \Sigma_{SFR} \) cut point (Fig. 2 top middle).

When we fit all the regions from the dual galaxies using the MARS method (Fig. 2 bottom row), we obtain a value of \( R^2_{\text{MARS}} = 0.67 \pm 0.06 \) and \( 0.59 \pm 0.03 \) on \( \log_{10} \Sigma_{HI} \) and \( \log_{10} \Sigma_{SFR} \), respectively higher than \( R^2_{\text{linear}} = 0.55 \) and similar cut point values to those in the individual dual galaxies (\( \log \Sigma_{HI}/(M_\odot \text{pc}^{-2}) = 3.27 \pm 0.17 \) and \( \log \Sigma_{SFR}/(M_\odot \text{yr}^{-1} \text{kpc}^{-2}) = 1.16 \pm 0.19 \). At larger spatial scales (240 and 500 pc), the duality disappears and a standard single power-law KS relation is recovered (see Fig. 3).

For the 12 non-dual galaxies, we find a single linear power law with an index \( N = 1.15 \pm 0.02 \) (Fig. 2 top right). The dual and non-dual behaviours are also present before applying the extinction correction in Fig. 4.

4.3. Radial distribution of the two regimes

To identify what causes the two branches in the SF laws for these four galaxies, we first investigate their spatial distribution. Figure 5 shows the cumulative distribution of the molecular gas mass of the regions, based on the \( \Sigma_{HI} \) cut selection, in the dual galaxies as a function of the radial distance. We find that the high-N regions are located in the central region of the galaxies, 50% (90%) at radii smaller than 0.50 kpc (0.85 kpc) from the centre. The molecular mass in the high-N regions follows the same radial distribution. The low-N regions are located at larger radii with a median radius of \( \sim 1 \) kpc, and only \( \sim 45\% \) of the regions are at radii lower than 0.88 kpc. We find the same trends using the cut on \( \Sigma_{SFR} \).

4.4. Self-gravity of the gas

We explored the dynamical state of molecular gas in the regions using the boundedness parameter \( (b \equiv \Sigma_{\text{rad}}/\sigma^2 \propto \alpha_{\text{vir}}^{-1}) \), where \( \sigma \) is the velocity dispersion and \( \alpha_{\text{vir}} \) the virial parameter. We obtained the velocity dispersion from the CO(2–1) moment 2. Figure 6 shows the cold molecular gas depletion time \( (t_{\text{dep}} = \Sigma_{HI}/\Sigma_{SFR}) \) as a function of the boundedness parameter \( (b) \) at 90 pc scales. Despite the scatter (\( \sim 2.5 \text{ dex in } t_{\text{dep}} \)), at these scales...
Table 4. Statistical parameters for the non-dual galaxies

<table>
<thead>
<tr>
<th>Galaxies</th>
<th>$R^2_{\text{linear}}$</th>
<th>Cut on $\log_{10}\Sigma_{\text{H}_2}$</th>
<th>Cut on $\log_{10}\Sigma_{\text{SFR}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cut point</td>
<td>$R^2_{\text{MARS}}$</td>
</tr>
<tr>
<td>ESO 297-G011</td>
<td>0.22</td>
<td>3.25 ± 0.12</td>
<td>0.13 ± 0.05</td>
</tr>
<tr>
<td>NGC 2369</td>
<td>0.63</td>
<td>3.45 ± 0.20</td>
<td>0.60 ± 0.03</td>
</tr>
<tr>
<td>NGC 3256</td>
<td>0.36</td>
<td>3.92 ± 0.16</td>
<td>0.24 ± 0.06</td>
</tr>
<tr>
<td>ESO 320-G030</td>
<td>0.18</td>
<td>2.89 ± 0.10</td>
<td>0.17 ± 0.03</td>
</tr>
<tr>
<td>MCG-02-33-098 W</td>
<td>0.65</td>
<td>3.50 ± 0.13</td>
<td>0.63 ± 0.05</td>
</tr>
<tr>
<td>MCG-02-33-098 E</td>
<td>0.27</td>
<td>3.02 ± 0.14</td>
<td>0.11 ± 0.05</td>
</tr>
<tr>
<td>NGC 5135</td>
<td>0.35</td>
<td>3.44 ± 0.18</td>
<td>0.33 ± 0.09</td>
</tr>
<tr>
<td>IC 4518 W</td>
<td>0.18</td>
<td>3.57 ± 0.11</td>
<td>0.15 ± 0.06</td>
</tr>
<tr>
<td>IC 4518 E</td>
<td>0.65</td>
<td>2.85 ± 0.09</td>
<td>0.63 ± 0.02</td>
</tr>
<tr>
<td>IRAS F17138-1017</td>
<td>0.50</td>
<td>2.75 ± 0.21</td>
<td>0.46 ± 0.07</td>
</tr>
<tr>
<td>IC 4734</td>
<td>0.79</td>
<td>3.55 ± 0.14</td>
<td>0.83 ± 0.05</td>
</tr>
<tr>
<td>NGC 7469</td>
<td>0.62</td>
<td>3.47 ± 0.11</td>
<td>0.63 ± 0.04</td>
</tr>
</tbody>
</table>

