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Letter to the Editor

Dense gas scaling relations at kiloparsec ~~scale~~ scales across nearby galaxies with the ALMA ALMOND and IRAM ~~30-m~~ 30m EMPIRE surveys

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ABSTRACT

[Note 1: General notes: A.) I have edited to UK English spelling and grammar conventions. B.) A&A uses the past tense to describe specific steps used in a study and the present tense to describe general methods as well as findings, including the findings of recent papers (within the past ten or so years). Please make sure my edits are accurate in this respect throughout the paper. . *]** Dense, cold gas is the key ingredient for star formation. Over the last two decades, HCN(1–0) emission has been the most accessible dense gas tracer for studying external galaxies. We present new measurements that demonstrate the relationship between dense gas tracers, bulk molecular gas tracers, and star formation in the ALMA ALMOND survey, the largest sample of resolved ($1-2$ kpc resolution) HCN maps of galaxies in the local Universe ($d < 25$ Mpc). We measured HCN/CO, a line ratio sensitive to the physical density distribution, and the star formation rate to HCN ratio (SFR/HCN), a proxy for the dense gas star formation efficiency, as a function of molecular gas surface density, stellar mass surface density, and dynamical equilibrium pressure across 31 galaxies (a factor of > 3 more compared to the previously largest such study, EMPIRE). HCN/CO increases (slope of ≈ 0.5 and scatter of ≈ 0.2 dex) and SFR/HCN decreases (slope of ≈ -0.6 and scatter of ≈ 0.4 dex) with increasing molecular gas surface density, stellar mass surface density, and pressure. Galaxy centres with high stellar mass surface densities show a factor of a few higher HCN/CO and lower SFR/HCN compared to the

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disc average, but the two environments follow the same average trend. Our results emphasise that molecular gas properties vary systematically with the galactic environment and demonstrate that the scatter in the Gao–Solomon relation (SFR/HCN) has a physical origin.

Key words. ISM: molecules – Galaxies: ISM – Galaxies: star formation

1. Introduction

Stars form from the coldest, densest substructures within molecular clouds. ~~Higher-critical density~~ Higher-critical-density molecular lines (~~“~~‘dense gas tracers~~”~~’) trace this denser subset of molecular gas, in contrast to ~~that~~ the less dense gas probed by low-J CO lines**[Note 2: Verify that your intended meaning has not been changed. ***]** . The brightest and most commonly used extragalactic dense gas tracers are HCN$(1-0)$ and HCO$^+$$(1-0)$, hereafter HCN and HCO$^+$. A nearly linear correlation has been observed between the star formation rate (SFR) and dense gas tracer luminosity across a wide range of scales ~~(e.g., ?????)~~(e.g. **?????**). This has been interpreted ~~to indicate~~ as an indication that dense gas plays a regulating role ~~for dense gas~~ in the star formation process. This prompts the question ~~“what sets~~ of what determines the amount of dense gas~~?” Moreover, already in~~ . Moreover, these early studies ~~there have been suggestions~~ suggested that the rate of star formation per unit dense gas tracer luminosity or dense gas mass ($\mathrm{SFE_{dense}} \equiv \mathrm{SFR}/M_\mathrm{dense}$) is not universal, but varies from ~~galaxy-to-galaxy and location-to-location~~ galaxy to galaxy and location to location (**???**).

Recently, the first dense gas tracer mapping surveys that cover whole galaxies have emerged. The ~~IRAM-30m large program~~ IRAM **[Note 3: Consider defining. ***]** 30m large programme EMPIRE[1] (**???**) obtained ~~∼ kpc-resolution~~ approximately kiloparsec-resolution maps of dense gas tracers (HCN, HCO$^+$, and HNC$(1-0)$) ~~,~~ and CO isotopologues for nine nearby galaxies. The ALMA ALMOND[2] survey (**?**) used the Morita Atacama Compact Array (ACA) to map HCN, HCO$^+$, and CS$(2-1)$ emission from 25 nearby galaxies that ~~overlap~~ were also mapped by the PHANGS–ALMA**[Note 4: Consider defining. ***]** CO$(2-1)$ survey**[Note 5: Verify that your intended meaning has not been changed. ***]** (**?**). Meanwhile, a number of smaller surveys observed dense gas tracers in ~~small samples of 1–4~~ samples of one to four galaxies (e.g. **????????**).

These mapping surveys confirmed significant variations in the SFR/HCN and HCN/CO ratios. SFR/HCN serves as a proxy for the star formation efficiency in denser gas. HCN/CO contrasts high and low critical gas density tracers and so probes the physical density distribution. Both quantities correlate with the local stellar and gas surface density, dynamical equilibrium pressure, and other environmental factors. These variations have a regular sense**[Note 6: I don’t understand what you mean here by "a regular sense". Please rephrase ***]** , with denser gas (higher HCN/CO) and lower SFR/HCN in ~~high surface density~~high-surface-density, high-pressure regions (e.g. **?**).

[1] Eight MIxing Receiver (EMIR) Multiline Probe of the Interstellar medium (ISM) Regulating galaxy Evolution; https://empiresurvey.yourwebsitespace.com

[2] ACA Large-sample Mapping Of Nearby galaxies in Dense gas.

At face value, this implies an environment-dependent dense gas star formation efficiency and gas density across the discs of star-forming galaxies.

This ~~letter~~ Letter presents new measurements of HCN/CO and SFR/HCN as a function of local conditions for the 25 galaxies in the ALMA ALMOND survey, which is the largest mapping survey of dense gas tracers in galaxy discs. We ~~synthesise ALMOND~~ synthesised ALMOND **[Note 7: data? ***]** with the IRAM ~~30-m~~ 30m EMPIRE survey, the first large dense gas tracer mapping survey, to present a homogeneously measured set of kiloparsec-resolution scaling relations that connect star formation, dense gas, and total molecular gas to these local environmental quantities for a total of 31 local ~~,~~ spiral galaxies.

2. Data and methods

We ~~use~~ used the HCN data presented in **?**, EMPIRE and **?**, ALMOND. The two ~~data sets are well-matched in~~ datasets are well matched in terms of sensitivity and resolution (see Appendix A~~,~~ ; median 1.47 kpc, 16-84% range 1.09-1.76 kpc). We ~~convolve~~ convolved all supporting data to the angular resolution of the HCN observations using the PyStructure package[3]. We ~~sample~~ sampled all maps with a ~~half-beam spaced~~ half-beam-spaced hexagonal grid and ~~compute~~ computed the integrated intensities of the HCN and CO lines by integrating over a velocity range determined by the velocity extent of the CO emission. The velocity integration mask ~~is~~ was built from 4-sigma CO peaks and expanded into adjacent 2-sigma channels. We ~~treat~~ treated the ratios HCN/CO and SFR/HCN as the quantities of interest and ~~measure how these~~ measured how they vary as a function of the molecular gas mass surface density ($\Sigma_{\rm mol}$), stellar mass surface density ($\Sigma_\star$), and dynamical equilibrium pressure ($P_{\rm DE}$).

