The Kennicutt–Schmidt Law and Gas Scale Height in Luminous and Ultraluminous Infrared Galaxies

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Abstract

A new analysis of high-resolution data from the Atacama Large Millimeter/submillimeter Array for five luminous or ultraluminous infrared galaxies gives a slope for the Kennicutt–Schmidt (KS) relation equal to 1.74\textsuperscript{0.07} for gas surface densities \(\Sigma_{\text{mol}} > 10^3 M_\odot pc^{-2}\) and an assumed constant CO-to-H\textsubscript{2} conversion factor. The velocity dispersion of the CO line, \(\sigma_v\), scales approximately as the inverse square root of \(\Sigma_{\text{mol}}\), making the empirical gas scale height determined from \(H \approx 0.5 \sigma_v^2/(\pi G \Sigma_{\text{mol}})\) nearly constant, 150–190 pc, over 1.5 orders of magnitude in \(\Sigma_{\text{mol}}\). This constancy of \(H\) implies that the average midplane density, which is presumably dominated by CO-emitting gas for these extreme star-forming galaxies, scales linearly with the gas surface density, which in turn implies that the gas dynamical rate (the inverse of the freefall time) varies with \(\Sigma_{\text{mol}}\), thereby explaining most of the super-linear slope in the KS relation. Consistent with these relations, we also find that the mean efficiency of star formation per freefall time is roughly constant, 5%–7%, and the gas depletion time decreases at high \(\Sigma_{\text{mol}}\), reaching only \(\sim 16\) Myr at \(\Sigma_{\text{mol}} \sim 10^3 M_\odot pc^{-2}\). The variation of \(\sigma_v\), \(\Sigma_{\text{mol}}\) and the constancy of \(H\) are in tension with some feedback-driven models, which predict \(\sigma_v\) to be more constant and \(H\) to be more variable. However, these results are consistent with simulations in which large-scale gravity drives turbulence through a feedback process that maintains an approximately constant Toomre \(Q\) instability parameter.

Supporting material: machine-readable table

1. Introduction

The Kennicutt–Schmidt (KS) relation describes the observed correlation between the star formation rate per unit area, \(\Sigma_{\text{SFIR}}\), and the surface density of gas, \(\Sigma_{\text{gas}}\). Because star formation is expected to follow the gas, a slope close to unity, as found for CO emission by Bigiel et al. (2008) and Leroy et al. (2008) or HCN emission by Gao & Solomon (2004), might not be surprising. However, star formation is a dynamical process involving the rate of conversion of gas into stars, so a mass dependence alone (as in the linear law) cannot be the full story. There has to be a time component, and for gravitating systems, that means a volume density is involved. The linear laws only depend on the gas surface density, rather than the volume density, so these laws presumably arise from selection effects in surveys that observe sub-regions of gas at a characteristic density, depending on the molecular transition used (Krumholz & Thompson 2007; Narayanan et al. 2008). The timescale is then the collapse time at that selected density, i.e., a constant. In contrast, the total gas should have a continuum of densities that widely participates in a gravity-driven condensation into dense clouds (Elmegreen 2015, 2018). If the average density increases with \(\Sigma_{\text{SFIR}}\), then the KS slope will be steeper than linear, such as the slope of 1.4 in the observations by Kennicutt (1998), de los Reyes & Kennicutt (2019), and others.

For a disk with gas surface density \(\Sigma_{\text{gas}}\) and scale height \(H\), the average midplane gas density is \(\rho_{\text{mid}} = \Sigma_{\text{gas}}/(2H)\), so the observed total gas slope of \(\sim 1.4\) can result from a gravity-driven model with a rate \((G \rho_{\text{mid}})^{0.5}\), provided that the disk scale height is about constant (Madore 1977; Larson 1988; Elmegreen 2018). In the Milky Way, the thickness of the molecular layer is indeed about constant inside the solar radius (Heyer & Dame 2015), but there is no direct view yet of the disk thickness in other galaxies where the KS relation has been measured.

The KS relation for starbursts and (ultra-)luminous infrared galaxies (U/LIRGS) has about the same \(\sim 1.5\) slope for CO as the total gas relation in galaxy disks (Kennicutt 1998; Gao & Solomon 2004; Krumholz et al. 2012; Gowardhan et al. 2017; Shi et al. 2018). This is presumably because most of the gas in starbursts is dense enough to emit CO and that molecule is not longer a sparse tracer subject to selection effects. The similar slope implies that even with extremely high star formation rate densities, the balance between feedback and self-gravity produces a vertical equilibrium with a relatively constant gas thickness, i.e., it is much more constant than the range of surface densities.

The purpose of this paper is to examine more closely the KS relation in the starburst regime and to estimate the disk thickness from the observed molecular gas velocity dispersion and surface density. From these we determine the average midplane density, freefall time, gas consumption time, and efficiency per freefall time. The results confirm the super-linear KS slope found previously for starbursts, and they reveal a nearly constant disk thickness, confirming the most basic model in which three-dimensional density primarily determines the rate at which gas turns into stars (Madore 1977; Silk 1987; Katz 1992; Elmegreen 1994, 2002; Krumholz & McKee 2005; Bacchini et al. 2019; see review in Krumholz 2014).
In what follows, Section 2 describes the observations and data processing. Section 3 derives the KS law, Section 3.2 determines the disk scale heights, and Section 3.3 derives the gas depletion time, freefall time, and efficiency per freefall time. Section 4 considers our observations in the context of various theoretical predictions, and Section 5 presents the conclusions.

2. Observations and Data Processing

To study the KS relation at high star formation rates, we searched the Atacama Large Millimeter/submillimeter Array (ALMA) archive for U/LIRGs for which suitable observations of the CO $J = 1−0$ line were available (Table 1). For each project, the raw $uv$-data were calibrated using the scripts retrieved from the archive and the CASA version used in the original calibration. All further processing was carried out in CASA versions 5.0–5.4. Continuum subtraction was performed on the $uv$-data using line-free channels. Cleaned image cubes were made using Briggs weighting with robust = 0.5 and channel widths of $20 \text{ km s}^{-1}$ ($26.4 \text{ km s}^{-1}$ for NGC 3256, $40 \text{ km s}^{-1}$ for Arp 220). Continuum images were made with the same weighting using the line-free channels. For three galaxies where the CO and the continuum images used different ALMA data sets, a common minimum $uv$-distance cutoff was used for both data sets and a taper was applied to roughly match the resulting beams. Finally, the continuum image and line cube were smoothed to have identical resolution. More details on the image processing are given in C. D. Wilson et al. (2019, in preparation).