Notes. The adjusted coefficient of determination ($R^2_{\text{MARS}}$) was obtained by linear fit. The breaking point and the adjusted coefficient of determination ($R^2_{\text{MARS}}$) were obtained by MARS fit in $\log_{10}\Sigma_{\text{H}_2}$ and $\log_{10}\Sigma_{\text{SFR}}$ for the non-dual galaxies.

Fig. 2. SFR surface density as a function of the molecular gas surface density using 90 (110) pc regions. Top left and top middle panels: the black and blue points correspond to the two different regimes (branches) identified in the four dual galaxies using the MARS method in each individual galaxy. Top right: the green circles correspond to the regions in the remaining 12 galaxies. Bottom row: the black and blue points correspond to the two branches identified using the MARS method in all the regions from the dual galaxies. The red, brown, and magenta solid lines indicate the best fit for each regime. The dashed lines indicate constant $t_{\text{dep}}$. 

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there is a weak trend with decreasing $t_{\text{dep}}$ for increasing $b$ in the dual galaxies (top left).

When we consider the low- and high-N regions separately (bottom row), we find that the high-N regions in both cuts show a slightly better correlation between $t_{\text{dep}}$ and $b$, while for the low-N regions the trend disappears. The high-N regions show gas with larger $b$ (with a mean $b$ parameter of $\log b/M_\odot\text{pc}^{-2}(\text{km s}^{-1})^{-2} \approx 0.52$) and have shorter $t_{\text{dep}}$ in both cuts than the low-N regions (with a mean $b$ of $\log b/M_\odot\text{pc}^{-2}(\text{km s}^{-1})^{-2} \approx 0.30$). The non-dual galaxies do not show a clear relation. Table 5 summarises the correlations.

Leroy et al. (2017) found, from the intensity weighted average on scales of 40 pc within regions of 370 pc, that gas with larger $b$ (more bound) exhibits shorter $t_{\text{dep}}$ in the spiral galaxy M51. This means that when $b$ increases the system is more gravitationally bounded. However, Kreckel et al. (2018) did not find any correlation between $b$ and $t_{\text{dep}}$ in another spiral (NGC 628) at 50 pc scales within 500 pc regions, which is in agreement with our results for the non-dual galaxies and the low-N regions in dual galaxies. For the high-N regions in the dual galaxies, $t_{\text{dep}}$ seems to decrease for increasing $b$ although the scatter is large. The depletion times in our sample are between four and eight times shorter than in these two spirals. This difference is consistent with what was found in previous works for starbursts (Daddi et al. 2010; Genzel et al. 2010; García-Burillo et al. 2012). However, for similar $b$, there is a factor of 10 in $t_{\text{dep}}$. As a consequence, it is not clear if a universal relation between $t_{\text{dep}}$ and $b$ exists.

4.5. Velocity dispersion of the gas

We explore the behaviour of the velocity dispersion in our sample. Figure 7 shows the SF efficiency of the cold molecular gas ($\text{SFE} = \Sigma_{\text{SFR}}/\Sigma_{\text{H}_2}$) as a function of the velocity dispersion ($\sigma$). The velocity dispersion was obtained from the CO(2–1) moment 2. We find that the global mean values of the $\sigma$ and SFE for the dual galaxies ($\log \sigma/\text{km s}^{-1} = 1.36 \pm 0.16$ and $\log \text{SFE/Myr}^{-1} = -2.56 \pm 0.26$) and for the non-dual galaxies ($\log \sigma/\text{km s}^{-1} = 1.41 \pm 0.18$ and $\log \text{SFE/Myr}^{-1} = -2.60 \pm 0.31$) are similar. However, when we consider the low- and high-N regions independently, the mean values are different. The high-N regions show higher mean values ($\log \sigma/\text{km s}^{-1} \sim 1.56$ for both

**Fig. 3.** SFR surface density as a function of the molecular gas surface density using 240 (top row) and 500 (bottom row) pc regions. The blue and green circles correspond to the regions of the dual galaxies at 90 pc and the non-dual galaxies, respectively. The dark orange and magenta solid lines indicate the best fit. The dashed lines indicate constant $t_{\text{dep}}$. 