Galaxy sample. Table E.1 lists our targets, their integrated properties, survey coverage, and the resolution of the HCN observations. ALMOND and EMPIRE target nearby ($d < 25\,$Mpc), $i < 75°$, star-forming (SFR $\sim 0.2 - 17\,M_\odot\,{\rm yr}^{-1}$) galaxies, which span stellar masses from $8 \times 10^9\,{\rm M}_\odot$ to $1 \times 10^{11}\,{\rm M}_\odot$ and SFRs from $0.2\,{\rm M}_\odot\,{\rm yr}^{-1}$ to $17\,{\rm M}_\odot\,{\rm yr}^{-1}$. We stress that ALMOND significantly increases the dynamic range of SFR and $M_\star$ (by ~~$\sim$~~ approximately a factor of 2) compared to the previous largest sample (i.e. ~~,~~ EMPIRE; see Fig. 1). Combining the surveys yields 31 unique galaxies. NGC 628, 2903, and 4321 ~~overlap between surveysand yield consistent results~~ were observed by both surveys, and their measurements are consistent (see Appendix A). To avoid duplicates, we ~~employ~~ employed the ALMOND data for these galaxies.

Star formation rate. We estimate ~~kpc-scale~~ the kiloparsec-scale SFR and SFR surface density ($\Sigma_{\rm SFR}$) following the methodology of the original ALMOND paper (**?**), which ~~uses~~ used a combination of infrared (IR; 22 μm) maps from ~~WISE (**?**)~~ Wide-field Infrared Survey Explore (WISE; **?**) and far-ultraviolet (FUV~~,~~; 154 nm) maps from ~~GALEX (**?**)~~ Galaxy Evolution Explorer (GALEX; **?**)

[3] https://github.com/jdenbrok/PyStructure

Fig. 1. ALMOND and EMPIRE on the star-forming main sequence (SFMS) of galaxies. Grey shows all galaxies from the PHANGS–ALMA survey (**?**). Red and blue markers present galaxies from the EMPIRE (**?**) and ALMOND surveys (**?**), respectively, ~~adopting~~ with the same SFR calibration adopted across the merged sample. Contours indicate 25, 50, and 75 percentile areas of the respective samples. The ~~black~~ solid black line marks the star-forming main sequence from z0MGS (**?**). The black squares and crosses indicate the presence of a bar or ~~active galactic nucleus (~~AGN ~~)~~ in the respective galaxy, taken from Table E.1.

. These maps ~~are~~ were taken from the z0MGS atlas (**?**) and converted to SFR following their best FUV+22μm prescription. Although EMPIRE employed *Spitzer* and *Herschel* IR measurements to estimate the SFR, here we ~~adopt~~ adopted the same methodology across EMPIRE and ALMOND, using the FUV+22μ~~m based SFR maps across~~ m-based SFR maps for the full sample.

Stellar mass. We ~~estimate~~ estimated the stellar mass surface density ($\Sigma_\star$) from *Spitzer* 3.6 µm observations (**??**). We ~~use~~ used the dust-corrected maps from **?** and ~~adopt~~ adopted a mass-to-light ratio of $\Upsilon_\star = 0.6\,\mathrm{M}_\odot\,\mathrm{L}_\odot^{-1}$.

Dynamical equilibrium pressure. The dynamical equilibrium pressure (P_DE) expresses the total interstellar pressure needed to support a disc in vertical dynamical equilibrium ~~(e.g., see **??**). We estimate~~ (e.g. see **??**). We estimated P_DE by calculating the weight of the ~~ISM~~ interstellar medium in the galaxy potential via~~:~~

$$P_\mathrm{DE} = \frac{\pi G}{2}\Sigma_\mathrm{gas}^2 + \Sigma_\mathrm{gas}\,\sqrt{2G\rho_\star}\,\sigma_\mathrm{gas,z}\,, \tag{1}$$

where $\Sigma_\mathrm{gas} = \Sigma_\mathrm{mol} + \Sigma_\mathrm{atom}$ is the total gas surface density, $\rho_\star$ is the stellar mass volume density, and $\sigma_\mathrm{gas,z} = 15\,\mathrm{km\,s^{-1}}$ (e.g. **?**) is the gas velocity dispersion perpendicular to the galactic disc. Computing $\rho_\star$ ~~requires~~ required estimates of the stellar scale heights, which ~~are~~ were estimated from measured stellar disc scale lengths by assuming a typical disc flattening ratio (see **??**, for more details). Estimating P_DE additionally ~~requires~~ required measurements of the atomic gas content, which ~~have been~~ were taken from H I ~~21-cm line observation (all at similar or higher angular resolution than HCN),~~ 21 cm line observations (all with angular resolutions similar to or higher than that of HCN). These observations were available for 26 galaxies of our sample (Table E.1), hence limiting the analysis of P_DE relations to those 26 galaxies.

Conversion factors, molecular gas surface density, and dense gas fraction. We ~~focus~~ focused on the ratios HCN/CO and SFR/HCN. For reference~~we convert~~ , we converted them to fiducial physical quantities using fixed conversion factors, $\alpha_\mathrm{CO} \equiv M_\mathrm{mol}/L_\mathrm{CO} \equiv \Sigma_\mathrm{mol}/W_\mathrm{CO}$ and $\alpha_\mathrm{HCN} \equiv M_\mathrm{dense}/L_\mathrm{HCN} \equiv \Sigma_\mathrm{dense}/W_\mathrm{HCN}$, adopting $\alpha_\mathrm{CO}^\mathrm{fix} = 4.35\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}\,(\mathrm{K\,km\,s^{-1}})^{-1}$ (**?**) and $\alpha_\mathrm{HCN} = 15\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}\,(\mathrm{K\,km\,s^{-1}})^{-1}$ (**?**). Aside from aiming to remain ~~"~~'close to the observations~~", we do~~ ', we did this because the en-

Fig. 2. Gao–Solomon relation. ~~Star formation rate (~~SFR ~~,~~ (top) and SFR/$L_{\rm HCN}$ (a proxy of $\rm SFE_{dense}$ ~~,~~; bottom) as a function of HCN luminosity ~~,~~ across a literature compilation and the ALMOND (blue circles) and EMPIRE (red circles) surveys. Note that we ~~re-calculate~~ re-calculated the SFR across EMPIRE galaxies using a combination of IR and FUV data (see Sect. 2). Our literature compilation contains HCN observations that include Galactic clumps and clouds (squares), resolved nearby galaxies (circles), and unresolved entire galaxies (diamonds). For more details on the compilation, see Appendix B. The plotted data points show all (3-sigma) detected sightlines. The ~~black~~ solid black line shows the median SFR/HCN computed from these data points across all ~~data sets~~ datasets (without duplicates across targets), and the dashed lines mark the 1-sigma scatter (Table 1). The bottom panel shows the ratio SFR/HCN as a function of $L_{\rm HCN}$, grouping the data into the same ~~sub-samples where~~ subsamples, for which the 10-percentile density contours of the respective ~~sub-samples~~ subsamples are shown. We plot ALMOND and EMPIRE data separately, and the blue and red contours present the 10-percentile levels of these surveys.

Table 1. Gao–Solomon relation.