We made integrated intensity (moment 0) and velocity dispersion (moment 2) maps from the CO cubes using $3\sigma$ and $4\sigma$ cutoffs, respectively, and limited the range to the channels containing CO emission. The primary beam correction was applied to the CO integrated intensity and continuum images. We make no correction for channelization effects in the moment 2 maps (see Sun et al. 2018); this will cause $\sigma_v$ to be slightly overestimated, but we estimate the effect is at most 12% for the narrowest lines in our data. We also use various combinations of these three maps to calculate the dynamically derived quantities described in Section 3. All images were then rebinned so that individual pixels would be approximately the size of the beam and therefore essentially independent. We calculated uncertainty images for the continuum and integrated intensity maps that included both the 5% absolute calibration uncertainty and the statistical measurement uncertainty. We propagate the uncertainties through the formula used to calculate the moment 2 map to obtain an equation for the uncertainty in the moment 2 map,

$$\sigma_v(I) = \frac{\sigma_v(I) \Delta v_{\text{chan}}}{\sqrt{I}} \frac{1}{\sigma_v(I)}$$

where $I$ and $\sigma_v$ are the CO $J = 1−0$ integrated intensity and its uncertainty, $\Delta v_{\text{chan}}$ is the velocity range used to calculate the moment maps, and $\sigma_v$ is the velocity dispersion from the moment 2 map. Only binned pixels with a signal-to-noise greater than 4 in all three images are included in our analysis below.

Our relatively small pixel sizes mean that the contribution to $\sigma_v$ from systematic velocity gradients, e.g., shear, inside each resolution element, is small. We estimated this beam-smearing effect for IRAS 13120−5453, which is the galaxy with the lowest spatial resolution in parsecs and thus is likely to be the most affected. We removed the uvtaper to produce moment 1 (velocity field) and moment 2 (velocity dispersion) maps at a resolution of $0''56$ to compare with our fiducial maps. We combined the moment 1 and moment 2 maps at both resolutions to determine corrected velocity dispersion maps from the quadratic differences between the mean value for the velocity dispersion and the standard deviation of the velocity field across each beam. At both resolutions, this procedure produced only a small decrease in $\sigma_v$ ($2\%−7\%$) compared to $\sigma_v$ measured directly from the moment 2 map. We also compared the velocity dispersion averaged over $1''\times1''$ pixels on maps at the two different resolutions. On average, the velocity dispersion in the $1''\times1''$ maps is $18\%$ larger than the value from the $0''56$ maps. Putting these two results together, we estimate that the velocity dispersion in a typical pixel is overestimated by at most $20\%$. We note that the very central pixel toward each galaxy nucleus, which is also typically the pixel with the highest gas surface density, might be more strongly affected by beam smearing. A pervasive overestimate of $\sigma_v$ by $20\%$ from velocity gradients inside the beam will not affect the slopes of the various scaling relations discussed in the next section.

3. The KS Law and Dynamically Derived Quantities

3.1. The KS Relation at High Surface Densities

We adopt the U/LIRG value for the CO-to-H$_2$ conversion factor (Downes & Solomon 1998) and include a factor of 1.36 for helium to convert the CO integrated intensities, $I_{\text{CO}(1−0)}$, in K km s$^{-1}$, to observed molecular gas surface densities, $\Sigma_{\text{mol}}$, in $M_\odot$ pc$^{-2}$, $\Sigma_{\text{mol}} = 1.36\Sigma_{\text{H}_2} = 1.088I_{\text{CO}(1−0)}$. We make no correction for the (poorly constrained) inclination of these disturbed systems, which will cause $\Sigma_{\text{mol}}$ and $\Sigma_{\text{SFR}}$ to somewhat overestimate the true surface density perpendicular to the disk. These surface densities exceed $100 M_\odot$ pc$^{-2}$, so we ignore any contribution from atomic gas. The expected high dust extinction means we need a star formation rate tracer that minimizes the effect of dust while still providing arcsecond-
scale resolution. The one star formation rate tracer that meets both these requirements is the radio continuum (Murphy et al. 2011). We exclude the nucleus of NGC 7469 from our analysis as this galaxy contains a strong active galactic nucleus (AGN) that contributes a significant fraction of the radio continuum emission.

In such gas-rich systems, thermal emission from dust can also contribute to the 93–106 GHz emission. We estimated the dust contribution by comparing published fluxes or ALMA images at 330–350 GHz (230 GHz for NGC 3256) with our continuum images. We find that dust contributes on average 10% of the emission at 93 GHz (15% at 106 GHz); the relative contribution at these two frequencies is consistent with a dust emissivity index \(\beta \sim 1.5–1.8\). The one exception is the western nucleus of Arp 220, where the dust contributes 40% of the flux (Sakamoto et al. 2017). We correct our measured continuum fluxes by these various factors to remove the contribution from dust emission before calculating the star formation rate.

The dust-corrected 93–106 GHz emission from these galaxies likely contains a mixture of thermal (free-free) and non-thermal (synchrotron) emission. Assuming an excitation temperature of 10^4 K and a non-thermal spectral index \(\alpha_{\text{NT}} = 0.83\) (Murphy et al. 2011), non-thermal emission should contribute \(\sim 25\%\) of the total emission at these frequencies, e.g., a thermal:non-thermal ratio of 3:1. We therefore calculate the star formation rate surface density, \(\Sigma_{\text{SFR}}\), using the thermal-only formula from Murphy et al. (2011). (For emission at 93 GHz, the thermal-only equation gives a \(\Sigma_{\text{SFR}}\) that is 24% larger than the value obtained with the standard thermal+non-thermal equation from Murphy et al. 2011.) However, it is possible for the thermal radio emission to be reduced if some of the ionizing photons are directly absorbed by dust (Murphy et al. 2011). Such absorption is difficult to quantify but could be an important process in these extreme systems. For example, Sakamoto et al. (2017) estimate the majority of the 106 GHz emission in Arp 220 is non-thermal. For NGC 7469, we have compared an archival 8 GHz image with our 93 GHz image, which suggests that \(\sim 50\%\) of the 93 GHz emission is non-thermal, e.g., a thermal:non-thermal ratio of 1:1 across the inner disk. Adjusting the standard thermal+non-thermal equation from Murphy et al. (2011) by assuming that dust absorption suppresses the thermal emission by a factor of 3 would double \(\Sigma_{\text{SFR}}\) compared to the values used here.