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cuts and log SFE/Myr$^{-1} = -2.41 \pm 0.44$ for cut on $\Sigma_{H_2}$ and log SFE/Myr$^{-1} = -2.10 \pm 0.40$ on $\Sigma_{SFR}$) than the low-N regions (log $\sigma$/km s$^{-1}$ $\sim$ 1.30 and log SFE/Myr$^{-1}$ $\sim$ -2.62 for both cuts). In addition, for the high-N regions the SFE increases with increasing $\sigma$, though the scatter is large ($\sim$2 dex).

The high-N regions are located in the central regions of the four dual objects, so we also investigate if the central regions of the non-dual galaxies have different SFE and/or $\sigma$. To do this, we consider the regions at radii <500 pc, which is where most of the high-N regions are located in the dual galaxies (see Sect. 4.3). Unlike the dual galaxies, we find that for the non-dual galaxies, the internal ($r < 500$ pc) and external regions have similar mean SFE (log SFE/Myr$^{-1} = -2.48 \pm 0.34$ and $-2.66 \pm 0.28$ for the internal and external regions respectively) and just slightly higher $\sigma$ (log $\sigma$/km s$^{-1}$ = 1.53 $\pm$ 0.18 and 1.36 $\pm$ 0.16, respectively).

The large scatter at these scales may be due to the fact that we can resolve individual regions, obtaining information from the clouds in different evolutionary phases (Kruijssen & Longmore 2014). Several SF models suggest that the dynamical state of the cloud, and not only its density, affects its ability to collapse and form stars (e.g. Krumholz & McKee 2005;
Fig. 6. Cold molecular gas depletion time, $t_{\text{dep}}$, as a function of the self-gravity of the regions (parameter $b$) at 90 pc scales for the dual (top left) and the non-dual galaxies (top right). The orange and magenta circles show the median $t_{\text{dep}}$ in bins of $b$. The points and error bars indicate the mean absolute deviation of the points in the bins. The values of these parameters estimated in M51 (Leroy+17) are shown in purple, and the open black rectangle represents the range of values in NGC 628 (Kreckel+18). The black and blue circles correspond to regions in the high- and low-N regimes, respectively, for the four dual objects (bottom row). The red and brown circles are the mean values of the regions in high- and low-N regimes, respectively. The error bars indicate the mean absolute deviation of the regions in high- and low-N regimes, respectively.

Table 5. Spearman rank correlation coefficients.

<table>
<thead>
<tr>
<th></th>
<th>$t_{\text{dep}}$ vs. $b$</th>
<th>SFE vs. $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\rho_s$</td>
<td>$p$-value</td>
</tr>
<tr>
<td>Dual</td>
<td>$-0.26$</td>
<td>6.13e$^{-17}$</td>
</tr>
<tr>
<td>High-N (cut on $\Sigma_{H_2}$)</td>
<td>$-0.38$</td>
<td>2.79e$^{-14}$</td>
</tr>
<tr>
<td>Low-N (cut on $\Sigma_{H_2}$)</td>
<td>$-0.18$</td>
<td>4.12e$^{-6}$</td>
</tr>
<tr>
<td>High-N (cut on $\Sigma_{SFR}$)</td>
<td>$-0.48$</td>
<td>2.51e$^{-10}$</td>
</tr>
<tr>
<td>Low-N (cut on $\Sigma_{SFR}$)</td>
<td>$-0.15$</td>
<td>1.22e$^{-5}$</td>
</tr>
<tr>
<td>Non-dual</td>
<td>$-0.13$</td>
<td>9.78e$^{-8}$</td>
</tr>
</tbody>
</table>

Notes. Spearman $\rho_{sp}$ rank correlation coefficients (two-sided $p$-values). We exclude the upper limits from the analysis. We consider the correlations to be statistically significant when $\rho_{sp} \geq 0.3$ and $p$-value $< 3\%$.

Hennebelle & Chabrier 2011; Federrath & Klessen 2013). These models focus on the properties of turbulent molecular clouds, proposing that the supersonic and compressive turbulence induces the formation of stars. In this case we would expect the SFE to increase with increasing gas velocity dispersion (Orkisz et al. 2017). This is consistent with our findings for the high-N regions in the dual galaxies. Cloud-cloud collisions could be enhanced near the location of the bar resonances in the central regions of these galaxies (Sánchez-García et al., in prep.). These collisions could result in an increased turbulence, which may induce a greater compression of the gas (increasing its density), and finally lead to an enhanced star formation. Moreover, the increase in gas density compensates for the high turbulence, causing, together, $b$ to increase in these central.
5. Conclusions

We have presented a high-resolution study of the star formation relation in a sample of 16 local LIRGs on spatial scales of ~90 pc. We have combined the SFR calculated from the HST/NICMOS Paγ emission with cold molecular gas from ALMA CO(2–1) data to probe the star formation relations.