Regime	$\log_{10}$ SFR/HCN $[\rm M_\odot\,yr^{-1}/(K\,km\,s^{-1}\,pc^2)]$ ($16^{\rm th}$, $50^{\rm th}$, $84^{\rm th}$) perc.	$\log_{10}$ IR/HCN $[\rm L_\odot/(K\,km\,s^{-1}\,pc^2)]$ ($16^{\rm th}$, $50^{\rm th}$, $84^{\rm th}$) perc.	$\log_{10}\ \tau_{\rm dep}^{\rm dense}$ [yr] ($16^{\rm th}$, $50^{\rm th}$, $84^{\rm th}$) perc.	σ [dex]
Clouds & Clumps	(−7.43, −6.89, −6.27)	(2.40, 2.94, 3.56)	(7.45, 8.07, 8.61)	0.70
Parts of Galaxies	(−7.23, −6.98, −6.65)	(2.60, 2.85, 3.18)	(7.82, 8.16, 8.41)	0.46
Entire Galaxies	(−7.16, −6.85, −6.56)	(2.67, 2.98, 3.27)	(7.74, 8.03, 8.33)	0.27
Combined	(−7.17, −6.87, −6.48)	(2.66, 2.96, 3.35)	(7.66, 8.05, 8.34)	0.52
ALMOND & EMPIRE	(−7.14, −6.84, −6.44)	(2.69, 2.99, 3.39)	(7.62, 8.02, 8.31)	0.35

Notes – Median dense gas ratios across the combined literature sample presented in Fig. 2, including ALMOND and EMPIRE, and for respective ~~sub-samples~~subsamples, including clouds ~~/clumps ,~~ and clumps and resolved and integrated galaxy surveys. The values across the 'Parts of Galaxies' studies are computed from unique targets ~~(i.e., **??????**, to avoid target duplication)~~ (i.e. **??????**, to avoid target duplication). The 'Combined' measurements are computed from the medians of each respective study. 'ALMOND & EMPIRE' results ~~are~~ were obtained from the medians of each respective galaxy (i.e. from 31 galaxies) and consider non-detections (in contrast to the other columns, which only consider 3-sigma detected data). All values are ~~displayed~~ on a logarithmic scale. Columns 2 and 3 list the 16th percentiles, medians, and 84th percentiles of $\log_{10}$ SFR/HCN and $\log_{10}$ IR/HCN. ~~Columns~~ Column 4 displays the dense gas depletion time ($\tau_{\rm dep}^{\rm dense}$) in units of years ~~and column~~ , and Col. 5 the 1-sigma scatter (σ) of the detected HCN data around the median value in units of dex. See Appendix B ~~regarding the~~ for details of the compilation.

vironmental dependence of the ~~HCN to dense~~ HCN-to-dense gas conversion factor, $\alpha_{\rm HCN}$, remains unclear, with no obvious best prescription and likely significant covariance with $\alpha_{\rm CO}$ (see **?**).

Nevertheless, to leverage recent progress in understanding $\alpha_{\rm CO}$ variations, we ~~employ~~ employed a variable $\alpha_{\rm CO}$ (hereafter $\alpha_{\rm CO}^{\rm var}$) when considering molecular gas surface density, $\Sigma_{\rm mol}$, or dynamical equilibrium pressure ($P_{\rm DE}$; see the paragraphs below) as independent variables (i.e. ~~,~~ on the x-axis). We ~~calculate~~ calculated

$$\left(\frac{\Sigma_{\rm mol}}{\rm M_\odot\,pc^{-2}}\right) = \alpha_{\rm CO}^{\rm var}\left(\frac{W_{\rm CO}}{\rm K\,km\,s^{-1}}\right)\cos(i)\ , \qquad (2)$$

adopting the ~~the~~ $\alpha_{\rm CO}^{\rm var}$ prescription from **?**. This $\alpha_{\rm CO}^{\rm var}$ depends on metallicity and $\Sigma_\star$ ~~. See~~ (see Appendix C for more details on the variable conversion factor and line ratio prescriptions, including references to the works synthesised by ~~?~~**?**).

When quoting HCN/CO, we cast our results in terms of CO(1 − 0) and ~~employ~~ employed the CO(2 − 1)/CO(1 − 0) line ratio calibration as a function of $\Sigma_{\rm SFR}$ to convert PHANGS–ALMA CO(2 − 1) ~~into~~ to CO(1 − 0) intensities (see Appendix C). EMPIRE already has CO(1 − 0) maps.

For both quantities, we provide reference conversions to physical units. We ~~calculate the "~~calculated the 'dense gas fraction~~"~~' as the ratio between dense and bulk molecular gas using ~~these~~ fixed conversion factors, $f_{\rm dense} \equiv M_{\rm dense}/M_{\rm mol} \propto$ HCN/CO~~:~~, as

$$f_{\rm dense} \approx 3.5 \left(\frac{W_{\rm HCN}}{\rm K\,km\,s^{-1}}\right)\left(\frac{W_{\rm CO}}{\rm K\,km\,s^{-1}}\right)^{-1} . \tag{3}$$

~~We convert~~ We converted SFR/HCN to an approximate star formation efficiency of dense molecular gas, $\rm SFE_{dense} \equiv SFR/M_{dense}$, via~~:~~

$$\left(\frac{\rm SFE_{dense}}{\rm yr^{-1}}\right) \approx 6.7\times10^{-2}\left(\frac{\Sigma_{\rm SFR}}{\rm M_\odot\,yr^{-1}\,pc^{-2}}\right)\left(\frac{W_{\rm HCN}}{\rm K\,km\,s^{-1}}\right)^{-1} . \tag{4}$$

3. Results and discussion

3.1. Gao–Solomon relation

In Fig. 2 we present the ~~"~~'Gao–Solomon~~"~~' relation (**?**), the scaling relationship between SFR and $L_{\rm HCN}$. We ~~place~~ placed ALMOND and EMPIRE in the context of a literature compilation that comprises 31 HCN surveys spanning from the Milky Way to the high-redshift universe. This includes observations of individual cores and molecular clouds within the Milky Way and the Local Group, spatially resolved maps of galaxies, and integrated galaxy data. On the x- and y-axes, we indicate both the observed luminosities (HCN and IR) and the inferred physical quantities ($M_{\rm dense}$ and SFR), assuming linear conversions with fixed conversion factors $\alpha_{\rm HCN}$ and $C_{\rm IR}$[4]. ALMOND and EMPIRE form the largest resolved galaxy ~~data set~~dataset, filling in the large gap in spatial scale, SFR, and $L_{\rm HCN}$ between ~~the~~ integrated galaxy and individual cloud studies.

In the bottom panel of Fig. 2, the y-axis displays the ratio between SFR and $L_{\rm HCN}$. Across the full literature sample, we find a median SFR/HCN of $1.3\times10^{-7}\,\rm M_\odot\,yr^{-1}\,(K\,km\,s^{-1}\,pc^2)^{-1}$ with a 1-sigma scatter of 0.52 dex, which is consistent with previous literature compilations ~~(e.g., **??**)~~ (e.g. **??**). We also ~~compute~~ computed the respective median $\rm SFE_{dense}$ values and scatter for the individual ~~sub-samples~~subsamples: clumps and clouds (squares), resolved galaxy observations (circles), and entire galaxies (diamonds). The values, along with the values specifically for ALMOND and EMPIRE, are listed in Table 1. Overall, the literature compilation demonstrates that the HCN luminosity is a reasonable predictor of the SFR from cloud to galaxy ~~scale across 10~~ scales across

[4] All data here have observed HCN, but for the y-axis we ~~adopt~~ adopted the best-estimate SFR and ~~convert~~ converted it to the equivalent $L_{\rm IR}$ using a constant IR-to-SFR conversion factor, $C_{\rm IR} = 1.48\times10^{-10}\,\rm M_\odot\,yr^{-1}\,L_\odot^{-1}$ (**?**)**[Note 8: Verify that your intended meaning has not been changed. ***]** .