Figure 1 shows the resolved KS relation for our sample. We fit the relation with a double power law using the AstroPy Modeling package with the break point location as a free parameter, and bootstrapped 10,000 times to get the fit parameters and uncertainties. We find a slope of 1.74\(\pm\)0.09 in the high surface density regime, with some indication of a shallower slope and increased scatter at surface densities below \(\sim 1000\ M_\odot\ pc^{-2}\). A single power-law fit to all of the data yields a nearly identical slope (1.73\(\pm\)0.08).

This steep power-law slope differs from the usual KS relation derived for CO emission, which is linear for local galaxies where \(\Sigma_{\text{CO}}\) tends to be less than several hundred \(M_\odot\ pc^{-2}\) (Bigiel et al. 2008; Leroy et al. 2013). For U/LIRGs in general, CO is a good measure of total gas surface density because most of the gas exceeds the threshold for CO emission. The transition from a linear CO law to a steep CO law at high \(\Sigma_{\text{gas}}\) was predicted in Elmegreen (2015). Gao & Solomon (2004) and Shi et al. (2018) also find a relatively steep CO law at high surface densities.

Narayanan et al. (2012) have suggested that the CO-to-H\(_2\) conversion factor, \(X_{\text{CO}}\), decreases with increasing CO intensity as

\[
X_{\text{CO}} = \min(4, 6.75 W_{\text{CO}}^{0.32}) \times 10^{20} \text{ cm}^{-2}(\text{K km s}^{-1})^{-1},
\]

where \(W_{\text{CO}} = I_{\text{CO}(1-0)}\); this equation does not include the factor for helium. (A similar result based more on star formation history than the instantaneous rate was suggested by Renaud et al. 2019, from the simulation of a merger.) This inverse dependence on \(W_{\text{CO}}\) would steepen the KS relation. If we write \(X_{\text{CO}} \propto W_{\text{CO}}^{-x}\), then a KS relation like \(\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{y}\) with an assumed constant \(X_{\text{CO}}\) converts to a steeper KS relation, \(\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{y/(1-x)}\), with a variable \(X_{\text{CO}}\). Taking \(y = 1.74\) and \(x = 0.32\), the revised slope would be 2.6. In what follows, we proceed with the assumption of a constant \(X_{\text{CO}}\) to facilitate comparisons with other studies, but we note the effect that Equation (1) would have on the slopes of the other relationships derived below.

### 3.2. Gas Scale Height

The equilibrium thickness of the gas disk in a galaxy depends on the balance between confining pressure from gravity and uplifting pressures from gas motions, magnetic
The gravitational forces are proportional to the total mass surface density inside the gas layer, \(\Sigma_{\text{total,GL}}\), plus vertical components of galactic gravity from remote regions. The relevant total surface density consists of gas plus the stars and the dark matter that reside inside the gas layer. Upward magnetic pressure including field line tension depends on the difference between \((B^2 - 2B^2_{\text{c}})/8\pi\) at the midplane and at the gas scale height, where \(B\) is the total field strength and \(B_{\text{c}}\) is the vertical component (Boulares & Cox 1990); cosmic ray pressure depends on the analogous difference for cosmic rays. Ostriker et al. (2010) suggest that the magnetic and cosmic ray contributions to the pressure gradient are much smaller than the turbulent pressure gradient because magnetic fields and cosmic rays extend to much greater heights than gas. Kim & Ostriker (2015) model a shearing box of magnetohydrodynamic turbulence with star formation feedback and determine that the vertical magnetic pressure gradient contributes an additional disk support that is \(\sim 0.3\) times the support from turbulent and thermal pressures. Denoting the average ratios of these pressure differences to the gas pressure by the constants \(\alpha \sim 0.3\) for the magnetic to turbulent plus thermal support ratio and \(\beta \sim 0\) for the cosmic ray to turbulent plus thermal support ratio (Parker 1966), the upward pressure is \(P_{\text{ISM}} = \rho_{\text{mid}}\sigma_{\text{gas}}^2(1 + \alpha + \beta)\) for average midplane gas density \(\rho_{\text{mid}}\) and combined thermal and turbulent velocity dispersion in the vertical direction, \(\sigma_v\).

The confining pressure from the disk is \(P_{\text{grav}} = 0.5\Sigma_{\text{gas}}g\), where \(0.5\Sigma_{\text{gas}}\) is the gas surface density in one-half the layer and \(g\) is the average gravitational potential in the midplane to that half. The gravitational acceleration comes from Poisson’s equation, \(\nabla \cdot g = 4\pi G\Sigma_{\text{total,GL}}\), with Gauss’s solution, giving \(g = 2\pi G\Sigma_{\text{total,GL}}\) at the effective top of the gas layer, i.e., at one scale height, \(H\). For a constant vertical velocity dispersion, \(g\) increases approximately linearly with height, so \(g = 0.5g\) and \(P_{\text{grav}} = 0.5\pi G\Sigma_{\text{gas}}\Sigma_{\text{total,GL}}\). These equations also come from exact solutions to the vertical equilibrium of an isothermal layer (Spitzer 1942). Setting \(P_{\text{ISM}} = P_{\text{grav}}\) in equilibrium and rearranging gives the gas disk half-thickness, 

\[
H = \frac{\Sigma_{\text{gas}}}{2\rho_{\text{mid}}} = \frac{\sigma_v^2(1 + \alpha + \beta)}{\pi G\Sigma_{\text{total,GL}}}.
\]  

(2)