We find that four galaxies from our sample show dual behaviour in their KS relation at 90 pc scales. The regime with higher gas and SFR surface densities is characterised by a steeper power-law index in the central region of the galaxies (r < 0.85 kpc). The other regime, which shows lower values of gas and SFR surface densities, is located in the more external disk regions. This dual behaviour disappears at large spatial scales (240 and 500 pc).

The gas in the central region of the dual galaxies shows greater turbulence (higher σ) and slightly stronger self-gravity (higher b) than the external region. These dynamical conditions of the gas might lead to more efficient star formation in the central region. The rest of the galaxies do not show a clear trend between these two parameters. These variations within each galaxy and among the galaxies in the sample suggest that the local dynamical environment plays a role in the star formation process. The fraction of AGN and bars is similar for dual and non-dual galaxies, although a larger sample is needed to evaluate their impact on the SF law at 90 pc scale.

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Fig. 7. SF efficiency of the molecular gas as a function of the velocity dispersion of the gas (σ) at 90 pc scales. Left and middle panels: cut on the ΣH₂ and ΣSFR axes for each galaxy, respectively. Colours are as in previous figures. The red and brown points and error bars indicate the mean and mean absolute deviation for the regions in high- and low-N regimes, respectively. Right panel: similar to the left and middle panels, but for non-dual galaxies. The central regions (r < 0.50 kpc) are represented in green and the more external regions in grey. The black and blue points and error bars represent the mean and mean absolute deviation values of the central and external regions, respectively. The orange and magenta points and error bars are the mean and mean absolute deviation for all the regions in each panel. The inverted triangles indicate upper limits.

References


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Appendix A: Figures

A.1. Star formation relation for individual galaxies and CO(2–1) maps and HST/NICMOS images

In this appendix we present the KS relations, the regions considered in this work, the ALMA CO(2–1) maps, and the HST/NICMOS Paα images for the whole sample.

**Fig. A.1.** Star formation relation and emission line maps used to obtain the location of the regions considered in NGC7130. *Top panels:* Same as Fig. 1, but applying the MARS method to the log $\Sigma_{\text{H}_2}$. *Bottom panels:* ALMA CO(2–1) (*left*) and HST/NICMOS Paα maps (*right*). This last map is smoothed to the ALMA resolution. The magenta filled ellipse (*bottom left*) represents the beam size (0''.36 × 0''.29 PA=69°).
Fig. A.2. Same as Fig. 1, but applying the MARS method to the log \( \Sigma_{H_2} \) (top left and middle) and log \( \Sigma_{SFR} \) (bottom left and middle). Right panels: ALMA CO(2–1) (top) and HST/NICMOS Pa\(\alpha\) maps (bottom). This last map is smoothed to the ALMA resolution. The magenta filled ellipse represents the beam size.

Fig. A.2. continued.
Fig. A.2. continued.

Fig. A.3. Same as Fig. A.1. Top left panel: SFR surface density ($\Sigma_{SFR}$) as a function of the molecular gas surface density ($\Sigma_{H_2}$) for the non-dual galaxies in the sample using 90 pc regions. The green circles indicate data points in each galaxy. The solid purple line indicates the best fit. The Spearman’s rank correlation coefficients ($\rho_S$) and the power-law index (N) of the derived best-fit KS relation are shown in the figure. The dashed lines indicate constant $t_{dep}$ values. Top right: Location of the regions on the CO(2–1) map (grey). Bottom panels: ALMA CO(2–1) (left) and HST/NICMOS Pa$\alpha$ (right) maps.
**NGC2369**

Fig. A.3. continued.

**NGC3256**

Fig. A.3. continued.
Fig. A.3. continued.

ESO320-G030

Fig. A.3. continued.

MCG-02-33-098-W

Fig. A.3. continued.
**MCG-02-33-098-E**

![Graph](image1)

![Map](image2)

**NGC5135**

![Graph](image3)

![Map](image4)

Fig. A.3. continued.
Fig. A.3. continued.

Fig. A.3. continued.
Fig. A.3. continued.
NGC7469

Fig. A.3. continued.