Fig. 3. Dense gas relations with a kiloparsec-scale environment. HCN/CO *(top)*, a proxy of $f_{\rm dense}$, and SFR/HCN *(bottom)*, a proxy of $\rm SFE_{dense}$, are shown as a function of stellar mass surface density ($\Sigma_\star$), molecular gas surface density ($\Sigma_{\rm mol}$), and dynamical equilibrium pressure ($P_{\rm DE}$) across 31 galaxies from ALMOND and EMPIRE. The markers denote significant stacked measurements (S/N $\geq$ 3) ~~stacked measurements~~ across disc (circle) and centre (triangle) spaxels. The downward and upward pointing arrows denote upper (HCN/CO) and lower limits (SFR/HCN). Filled contours show 25, 50, and 75 percentile kernel density estimates. Across centres, we indicate the presence of an AGN (cross). All relations have been fitted with `LinMix`, taking ~~into account~~ measurement uncertainties and upper ~~/~~and lower limits into account (parameters in Table 2). The ~~black~~ solid black line shows the best-fit line, and the grey-shaded area indicates the 1-sigma scatter of S/N $\geq$ 3 data. The right panels show violin plots of the HCN/CO and SFR/HCN distribution across the respective samples (disc, centre, centre with ~~AGN~~AGNs**[Note 9: or "an AGN". ***]**), where the black bar and white markers indicate the 25th to 75th percentile range and the median, respectively, across the S/N $\geq$ 3 data. The vertical cyan lines in the disc violins mark the median computed from all S/N data.

ten orders of magnitude. However, at any given HCN luminosity, there is a significant scatter, $\sigma \sim 0.5$ dex. Moreover, the scatter increases from large (entire galaxy; $\sigma = 0.27$ dex) to small scales (clouds; $\sigma = 0.70$ dex), suggesting that there are significant variations ~~of~~ in $\rm SFE_{dense}$ within galaxies (discussed in Sect. 3.2) that average out at integrated galaxy scales.

SFR/HCN can be interpreted, with significant uncertainty due to the uncertain conversion factor, as the rate per unit mass at which dense molecular gas converts into stars. Across the detected sightlines of the full literature sample, we find a median $\rm SFE_{dense} \approx 8.9 \times 10^{-9}\,yr^{-1}$, or equivalently ~~,~~ a median dense gas depletion time of $\tau_{\rm dep}^{\rm dense} \approx 112$ Myr, indicating that the rate of present-day star formation would consume the available dense gas in this time period. For reference, this is ≈ 10 times lower than estimates for $\tau_{\rm dep}^{\rm mol}$, the overall molecular gas depletion time in similar samples (**?**). The star formation efficiency per ~~free-fall~~ freefall time, $\epsilon_{\rm ff}^{\rm dense} = {\rm SFE_{dense}} \cdot t_{\rm ff}^{\rm dense}$, is of theoretical interest ~~(e.g., **??**)~~ (e.g. **??**) because it captures the efficiency of star formation relative to the timescale expected for gravitational collapse, and so ~~normalizes~~ normalises for density. The ~~free-fall~~ freefall time of the dense molecular gas ~~is~~ was computed as $t_{\rm ff}^{\rm dense} = 0.8$ Myr, assuming that HCN traces gas above a density of $n_{\rm H_2}^{\rm dense} \approx 3 \times 10^3\,{\rm cm^{-3}}$ (**??**). Across the full literature sample, we obtain a median $\epsilon_{\rm ff}^{\rm dense} \approx 0.7\,\%$, which suggests that only 0.7 % of the dense molecular gas is converted into stars per gravitational collapse timescale. This demonstrates that even in the dense gas, star formation appears to be an extremely inefficient process.

3.2. Dense gas relations with the environment

Figure 2 shows significant scatter in SFR/HCN. Previous works ~~find~~ have found that both SFR/HCN and HCN/CO depend systematically on environmental factors, including the stellar mass surface density ($\Sigma_\star$), the molecular gas mass surface density (Σ_{mol}), and the interstellar pressure inferred from dynamical equilibrium (P_{DE}; **???**). The combined ALMOND and EMPIRE samples are ideal ~~to measure~~ for measuring these environmental variations. Individual regions follow the overall Gao–Solomon relation and show a comparable scatter to the full literature sample. The ~~resolution of ~ kiloparsec~~ kiloparsec-scale resolution is, on the one hand, high enough to resolve galaxies into discrete regions~~like~~, including centres, bars, and spiral arms~~and~~, but is, on the other hand, coarse enough to average over many individual regions to access the time-averaged mean HCN/CO and SFR/HCN.

In Fig. 3 we use ALMOND and EMPIRE to make the most rigorous measurement to date of the scaling relations relating HCN/CO and SFR/HCN to these environmental factors. For each galaxy we spectrally ~~stack~~ stacked the HCN(1 – 0) and CO(1 – 0) lines in bins of $\Sigma_\star$, Σ_{mol}, and P_{DE} using `PyStacker`[5]. We ~~use~~ used the CO data, which ~~has~~ have a much higher signal-to-noise ratio than the HCN, to determine the local mean reference velocity for the stacks (see **?**, and references therein for details on the spectral stacking methodology; Appendix D presents the spectral stacks of HCN and CO). For bins in which the stacks do not yield 3-sigma HCN detections, we ~~estimate~~ estimated upper limits for HCN/CO and lower limits for SFR/HCN. We ~~fit~~ fitted the combined set of stacks (including upper limits) for all galaxies using a linear function of the form ~~:~~

$$\log_{10} Y = b + m \cdot (\log_{10} X - x_0)\ , \tag{5}$$

where $X = \{\Sigma_\star, \Sigma_{\mathrm{mol}}, P_{\mathrm{DE}}\}$ and $Y = \{\mathrm{HCN/CO}, \mathrm{SFR/HCN}\}$ are the x- and y-axis variables, respectively. The slopes and intercepts are denoted as m and b, and $x_0 = \{2.4, 1.4, 5.0\}$ is a value close to the median X value. ~~Centering~~ Centring the fit at x_0 minimises the covariance between m and b. The fitting ~~is~~ was performed with the linear regression tool `LinMix`[6], which takes ~~into account~~ measurement uncertainties and 3-sigma upper (lower) limits on HCN/CO ~~(SFR/HCN; see e.g. **?**, for more details on the fitting routine)~~ (SFR/HCN) into account (see e.g. **?**, for more details on the fitting routine). The fit parameters are presented in Table 2. ~~Note~~ We note that the range of $\Sigma_\star$, Σ_{mol}, and P_{DE} covered by these results corresponds to the ~~molecular gas dominated, inner~~inner, molecular-gas-dominated parts of galaxies, where most stars form.

We ~~measure~~ find strong correlations between the stacked HCN/CO and all three quantities, and anti-correlations between SFR/HCN and the same quantities (Fig. 3 and Table 2). HCN/CO increases ~~, while~~ and SFR/HCN decreases with increasing $\Sigma_\star$, Σ_{mol}, and P_{DE}. The slopes are significant, with both HCN/CO and SFR/HCN changing by ~ 1 dex across our sample. ALMOND and EMPIRE ~~show~~ have consistent results despite using different telescopes and using different CO lines (see Appendix A).