For some applications, it is important to consider vertical forces from additional mass outside the disk region. One example of such a force is the vertical component of the three-dimensional gravitational acceleration toward the inner part of the galaxy, which contains the total mass that also gives the rotation curve at velocity \(v_{\text{rot}}(R)\) for galactocentric radius \(R\). At height \(H\), this is the geometric fraction \(H/R\) of the total acceleration, \(GM_{\text{galaxy}}/R^2\) for galaxy mass \(M_{\text{galaxy}}\) inside \(R\). The average perpendicular acceleration in the gas layer is about half of this, \(g_{\text{galaxy}} = 0.5GM_{\text{galaxy}}H/R^3\). The ratio of this to the pure disk component is 

\[
\frac{g_{\text{galaxy}}}{g} = 0.5\left(\frac{M_{\text{galaxy}}}{M_{\text{disk,GL}}}\right)\left(\frac{H}{R}\right),
\]  

(3)

where \(M_{\text{disk,GL}} = \pi R^2\Sigma_{\text{total,GL}}\) is the effective disk mass inside the vertical thickness of the gas layer out to radius \(R\), ignoring gradients in surface density. This ratio enters Equation (2) as \((1 + g_{\text{galaxy}}/g)\) multiplying the surface density, \(\Sigma_{\text{total,GL}}\), in the denominator.

Writing \(\mu = M_{\text{disk,GL}}/M_{\text{galaxy}} < 1\) as the ratio of masses and \(\xi = \sigma_v^2(1 + \alpha + \beta)/v_{\text{rot}}^2 < 1\) as the squared ratio of the gas velocity dispersion supplemented by magnetic and cosmic ray pressures to the galaxy rotation speed, Equation (2), including this additional force of gravity, becomes 

\[
\left(\frac{H}{R}\right)\left(1 + \frac{H}{2\mu R}\right) = \frac{\xi}{\mu},
\]  

(4)

which has the solution 

\[
\frac{H}{R} = (\mu^2 + 2\xi)^{1/2} - \mu.
\]  

(5)

Sample values for a galaxy disk might be \(\mu \sim 0.5\) and \(\xi \sim 0.1\); for such \(\xi \ll \mu\), \(H/R \sim \xi/\mu \sim 0.2\) in this case. Then \(g_{\text{galaxy}}/g \sim \xi/(2\mu^2) \sim 0.2\) is a small correction to Equation (2). For ULIRGs, the disk may dominate giving \(\mu \sim 1\); also, for \(\alpha/\sigma_v \sim 0.3\) (as in IRAS 13120–5453), \(\xi \sim 0.12\) (assuming \(\alpha + \beta = 0.3\)). Then \(H/R \sim 0.11\) and \(g_{\text{galaxy}}/g \sim 0.05\).

Combining these terms, Equation (2) becomes 

\[
H = \frac{\sigma_v^2}{\pi G\Sigma_{\text{gas}}} \times \left(1 + \alpha + \beta + \frac{1 + g_{\text{galaxy}}/g}{1 + \bar{g}_{\text{galaxy}}/\bar{g}}\right) \times \left(\frac{\Sigma_{\text{gas}}}{\Sigma_{\text{total,GL}}}\right).
\]  

(6)

In the solar neighborhood, the stellar midplane density is \(0.043 \pm 0.004 M_\odot \text{pc}^{-3}\), the dark matter density is \(0.013 \pm 0.003 M_\odot \text{pc}^{-3}\), and the gas density is \(0.041 \pm 0.004 M_\odot \text{pc}^{-3}\) (McKee et al. 2015). Thus, locally \(\Sigma_{\text{gas}}/\Sigma_{\text{total,GL}} \sim 0.42\). In U/LIRGs, the stellar and gas densities might be much higher than the dark matter density because of torques that drive the disk mass inward, and then \(\Sigma_{\text{gas}}/\Sigma_{\text{total,GL}} \sim 0.5\). In gas-rich galaxies at high redshift, the dark matter and gas surface densities could be comparable and the stellar surface density slightly smaller, making the ratio around 0.5 again. We discussed above the term from remote gravity, concluding that \(g_{\text{galaxy}}/g \sim 0.05–0.2\) for conditions representative of our galaxies. For the magnetic and cosmic ray contributions to supporting pressure, we follow the suggestion in Kim & Ostriker (2015) that \(\beta + \alpha \sim 0.3\). Thus the second and third terms in Equation (6) combine to give a factor of \(\sim 0.5\) and we write for our highly molecular galaxies,

\[
H \approx 0.5 \frac{\sigma_v^2}{\pi G\Sigma_{\text{mol}}}.
\]  

(7)

We consider the value of \(H\) in Equation (7) to be an empirical scale height because the relevant quantities are directly observable for a moderately inclined galaxy. The approximations discussed above suggest there might be \(\sim 50\%\) variations from region to region in normal and starburst disks. More detailed discussions of vertical equilibrium are in Narayan & Jog (2002), with further applications in, for example, Banerjee et al. (2011), Elmegreen (2011), Elmegreen & Hunter (2015), Benincasa et al. (2016), and Bacchini et al. (2019).

Equation (7) was used to calculate pixel-by-pixel maps of the distribution of \(H\) for each galaxy, where \(\sigma_v\) is the velocity dispersion of the molecular gas as measured by the moment 2
map. Figure 2(a) shows that $H$ is relatively constant across our sample. The mean values range from $150 \pm 15$ pc in NGC 7469 to $190 \pm 20$ pc in NGC 3256. These scale heights are a factor of $\sim 2$ larger than the molecular gas scale heights derived for six spiral galaxies where H$_2$ dominates in the central kiloparsecs (Bacchini et al. 2019); however, this factor of 2 is much less than the $10^4$ range in gas surface density in the two samples combined.

Figure 2(b) plots the velocity dispersion versus the molecular surface density. The dispersion, $\sigma_v$, increases as roughly the square root of $\Sigma_{mol}$ for the combined sample and also for different positions inside each galaxy, except for NGC 7479, where the range in surface density is small. This increase is consistent with the constancy of $H$, considering Equation (7). The velocity dispersions range from 30 to 160 km s$^{-1}$, and are much higher than in normal galaxy disks. Given the highly concentrated star formation and high orbital speeds in U/LIRGs, it is not surprising that their gas velocity dispersions would be much higher and their gas disks slightly thicker than those in more quiescent spiral galaxies.

The three galaxies in Figure 2 with significant ranges of gas surface density (IRAS 17208–0014, Arp 220, and NGC 3256) show a trend for $H$ to decrease slightly with increasing $\Sigma_{mol}$. For the two ultraluminous galaxies, $\sigma_v$ may also be slightly more constant with $\Sigma_{mol}$. These galaxies have the highest $\Sigma_{mol}$—greater than 2000 $M_{\odot}$ pc$^{-2}$ and also the highest $\sigma_v$, exceeding 100 km s$^{-1}$. These line widths are getting close to the rotation speeds of galaxies, and the excessively high surface densities suggest overlap or strong shock regions in these merging systems. Significant deviations from the plane-parallel model of equilibrium vertical support should be expected. Still, their average empirical thicknesses are comparable to those in the other galaxies.

If $X_{\text{CO}}$ decreases with the integrated CO line as $W_{\text{CO}}^5$ for $x = 0.32$ (Narayanan et al. 2012), then $H$ versus $\Sigma_{mol}$ and $\sigma_v$ versus $\Sigma_{mol}$ would both become steeper. The calculation of $H$ shown in Figure 2 assumes $X_{\text{CO}}$ is constant, so a constant $H$ means that $\sigma_v^2/W_{\text{CO}}$ is constant. With a variable $X_{\text{CO}}$, $\Sigma_{mol} \propto W_{\text{CO}}^{1-x}$, so we should have plotted $\sigma_v^2/W_{\text{CO}}^{1-x}$. Given that $\sigma_r^2/W_{\text{CO}}$ is constant, this new $H$ would be proportional to $W_{\text{CO}}$, which means that $H \propto \Sigma_{mol}^{(1-x)} \propto \Sigma_{mol}^{0.47}$. Similarly, $\sigma_v$ would be proportional to $\Sigma_{mol}$ to the power $0.5/(1 - x) = 0.74$ instead of 0.5.

### 3.3. Gas Depletion Time, Freefall Time, and Efficiency Per Freefall Time

We now estimate the midplane gas density from $\rho_{\text{mid}} = \Sigma_{mol}/(2H)$ and calculate the freefall time, $t_{ff}$, via

$$t_{ff} = \left(\frac{3\pi}{32G\rho_{\text{mid}}}\right)^{1/2} = \frac{\sqrt{3}}{4G} \frac{\sigma_v}{\Sigma_{mol}}.$$  \hspace{1cm} (8)

Figure 3 shows that the freefall time decreases as the gas surface density increases, which is a consequence of the nearly constant scale height such that $\rho_{\text{mid}} \propto \Sigma_{mol}$. It is also striking that the freefall times at the highest surface densities are extremely short (<2 Myr). If we adopt our beam size as an alternative measure of the extent of the gas emission along the line of sight (Utomo et al. 2018), then the midplane density would be reduced by factors of only 1–2.3 and the freefall times would be increased by factors of only 1–1.5 for our sample. The variable X(CO) from Equation (1) would have only a small effect on the observed trend.

Larger possible errors for the most extreme regions might arise from the $g_{\text{galaxy}}/g$ term as a scale height correction (Equation (3)) in the bulge or nuclear regions where the stellar density might be high, and by ignoring excessive magnetic and cosmic ray pressures. For example, the maximum average midplane density implied from our analysis is $n_{HI} \sim 600$ cm$^{-3}$. This is much smaller than the mean densities implied by $\sim 120$ pc resolution observations of Arp 220, which are $(2-9) \times 10^4$ cm$^{-3}$ toward the two nuclei (Wilson et al. 2014). In the eastern nucleus, where $\Sigma_{mol} \sim 7 \times 10^4 M_{\odot}$ pc$^{-2}$ (Wilson et al. 2014), Rangwala et al. (2015) have modeled the CO emission as a turbulent rotating disk and estimate the velocity dispersion to be 85 km s$^{-1}$. The high surface density combined with a relatively modest velocity dispersion implies an empirical scale height of just 4 pc, which seems to be unphysically small. Clearly the simple formalism of Equation (7) breaks down in this regime; additional upward force would have to come from additional magnetic and cosmic ray pressures. A more accurate calculation would correct for
the inclination of the disk, which Barcos-Muñoz et al. (2015) estimate to be $53.5^\circ$. In addition, the surface density in Wilson et al. (2014) is in fact an upper limit obtained by assuming the gas mass is equal to the dynamical mass. If we assume instead that the gas makes up 50% of the total mass in this region and correct for inclination and helium, the face-on surface density becomes $\Sigma_{mol} = 2.2 \times 10^7 M_\odot pc^{-2}$. Correcting the equation for $H$ to use $\mu = 0.5$, $\sigma_v/v_{rot} \sim 1$ (Rangwala et al. 2015), and $\alpha = \beta = 1$ to include increased magnetic and cosmic ray pressure, we obtain $H \sim 25$ pc. This value for $H$ in turn implies a midplane density of $1.3 \times 10^3$ $cm^{-3}$ and freefall time $t_{ff}$ of just 0.27 Myr. We do not have an easy measure of $\Sigma_{SFR}$ on this same scale; if we use our KS fit to estimate it from $\Sigma_{mol}$, we obtain $\Sigma_{SFR} = 2500 M_\odot kpc^{-2} yr^{-1}$. This in turn gives a gas depletion time $t_{dep} = 8.8$ Myr and efficiency per freefall time $\epsilon_{ff} = 0.031$ (see below).

We calculate the instantaneous gas depletion time, $t_{dep}$ from

$$t_{dep} = \frac{\Sigma_{mol}}{\Sigma_{SFR}}. \tag{9}$$

Figure 3 shows that, like the freefall time, the gas depletion time decreases as the gas surface density increases, although with increased scatter at lower surface densities. This decrease is a natural result of the power-law slope of 1.7 seen in the KS relation in Figure 1. It implies that starbursts are truly bursty: they cannot sustain their high star formation rates for very long unless gas accretes into the starburst region at an equally high rate. The variable $X$(CO) from Equation (1) would result in a trend of increasing efficiency with increasing gas surface density.