The enhanced HCN/CO in ~~high-surface density~~high-surface-density, high-pressure environments indicates that a deeper gravitational potential and more abundant overall molecular gas lead

[5] https://github.com/PhangsTeam/PyStacker
[6] https://github.com/jmeyers314/linmix

Table 2. Dense gas tracer and environment in ALMOND and EMPIRE.

$\log_{10}(Y)$	$\log_{10}(X)$	x_0	m (unc.)	b (unc.)	σ	$r_{\rm Pearson}$
	$\Sigma_\star$	2.4	0.55 (0.03)	−1.71 (0.01)	0.21	0.77
HCN/CO	$\Sigma_{\rm mol}$	1.4	0.65 (0.05)	−1.79 (0.02)	0.23	0.70
	$P_{\rm DE}/k_{\rm B}$	5.0	0.48 (0.04)	−1.81 (0.02)	0.22	0.76
	$\Sigma_\star$	2.4	−0.61 (0.04)	−6.84 (0.02)	0.28	−0.70
SFR/HCN	$\Sigma_{\rm mol}$	1.4	−0.67 (0.08)	−6.77 (0.02)	0.34	−0.56
	$P_{\rm DE}/k_{\rm B}$	5.0	−0.55 (0.05)	−6.73 (0.03)	0.34	−0.66

Notes – Fit parameters obtained via linear regression with `LinMix` via ~~Equ~~Eq. 5 to the data shown in Fig. 3. The parameters x_0, m, ~~b~~ b, and σ are the ~~x–axis~~ x-axis offset, slope, intercept, and scatter of the relation. $r_{\rm Pearson}$ denotes the Pearson correlation coefficient~~, where all p–values are much smaller~~ ; all p-values are much less than 0.01. $\Sigma_\star$ and $\Sigma_{\rm mol}$ are given in units of $\mathrm{M_\odot\,pc^{-2}}$; and $P_{\rm DE}/k_{\rm B}$ in $\mathrm{K\,cm^{-3}}$.

to the formation of denser molecular clouds. This picture agrees well with the one that has emerged from ~~high physical resolution~~ high-physical-resolution CO imaging, which shows that the mean cloud-scale gas surface density and velocity dispersion correlate with these same environmental factors (**?**). In fact, one of the main results from ALMOND has been a good direct correlation between the cloud-scale gas properties and the density-sensitive HCN/CO line ratio (**?**). ~~Indeed, the~~ The fact that spectroscopic (presented here) and CO imaging results show similar trends as a function of galactic environment provides strong evidence that the physical properties of molecular clouds vary ~~in their physical properties~~ as a function of the galactic environment. The HCN/CO variations that we observe are continuous across the whole range of our sample, with a ~ 0.2 dex scatter about the correlation.

SFR/HCN anti-correlates with $\Sigma_\star$, $\Sigma_{\rm mol}$, and $P_{\rm DE}$. This anti-correlation is also significant, though the correlation coefficient is weaker, and the data show more residual scatter in SFR/HCN compared to the trends in HCN/CO. At face value, this indicates that the denser molecular gas that effectively emits HCN is less efficiently converted to stars in ~~high surface density~~high-surface-density, high-pressure parts of galaxies. A popular explanation for this trend has been that HCN-emitting material in these denser environments does not necessarily uniquely correspond to the overdense, self-gravitating parts of clouds that collapse to form stars (e.g. **??????**)

3.3. Dense gas ratios in galaxy centres

The centres of galaxies often exhibit high $\Sigma_{\rm mol}$, $\Sigma_\star$, and $P_{\rm DE}$ ~~, hence~~; hence, one expects high HCN/CO and low SFR/HCN in galaxy centres compared to the discs. In Fig. 3 we separately indicate galaxy centres in contrast to the rest of the galaxy. For this exercise, we ~~consider~~ considered the central kiloparsec-scale, ~~beam size~~ beam-size aperture as the centre and refer to the remaining galaxy parts as the disc.

We find that centres typically have high HCN/CO (median of 0.045 compared to the disc median of 0.013~~, which~~) that are not consistent within the 1-sigma scatter ~~;~~ (Table E.2) and low SFR/HCN (median of $7.8\times10^{-8}\,\mathrm{M_\odot\,yr^{-1}\,pc^{-2}\,(K\,km\,s^{-1})^{-1}}$ compared to the disc median of

$1.3 \times 10^{-7}\,\mathrm{M_\odot\,yr^{-1}\,pc^{-2}\,(K\,km\,s^{-1})^{-1}}$ ~~,~~ (but overlapping 1-sigma intervals)**[Note 10: Verify that your intended meaning has not been changed. ***]** . In the following, we base our discussion of the centre-disc comparison on the relations with $\Sigma_\star$, which have uncorrelated axes, in contrast to the relations with $\Sigma_{\rm mol}$ and $P_{\rm DE}$, which depend on the CO line intensity. To first order, centres appear to follow the same average HCN/CO and SFR/HCN against $\Sigma_\star$ trend, showing a continuous extension of the disc trends~~,~~. The higher HCN/CO (lower SFR/HCN) in galaxy centres then simply results from the high $\Sigma_\star$ ($\Sigma_{\rm mol}$, $P_{\rm DE}$) environment of centres. However, there are some deviations from this simple picture in the SFR/HCN against $\Sigma_\star$ relation. On the one hand, the disc measurements in intermediate $\Sigma_\star$ environments ($\Sigma_\star \approx 2 \times 10^2\,\mathrm{M_\odot\,pc^{-2}} - 1 \times 10^3\,\mathrm{M_\odot\,pc^{-2}}$) tend to have low SFR/HCN compared to the average trend, while centres show high SFR/HCN across the same $\Sigma_\star$ range. These deviations could be explained via variations with dynamical environments ~~(e.g. **?**, found a low SFR/HCN in the galactic bar),~~ (e.g. **?** found a low SFR/HCN in the galactic bar) but remain speculative due to the coarse, ~~kiloparsec~~ kiloparsec-scale resolution of the ALMOND and EMPIRE observations and hence require higher-resolution observations that resolve these morphological regions.

If taken at face value, the low $\mathrm{SFE_{dense}}$ in galaxy centres could imply that these environments are typically less ~~efficiently~~ efficient at forming stars per unit of dense gas mass, which could be explained by the higher gas turbulence in these environments acting against gravitational collapse ~~(e.g., **??**)~~(e.g. **??**). However, a similarly likely explanation is that HCN might not be a robust tracer of dense gas in galaxy centres ~~(e.g.,~~ – for example due to increased optical depth, ~~infrared pumping , e.g. **?**,~~ IR pumping (e.g. **?**), or electron excitation, ~~e.g. **?**)~~ (e.g. **?**) – and potentially trace more of the bulk gas in these high-density regions (see the explanation above). Therefore, we might expect ~~that~~ $\alpha_{\rm HCN}$ ~~varies~~ to vary between disc and centre regions. For instance, if one assumes that $\alpha_{\rm HCN}$ variations are driven by optical depth effects and vary similarly to $\alpha_{\rm CO}$ (**??**), $\alpha_{\rm HCN}$ would be lower in galaxy centres and thus yield higher $\mathrm{SFE_{dense}}$ that are more comparable to disc values.

One might expect that active galactic nuclei (~~AGN~~AGNs) boost HCN emission ~~(e.g., **??**)~~(e.g. **??**) , deplete gas (e.g. **?**), or quench star formation ~~(e.g., **?**)~~(e.g. **?**). In Fig. 3 we additionally indicate the presence of an AGN (cross; 14 galaxies) for the galaxy centres and show their median and distribution in the right panels. We find that active centres have 50 % higher HCN/CO and lower ~~SFR~~SFRs, though distributions are similar to those found in non-active galaxies and the differences are not significant at the 1-sigma level. ~~Likely, the variations of~~ The variations in dense gas and star formation in AGN-affected regions are likely not well resolved at the scales ~~($\sim 1-2$ kpc)~~ probed in this study ~~and require sub-kiloparsec resolution~~ ($\sim 1-2$ kpc) and require sub-kiloparsec-resolution observations.

4. Conclusions

We present the resolved 1–2 kpc resolution dense gas tracer scaling relations for ALMA ALMOND, a survey of HCN emission from 25 star-forming disc galaxies. Combining ALMOND with the IRAM ~~30-m~~ 30m EMPIRE survey, we ~~measure~~ measured how HCN/CO and SFR/HCN, observational quantities sensitive to the gas density and star formation efficiency of dense gas, depend on the local stellar and molecular gas mass surface density ($\Sigma_\star$ and $\Sigma_{\rm SFR}$) and the estimated dynamical equilibrium pressure ($P_{\rm DE}$). Our total sample of 31 resolved galaxies represents a factor of > 3 increase compared to the previous state-of-the-art**[Note 11: There is a word missing here. "survey"? ***]** . HCN/CO correlates with all three environmental measures, showing similar trends to those found for cloud-scale (∼ 100 pc) CO imaging. Our results support the view that the physical state of molecular gas depends on the galactic environment. SFR/HCN anti-correlates with surface density and $P_{\rm DE}$, though ~~these~~ they show moderately more scatter than the HCN/CO correlations. This reinforces the notion that the scatter in the ~~Gao-Solomon~~ Gao–Solomon relation is physical in origin and that the relation between any specific dense gas tracer and star formation activity ~~appears~~ is environment-dependent. While the physical explanations for each of these trends remain subjects of active research, their presence in the data is clear, and ALMA ALMOND + IRAM ~~30-m~~ 30m EMPIRE provides the best measurement to date in the ~~molecular gas-dominated~~molecular-gas-dominated, star-forming parts of massive disc galaxies.

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ADS/JAO.ALMA#2012.1.00650.S,
ADS/JAO.ALMA#2013.1.01161.S,
ADS/JAO.ALMA#2015.1.00925.S,
ADS/JAO.ALMA#2015.1.00956.S,
ADS/JAO.ALMA#2017.1.00230.S,
ADS/JAO.ALMA#2017.1.00392.S,
ADS/JAO.ALMA#2017.1.00766.S,
ADS/JAO.ALMA#2017.1.00815.S,
ADS/JAO.ALMA#2017.1.00886.L,
ADS/JAO.ALMA#2018.1.01171.S,
ADS/JAO.ALMA#2018.1.01651.S,
ADS/JAO.ALMA#2018.A.00062.S.
ADS/JAO.ALMA#2019.2.00134.S,
ADS/JAO.ALMA#2021.1.00740.S,
ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work makes use of data products from the ~~*Wide-field Infrared Survey Explorer (WISE)*~~Wide-field Infrared Survey Explorer (WISE), which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by NASA. This work is based in part on observations made with the ~~*Galaxy Evolution Explorer (GALEX). GALEX*~~ Galaxy Evolution Explorer (GALEX). GALEX is a NASA Small Explorer, whose mission was developed in cooperation with the Centre National d'Etudes Spatiales (CNES) of France and the Korean Ministry of Science and Technology. ~~*GALEX*~~ GALEX is operated for NASA by the California Institute of Technology under NASA contract NAS5-98034.

Data availability

The HCN and CO data products used in this paper are publicly available via `https://www.iram.fr/ILPA/LP015/` (EMPIRE), `https://www.canfar.net/storage/list/phangs/RELEASES/`

ALMOND/ (ALMOND), and https://www.canfar.net/storage/list/phangs/RELEASES/PHANGS-ALMA/ (PHANGS–ALMA). The HCN literature compilation, data products and tables presented in this work are publicly available via https://www.canfar.net/storage/list/phangs/RELEASES/Neumann_etal_2024b/. The Python scripts used to create the data products, figures and tables are available via https://github.com/lukas-neumann-astro/publications/tree/main/Neumann_etal_2024b/.

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List of Objects

Appendix A: EMPIRE ~~vs~~ versus ALMOND

There are three galaxies (i.e. NGC 628, NGC 2903, NGC 4321) that have been mapped in dense gas tracers (e.g. HCN(1 – 0)) by both surveys, EMPIRE, using the IRAM 30 m, and ALMOND, using

Fig. A.1. EMPIRE versus ALMOND: HCN(1 – 0) average spectra. The blue and red lines show average HCN brightness temperatures within $r_{\rm gal} \leq 5$ kpc obtained from spatially and spectrally matched ALMOND and EMPIRE observations, respectively, across the three galaxies NGC 628, NGC 2903, NGC 4321 from top to bottom. The grey dashed line shows (homogenised) CO(2 – 1) intensities from PHANGS–ALMA (**?**), scaled down by a factor of 20. The grey-shaded area indicates the velocity-integration window constructed using the highly significant CO(2 – 1) data. The resulting integrated intensities are quoted in the text.

the ACA at similar spectral (a few km s^{-1}) and angular resolution (a few tenths of arcseconds) and sensitivity (a few mK). In Figs. A.1 to A.3 we compare the HCN(1 – 0) data from both surveys. We homogenise the two ~~data sets~~ datasets by convolving to the best common spectral (i.e. 10 km s^{-1}) and spatial (i.e. 33″) resolution and ~~reproject~~ re-project to the same half-beam size hexagonal pixel grid.

Figure A.1 shows average HCN(1 – 0) spectra computed across all sightlines within 5 kpc from the galactic centre. We additional overlay CO(2 – 1) average spectra obtained from PHANGS–ALMA (**?**), to indicate molecular line emission from a highly significant tracer. This line has been used to infer the velocity-integration window from which we compute HCN(1 – 0) integrated intensities of 41.6 ± 7.3 K km s^{-1}, 39.5 ± 10.7 K km s^{-1} in NGC 628, 427.8 ± 47.5 K km s^{-1}, 495.7 ± 143.5 K km s^{-1} in NGC 2903, and 475.0 ± 34.6 K km s^{-1}, 570.2 ± 84.8 K km s^{-1} in NGC 4321 from ALMOND and EMPIRE, respectively. The average spectra show similar shape and amplitude, demonstrating little to no bias between ALMOND and EMPIRE observations. The integrated line intensities yield consistent values within their uncertainties. The largest deviations are observed at large velocity offsets from the galaxies' ~~systemtic~~ systematic velocities, potentially linked to poor baseline subtraction.

Figures A.2 and A.3 present a voxel-by-voxel, or pixel-by-pixel comparison between the ALMOND and EMPIRE HCN(1 – 0) brightness temperatures (ppv cube) and integrated intensities (moment-0 map). We find that brightness temperatures and integrated intensities agree well between ALMOND and EMPIRE in all galaxies (deviations $\leq$ 50 % across most detected sightlines) and show little bias ($\leq$ 10 % on average across all data). At lower integrated intensities ($\lesssim 10^{-1}$ K km s^{-1}), EMPIRE yields moderately larger values than ALMOND, which could indicate differences in the calibration and data reduction pipelines.