The decrease in $t_{dep}$ toward high $\Sigma_{mol}$ is not new. For example, Utomo et al. (2017) recently found a similar result for normal galaxies that $t_{dep}$ decreases in galaxy centers where $\Sigma_{mol}$ is higher. Such a trend is expected for a super-linear KS relation $\Sigma_{SFR} \propto \Sigma_{gas}$ as the ratio $\Sigma_{gas}/\Sigma_{SFR} \propto \Sigma_{gas}^{-1}$ decreases with increasing $\Sigma_{gas}$ for $y > 1$. Colombo et al. (2018) determined the ratio of the gas depletion time to the orbit time for 39 local galaxies, finding a nearly constant ratio within each Hubble type and a systematically smaller ratio for later types.

This result is consistent with our decrease in $t_{dep}$, as orbit time decreases closer to the center where $\Sigma_{mol}$ is increasing.

Finally, we calculate the star formation efficiency per freefall time, $\epsilon_{ff}$ from

$$\epsilon_{ff} = \frac{t_{ff}}{t_{dep}} = \frac{\sqrt{3} \sigma_v \Sigma_{SFR}}{4G \Sigma_{mol}^2}. \tag{10}$$

Figure 3 shows that $\epsilon_{ff}$ is roughly constant with mean values of 5%–7% in each of the five galaxies. These efficiencies are nearly an order of magnitude larger than those determined in spiral disks (e.g., Utomo et al. 2018), and similar to the efficiencies estimated for individual molecular clouds (see review in Krumholz et al. 2019). The variable $X$(CO) from Equation (1) would result in a trend of increasing efficiency with increasing gas surface density.

4. Discussion

There are several models for star formation and the origin of interstellar turbulence that make predictions about how the various quantities discussed here should scale with each other. These models usually involve some feedback control involving these quantities and the star formation rate, and they all reproduce the KS relation well enough. An important question is whether they also reproduce the other relations found here, such as the correlation of velocity dispersion with gas surface density.

There are essentially four feedback processes that seem to be important for interstellar equilibria: (1) the regulation of a two-phase interstellar medium through heating by starlight; (2) the limitation of density and collapse rate in molecular clouds through dispersal by internal star formation; (3) the maintenance of the disk scale height, midplane density, and average star formation rate through turbulence driven by star formation; and (4) the maintenance of a marginally stable interstellar medium on large scales through self-control of the Toomre $Q$ parameter. (Feedback driven by an AGN is beyond the scope of this discussion.) We view the first of these as a minimum constraint for star formation to occur at all, since gaseous gravity needs cool and moderate-density clouds to bring together in order to make the giant molecular clouds in which
most stars form. A recent observational confirmation of this type of thermal feedback is in Herrera-Camus et al. (2017), and a detailed model is in Hill et al. (2018). The second and third processes control the star formation rate by different means, the second on small scales inside individual OB associations by clearing away the dense gas and stopping star formation locally, and the third on scales comparable to the scale height by pumping interstellar turbulence and inflating the disk so as to lower the average density and slow the large-scale collapse. The fourth process controls the velocity dispersion of the gas through spiral and large-scale Jeans instabilities, which operate faster and pump in more turbulent energy when the dispersion is low. These Jeans instabilities may also promote giant molecular cloud formation, giving the fourth process a connection to star formation.

Ostriker et al. (2010) proposed a model that is applicable to starburst galaxies like those considered here, although their simulations probe somewhat lower gas surface densities of 100–1000 $M_{\odot}$ pc$^{-2}$. Along with Ostriker & Shetty (2011) and Shetty & Ostriker (2012), they suggest that the star formation rate and the phases of the interstellar medium are both regulated by massive young stars through momentum input via supernovae and radiative heating, respectively. With momentum input primarily from supernovae (which dominate stellar winds, H II regions, and radiative forcing on grains—see Ostriker & Shetty 2011), the turbulent speed equals approximately $0.4 \epsilon_{\delta} p^{v}/m^{s}$, where $\epsilon_{\delta} \sim 0.005$ is the assumed efficiency of star formation per unit freefall time at the midplane density, and $p^{v}/m^{s} \sim 3000$ km s$^{-1}$ is the assumed supernova momentum input per unit stellar mass formed. The velocity dispersion derived in this way equals a fixed $\sim 6$ km s$^{-1}$, independent of $\Sigma_{\text{gas}}$ or $\Sigma_{\text{SFR}}$ (see Equation (22) in Ostriker & Shetty 2011). Numerical simulations in a shearing box that resolve the disk thickness (Shetty & Ostriker 2012) confirm this result, showing that $\sigma$ increases from only 4 to 5 km s$^{-1}$ as $\Sigma_{\text{gas}}$ increases by a factor of $\sim 10$ (see their Figure 11). As a result of this near constancy in velocity dispersion, the predicted disk scale height varies inversely with $\Sigma_{\text{gas}}$. Their simulations show this inverse relationship (Figure 13(a) in Shetty & Ostriker 2012) over a factor of $\sim 10$ in $\Sigma_{\text{gas}}$, but the trend in $H$ is flattened somewhat by a corresponding increase in the ratio of turbulent pressure to vertical momentum flux from star formation. These predictions differ from the observations here, which show a $\sigma_{v}$ that increases with $\Sigma_{\text{gas}}$ and imply a constant $H$.