The comparison between ALMOND and EMPIRE demonstrated that both ~~data sets~~ datasets yield consistent HCN(1 – 0) intensities and subsequent data products. In this work, we employ the ALMOND data for the three galaxies NGC 628, NGC 2903, NGC 4321, due to the slightly better angular resolution and sensitivity of the ALMOND survey.

Figure A.4 shows the HCN/CO and SFR/HCN versus $\Sigma_\star$, $\Sigma_{\rm mol}$, and $P_{\rm DE}$ scaling relations across ALMOND (blue hexagons) and EMPIRE (red circles) at kiloparsec resolution. Our best-fit relations are similar, though slightly steeper, to those reported by **?** but are now measured for a larger

Fig. A.2. EMPIRE versus ALMOND: HCN(1 – 0) brightness temperature. Green data points present data, where EMPIRE and ALMOND both yield a 3-sigma detection. Grey data shows low-significant data points. The dashed line marks the 1-to-1 relation, where the dotted lines indicate a ±50 % deviation.

Fig. A.3. EMPIRE versus ALMOND: HCN(1 – 0) integrated intensity. Similar to Fig. A.2, but showing the integrated intensities (moment-0) computed across a CO-inferred velocity integration window. Orange and grey points denote data above and below 3-sigma, respectively.

Fig. A.4. Similar to Fig. 3, but separately showing kiloparsec-scale, stacked measurements from ALMOND (blue hexagons) and EMPIRE (red circles). The best-fit line (solid black line) and the corresponding 1-sigma scatter (grey-shaded area) are computed from the combined data using `LinMix`.

and more diverse sample of galaxies. The steeper slopes have two reasons: a) the ALMOND sample shows steeper trends, and (b) the inclusion of non-detections into the fitting routines yields ∼ 10 % steeper slopes. We observe a larger scatter across the full sample of 31 galaxies compared to the nine EMPIRE galaxies alone, suggesting that the more diverse sample captures a wider range of conditions not captured by the simple scaling relations.

Appendix B: Dense gas literature

In Fig. 2 we present a literature compilation of HCN surveys from local parsec scale over resolved, kiloparsec scale, to unresolved, entire galaxy observations. The cloud- and clump-scale measurements are taken from observations within the Milky Way (**????**), the CMZ (**??**), and the Local Group, ~~i.e. LMC /SMC~~ namely LMC and SMC **[Note 12: Consider defining. ***]** (**??**), M31 (**?**), M33 (**?**), and low-metallicity local group galaxies (**?**). Resolved galaxy observations, typically from nearby galaxies at 100 pc to 2 kiloparsec scales, include M82 (**?**), M51 (**????**), NGC 4038/39 (**?**), NGC 3351, NGC 3627, NGC 4254, NGC 4321, NGC 5194 (**?**), NGC 3627 (**?**), NGC 1068 (**?**), NGC 6946 (**?**), NGC 4321 (**?**), NGC 253 (**?**), and the two larger-sample surveys EMPIRE (nine galaxies; **?**) and ALMOND (25 galaxies; **?**). Integrated-galaxy data cover LIRG ~~/ULIRG~~ and ULIRG **[Note 13: Consider defining. ***]** and AGN galaxies (**?????**), early-type galaxies (**?**), and high-redshift galaxies (**??**).

Appendix C: Conversion factors

For EMPIRE, we use the CO(1 – 0) maps obtained as part of the survey. For ALMOND, we use PHANGS–ALMA CO(2 – 1) maps, which we convert to an equivalent CO(1 – 0) intensity before applying α_{CO}. To do this, we estimate a line ratio, R_{21}, based on the local SFR surface density

Fig. D.1. Spectral stacks of CO (olive) and HCN (purple) across NGC 4321 in logarithmically-spaced bins of $\Sigma_\star$. The grey-shaded area indicates the velocity-integration window applied to compute the integrated intensities of the stacked spectra. The labelled boxes show the peak intensity and S/N of the integrated intensities of CO and HCN, respectively, for each stacked spectrum.

($\Sigma_{\rm SFR}$) following ~~????~~?, ?, and ?:

$$R_{21} = \frac{\mathrm{CO}(2-1)}{\mathrm{CO}(1-0)} = 0.65 \left(\frac{\Sigma_{\rm SFR}}{1.8 \times 10^{-2}\,\mathrm{M_\odot\,yr^{-1}\,kpc^{-2}}} \right)^{0.125} , \tag{C.1}$$

with minimum R_{21} of 0.35 and maximum 1.0. Then we scale the CO(2 – 1) intensity by R_{21}^{-1} to present our results in terms of CO(1 – 0) intensity.

To compute $\Sigma_{\rm mol}$ and $P_{\rm DE}$, we adopt the variable $\alpha_{\rm CO}$ prescription from ~~?, their table 1~~?, their Table 1 , which accounts for variations with metallicity (Z; $\mathrm{Z}_\odot$ is the solar metallicity) and stellar mass surface density ($\Sigma_\star$):

$$\alpha_{\rm CO}^{\rm var} = \alpha_{\rm CO}^{\rm fix} \left(\frac{Z}{\mathrm{Z}_\odot} \right)^{-1.5} \left(\frac{\max(\Sigma_\star,\, 100\,\mathrm{M_\odot\,pc^{-2}})}{100\,\mathrm{M_\odot\,pc^{-2}}} \right)^{-0.25} . \tag{C.2}$$

Stellar mass maps are inferred from *Spitzer* 3.6 μm observations as explained in Sect. 2. Metallicities are estimated based on simple scaling relations, following **?**. These use a global mass-metallicity relation (**?**) and employ a radial metallicity relation with a fixed gradient of −0.1 dex normalised by the effective radius of each galaxy (**?**).

Appendix D: Spectral stacking of HCN and CO

We compute spectral stacks of HCN(1 – 0) and CO(1 – 0) line emission in bins of stellar mass surface density, $\Sigma_\star$, molecular gas surface density, $\Sigma_{\rm mol}$, and dynamical equilibrium pressure, $P_{\rm DE}$, across the merged sample of 31 galaxies studied in this work. For the ALMOND sample, the CO(2 – 1) intensities from PHANGS–ALMA are first converted into CO(1 – 0) intensities using the line ratio calibration from Sect. C. We note, however, that this has no effect on the stacking procedure. We stack in logarithmic bins for each galaxy individually, selecting ten bins from a fixed minimum ($\Sigma_\star = 3 \times 10^1\,\mathrm{M_\odot\,pc^{-2}}$, $\Sigma_{\rm mol} = 5\,\mathrm{M_\odot\,pc^{-2}}$, $P_{\rm DE} = 1 \times 10^4\,k_{\rm B}\,\mathrm{K\,cm^{-3}}$) to the maximum value of each galaxy. For the centres versus disc HCN scaling relations (Fig. 3), we exclude the centres from the stacking and stacks across the remaining sightlines adopting nine bins. Figure D.1 shows exemplary spectral stacks of HCN(1 – 0) and CO(1 – 0) as a function of $\Sigma_\star$ across the galaxy NGC 4321.

Appendix E: Additional tables

Table E.1 presents the combined galaxy sample composed of 31 galaxies from the EMPIRE and ALMOND surveys, along with their coordinates and global properties.

Table E.1. Galaxy sample (EMPIRE + ALMOND).