The U/LIRGS in our sample have more important sources of turbulence than supernova and stellar feedback, such as gas accretion and large-scale shocks and tidal forces from a merger. For example, H I velocity dispersions are $\sim 5 \times$ higher than normal in the interacting galaxies NGC 2207/IC 2163 (Elmegreen et al. 1993), Arp 82 (Kaufman et al. 1997), Arp 84 (Kaufman et al. 1999), and NGC 5774/5 (Irwin 1994). A model for these increases was in Wetzel et al. (2007). Tidal forcing of turbulence was also proposed for the Small Magellanic Cloud by Chepurnov et al. (2015). Regarding the fourth feedback process mentioned above, observations of the multi-fluid stability parameter $Q_{3F}$, including stars, atomic gas, and molecular gas, find that $Q_{3F}$ is about constant for all measured radii in a large number of galaxies in the HERACLES and THINGS surveys (Romeo & Mogotsi 2017). These observations also suggest that this marginal stability is regulated mostly by the stellar component, in which case $\sigma$, for the gas results from kinetic energy input through stellar gravitational processes, such as spiral waves and spiral shock fronts. Such a result was also demonstrated numerically in simulations by Bournaud et al. (2010) and Combes et al. (2012) for whole galaxy disks. Those simulations reproduced the whole-disk power spectra observed in the LMC and M33, respectively, including the transition from a relatively flat power spectrum on large scales to a steeper power spectrum on small scales, with the break scale equal to the disk thickness (see also Elmegreen et al. 2001). What is important for the present discussion is that this double power-law power spectrum arose in simulations both with and without star formation feedback, suggesting that even the 3D part of the turbulence, on scales smaller than the disk thickness, can arise entirely from a turbulent cascade from larger-scale 2D turbulence driven by disk gravity. The primary role of supernova and other young stellar feedback in these models was to break apart the dense clouds that form, preventing too much dense gas and too much star formation (i.e., the second process mentioned above). Models in Hopkins et al. (2011), Orr et al. (2018), and others in the FIRE simulation group also stress the importance of cloud-dispersing feedback to prevent too much star formation. This mode of young stellar feedback, which operates on the scale of giant molecular clouds, is distinct from that in Ostriker et al. (2010), which is proposed to operate on the scale of the disk thickness.

The cascade from large-scale 2D motions driven by disk self-gravity to small-scale 3D motions, including vertical motions that affect the scale height, was illustrated in Shi & Chiang (2014). They show in their Figure 9 how radial motions induced by disk gravity converge on a point and mix at high pressure, diverting some of the kinetic energy into the vertical direction. Their Figure 7 shows an increase in the velocity dispersion with vertical position in the disk. Shi & Chiang (2014) note that these high latitudes are not unstable by themselves but are forced to be turbulent by long-range gravitational forces from mass perturbations centered on the midplane. Observations of the variation of gas velocity dispersion with height in a galaxy might distinguish between gravity-driven turbulence and stellar-feedback-driven turbulence on the scale of the disk thickness.

Bournaud et al. (2009) show simulation results for self-gravitating disks that are more directly related to the observations here. Their Figure 4 plots the disk thickness versus radius in six model galaxies where turbulent forcing is entirely by disk gravity. The thickness is constant because the forcing by disk mass perturbations is proportional to the inertial response by the same mass. They compare this to external forcing by minor mergers, which produces a disk flare. The constant thicknesses of the starburst disks observed here could result from the same internal gravitational forcing, with star formation feedback playing a more local role in preventing excessively high gas densities and run-away star formation.

This discussion illustrates some of the complexities involved with feedback, including the many types of feedback. Sometimes an observation can support two or more physically distinct models. The KS relation is such an observation because it contains only the projected star formation rate and gas surface density and does not include additional information such as the velocity dispersion, which might be used to distinguish among the theories. A recent observation of star formation rates in gas-rich starburst galaxies similar to those
discussed here illustrates the ambiguity. Fisher et al. (2019) derive star formation rates, surface densities, pressures, and other quantities to test a feedback model of star formation. One result was that \( \Sigma_{\text{SFR}} \propto P^{0.75} \) for pressure \( P \), which is the same as the usual KS relation, \( \Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.5} \) if \( P \propto G \Sigma_{\text{gas}}^2 \) when stars and gas scale together, as they assume. Thus, we suspect their galaxies also have a constant disk thickness. Fisher et al. (2019) find

\[
\log(t_{\text{dep}}) = -1.04 \log(\sigma) + 1.71 \tag{11}
\]

for \( t_{\text{dep}} \) in Gyr and velocity dispersion \( \sigma \), in km s\(^{-1}\). If we let

\[
t_{\text{dep}} = t_{\text{ff}} / \epsilon_{\text{ff}} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} / \epsilon_{\text{ff}} \tag{12}
\]

and use Equation (11) to substitute \( \sigma \) for \( t_{\text{dep}} \) along with \( \epsilon_{\text{ff}} = 0.01 \), we obtain

\[
\sigma = 7.7 \times 10^{17} \rho^{1/2} \text{ (cgs units).} \tag{13}
\]

But from Equation (7),

\[
H = 0.5 - \frac{\sigma^2}{\pi G \Sigma_{\text{gas}}} = 2.97 \times 10^{35} \frac{\rho}{\pi G \Sigma_{\text{gas}}} = 2.97 \times 10^{35} \left( \frac{\Sigma_{\text{gas}}}{2H\pi G \Sigma_{\text{gas}}} \right) = 7.08 \times 10^{41}/H, \tag{14}
\]

from which we can multiply both sides by \( H \), take the square root, and convert to parsecs to obtain a constant (and relatively large) \( H = 270 \) pc. (A higher efficiency of \( \epsilon_{\text{ff}} = 0.05 \) would result in \( H = 54 \) pc.) Thus, the Fisher et al. (2019) result suggests a constant \( H \), which is unlike their preferred feedback model of Ostriker et al. (2010). This is not to say there is no star formation feedback, but that \( H \) may come from other types of kinetic energy input, and star formation feedback is too small-scale to dominate the turbulence that maintains \( H \) in our galaxies.

Other recent studies of the origin of interstellar turbulence have varying conclusions. Zhou et al. (2017) observed eight local galaxies and found no correlation between the turbulent speed and star formation rate per unit area. They also found that the turbulent speed was higher than what was expected from star formation alone and that additional sources are needed such as self-gravity, shear, and magnetic instabilities. Johnson et al. (2018) observed several hundred star-forming galaxies at small and intermediate redshifts and found a slight increasing trend of velocity dispersion with star formation rate density, but also suggested an important role for gravitational instabilities at high gas fractions in driving turbulence. Still, they could not distinguish between models where turbulence is driven by star formation feedback from those where turbulence is driven by self-gravity. Hung et al. (2019) model the turbulent speed as a function of cosmological redshift, including accretion, star formation feedback and disk self-gravity. They find that star formation bursts follow accretion bursts, but so does star formation feedback, and all three sources contribute to turbulence in different degrees at different times. Wu et al. (2019) also find that a combination of young stellar feedback and gravitational instabilities are required for the observed turbulence. On smaller scales, Jin et al. (2017) found in simulations that turbulence in Milky Way type molecular clouds can be a remnant of their formation by large-scale gravitational instabilities, without needing star formation feedback. Similarly, Vázquez-Semadeni et al. (2019) suggest that molecular cloud motions are gravitational in origin, although more like collapse than turbulence.

5. Conclusions

A new analysis of ALMA data for five luminous and ultraluminous infrared galaxies indicates that the KS relation for \( \Sigma_{\text{gas}} > 10^3 M_\odot \text{ pc}^{-2} \) has a slope of \( 1.74^{+0.09}_{-0.07} \), slightly steeper than the slope of the KS relation for total gas in main galaxy disks. Combining the molecular gas surface densities and velocity dispersions, we determine empirical gas scale heights of 150–190 pc, with little systematic variation over 1.5 orders of magnitude in \( \Sigma_{\text{gas}} \). This nearly constant scale height implies that the average midplane density varies almost linearly with the gas surface density, and thus the gas dynamical rate varies approximately with the square root of this surface density, giving the observed super-linear slope in the KS relation.

Star formation appears to be initiated by gravitational condensations in the average interstellar medium, with a rate given by the freefall time obtained from the square root of average density and the average density given by the ratio of the surface density to the disk thickness. Turbulent speeds that determine this thickness may also come from gravitational energy, pumped in by spiral arms and the associated shocks and by kiloparsec-scale Jeans instabilities. Star formation feedback then plays the essential role of halting the collapse at a high density so as to prevent all the gas from turning into stars in a freefall time. In this interpretation, star formation feedback helps regulate the efficiency per unit freefall time by partitioning the gas into a wide range of densities and dispersing the densest regions before they collapse completely.

Averaged over sufficiently large scales, the star formation rate is well approximated by the three-dimensional dynamical law, \( \epsilon_{\text{ff}} \rho_{\text{mid}}/H_{\text{ff}} \), for freefall time \( t_{\text{ff}} \) proportional to \( (G\rho_{\text{mid}})^{-0.5} \) and an approximately constant efficiency per unit freefall time, \( \epsilon_{\text{ff}} \). Because the disk thickness and \( \epsilon_{\text{ff}} \) are much more constant than either \( \Sigma_{\text{gas}} \) or \( \rho_{\text{mid}} \), integration over the thickness of the disk in starburst galaxies preserves the mathematical form of this law with the substitution of surface density for space density. This model is roughly similar in spiral galaxies, although it may be more complicated in the gas-dominated regions if the scale height varies significantly (e.g., Barnes et al. 2012; Elmegreen 2015; Elmegreen & Hunter 2015; Bacchini et al. 2019).

The reasons for the nearly constant values of \( \epsilon_{\text{ff}} \) and scale height \( H \) in these starbursts are not evident from the present observations although several possibilities were suggested in Section 4. Both are larger than in disk galaxies with lower star formation rates: \( \epsilon_{\text{ff}} \) by a factor of \( \sim 5–10 \) and \( H \) by a factor of \( \sim 2 \). However, these higher values barely affect the overall KS relation because the gas surface density and star formation rate per unit area vary by many orders of magnitude, and the higher \( \epsilon_{\text{ff}} \) and \( H \) found here partially cancel each other in the three-dimensional dynamical law of star formation.

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Facility: ALMA.

Software: astropy (Astropy Collaboration et al. 2013), CASA (McMullin et al. 2007).

Appendix

Binned Data Table

We provide the binned data used in this paper as a machine-readable table (Table 2). In this table, each row reports our measurements for one large pixel in one galaxy. The contents of the rows are as follows:

1. The name of the galaxy tagged with a pixel identifier, and the central coordinates of the pixel in decimal degrees.
2. The observed CO $J = 1-0$ CO velocity dispersion with its corresponding rms uncertainty.
3. The logarithmic value and logarithmic uncertainty for: the molecular gas surface density, $\Sigma_{mol}$; the star formation rate surface density, $\Sigma_{SFR}$; the depletion time, $\tau_{dep}$; the freefall time, $t_{ff}$; the efficiency per freefall time, $\epsilon_{ff}$; and the molecular gas scale height, $H$.

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**Table 2**

Binned Data Used in This Paper

| Name          | R.A. (°) | Decl. (°) | $\sigma_r$ (km s$^{-1}$) | $\sigma_{rot}$ (km s$^{-1}$) | $\log(\Sigma_{mol})$ (M$_\odot$ yr$^{-1}$) | $\sigma_{mol}$ (M$_\odot$ yr$^{-1}$) | $\log(\Sigma_{SFR})$ (M$_\odot$ yr$^{-1}$) | $\sigma_{SFR}$ (M$_\odot$ yr$^{-1}$) |
|---------------|---------|-----------|--------------------------|-----------------------------|-----------------------------------------|------------------------------------|------------------------------------------|-------------------------------------|
| ngc3256_0     | 156.96340 | -43.90599 | 77.91373                 | 2.38255                     | 2.76649                                 | 0.02179                             | 0.63557                                  | 0.03663                             |
| ngc4769_0     | 345.81550 | 8.87347   | 29.82338                 | 2.65686                     | 2.66638                                 | 0.02194                             | 0.54669                                  | 0.04438                             |
| iras13120_0   | 198.77642 | -55.15663 | 73.87565                 | 2.90342                     | 3.11749                                 | 0.02217                             | 1.4427                                   | 0.04147                             |
| iras17208_0   | 260.84161 | -28.3731  | 105.08624                | 5.254825                    | 3.32882                                 | 0.02874                             | 1.72986                                  | 0.05694                             |
| arp220_0      | 233.73872 | 23.50297  | 128.64619                | 3.54144                     | 3.61592                                 | 0.02194                             | 2.16013                                  | 0.02546                             |

(This table is available in its entirety in machine-readable form.)