Galaxy	R.A. (J2000)	Dec. (J2000)	d (Mpc)	i (°)	$\log_{10} M_\star$ ($M_\odot$)	$\log_{10}$ SFR ($M_\odot\,yr^{-1}$)	$\log_{10}$ (SFR/$M_\star$) (yr^{-1})	Bar	AGN	SFR trace
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
NGC 0628	1°36′41.7252″	15°47′1.1148″	9.84	8.90	10.34	0.24	−10.10	✗	✗	W4+FUV
NGC 1097	2°46′18.949 68″	−30°16′28.83″	13.58	48.60	10.76	0.68	−10.08	✓	✓	W4+FUV
NGC 1365	3°33′36.3648″	−36°8′25.4544″	19.57	55.40	10.99	1.23	−9.76	✓	✓	W4+FUV
NGC 1385	3°37′28.5636″	−24°30′4.1832″	17.22	44.00	9.98	0.32	−9.66	✗	✗	W4+FUV
NGC 1511	3°59′36.5904″	−67°38′2.148″	15.28	72.70	9.91	0.36	−9.55	✗	✗	W4+FUV
NGC 1546	4°14′36.2928″	−56°3′39.2328″	17.69	70.30	10.35	−0.08	−10.43	✗	✗	W4+FUV
NGC 1566	4°20′0.3816″	−54°56′16.836″	17.69	29.50	10.78	0.66	−10.13	✓	✓	W4+FUV
NGC 1672	4°45′42.4896″	−59°14′50.1252″	19.40	42.60	10.73	0.88	−9.85	✓	✓	W4+FUV
NGC 1792	5°5′14.3256″	−37°58′50.016″	16.20	65.10	10.61	0.57	−10.04	✗	✗	W4+FUV
NGC 2566	8°18′45.6072″	−25°29′58.272″	23.44	48.50	10.71	0.94	−9.77	✓	✗	W4
NGC 2903	9°32′10.1064″	21°30′3.0276″	10.00	66.80	10.63	0.49	−10.15	✓	✗	W4+FUV
NGC 2997	9°45′38.7936″	−31°11′27.924″	14.06	33.00	10.73	0.64	−10.09	✗	✗	W4+FUV
NGC 3059	9°50′8.16″	−73°55′19.902″	20.23	29.40	10.38	0.38	−10.00	✓	✗	W4
NGC 3184	10°18′16.9416″	41°25′27.6348″	12.58	16.00	10.36	0.11	−10.24	✓	✓	W4+FUV
NGC 3521	11°5′48.576″	−0°2′9.4164″	13.24	68.80	11.02	0.57	−10.45	✗	✗	W4
NGC 3621	11°18′16.3008″	−32°48′45.36″	7.06	65.80	10.06	−0.00	−10.06	✗	✓	W4+FUV
NGC 3627	11°20′15.0048″	12°59′29.4″	11.32	57.30	10.83	0.58	−10.25	✓	✓	W4+FUV
NGC 4254	12°18′49.632″	14°24′59.0832″	13.10	34.40	10.42	0.49	−9.94	✗	✗	W4+FUV
NGC 4303	12°21′54.9312″	4°28′25.4784″	16.99	23.50	10.52	0.73	−9.80	✓	✓	W4+FUV
NGC 4321	12°22′54.9288″	15°49′20.2944″	15.21	38.50	10.75	0.55	−10.19	✓	✗	W4+FUV
NGC 4535	12°34′20.304″	8°11′52.7028″	15.77	44.70	10.53	0.33	−10.20	✓	✗	W4+FUV
NGC 4536	12°34′27.0672″	2°11′17.6748″	16.25	66.00	10.40	0.54	−9.86	✓	✗	W4+FUV
NGC 4569	12°36′49.824″	13°9′46.35″	15.76	70.00	10.81	0.12	−10.68	✓	✓	W4+FUV
NGC 4826	12°56′43.6416″	21°40′59.0988″	4.41	59.10	10.24	−0.69	−10.93	✗	✓	W4+FUV
NGC 5055	13°15′49.296″	42°1′45.4008″	9.02	59.00	10.79	0.31	−10.48	✗	✗	W4+FUV
NGC 5194	13°29′52.6896″	47°11′42.5472″	8.56	21.00	10.65	0.64	−10.01	✗	✓	W4+FUV
NGC 5248	13°37′32.0064″	8°53′6.702″	14.87	47.40	10.41	0.36	−10.05	✓	✗	W4+FUV
NGC 5643	14°32′40.776″	−44°10′28.596″	12.68	29.90	10.34	0.41	−9.92	✓	✓	W4
NGC 6300	17°16′59.472″	−62°49′13.98″	11.58	49.60	10.47	0.28	−10.19	✓	✓	W4
NGC 6946	20°34′52.6032″	60°9′12.654″	7.34	33.00	10.47	0.77	−9.70	✓	✗	W4+FUV
NGC 7496	23°9′47.2848″	−43°25′40.26″	18.72	35.90	10.00	0.35	−9.64	✓	✓	W4+FUV

Notes – (2) Right ascension, (3) declination, (4) distance (**?**), and (5) inclination angle (**?**). Integrated galaxy properties, (6) global stellar mass and (7) global SFR, taken from **?**. (9) Presence of a galactic bar (**??**), and/or (10) AGN (**?**). (11) Employed SFR tracers using WISE 22 µm (**?**) or a combination of WISE and GALEX-FUV (**?**), aopted from (**?**). (12) Archival H I 21-cm line emission data, taken from THINGS (**?**), VIVA (**?**), VLA–HERACLES, PHANGS–VLA (Utomo et al. in prep.), PHANGS–MeerKAT (**?**, ; Pisano et al. in prep.), and MHONGOOSE (**?**). (13) Archival CO observations from PHANGS–ALMA (CO(2 − 1); **?**) for ALMOND galaxies, and EMPIRE (CO(1 − 0); **?**), PAWS (CO(1 − 0); **?**) for EMPIRE galaxies. (14) Adopted HCN data from ALMOND (**?**) and EMPIRE (**?**). (15) HCN native angular resolution and (16) corresponding linear resolution, given the distance d.

Table E.2 lists percentile and median HCN/CO and SFR/HCN values for centre and discs environments discussed in ~~See~~Sect. 3.3.

Table E.2. Galaxy centres vs . discs.

$\log_{10}(Y)$	environment	(16^{th}, 50^{th}, 84^{th}) perc. (S/N $\geq$ 3)	median (all S/N)
HCN/CO	disc	(−1.96, −1.72, −1.51)	−1.87
	centre	(−1.60, −1.35, −1.04)	−1.35
	centre (AGN)	(−1.43, −1.30, −1.03)	−1.28
	centre (non-AGN)	(−1.62, −1.43, −1.22)	−1.43
SFR/HCN	disc	(−7.21, −6.93, −6.56)	−6.85
	centre	(−7.39, −7.13, −6.57)	−7.11
	centre (AGN)	(−7.44, −7.19, −6.70)	−7.23
	centre (non-AGN)	(−7.31, −7.11, −6.57)	−7.11

Notes – 16^{th} percentiles, medians, and 84^{th} percentiles of HCN/CO and SFR/HCN across significant data (S/N $\geq$ 3) in disc and centre environments. For the centres, we also present percentile values among centres with and without AGNs. The last column additionally lists the median values across all S/N data, this means including non-detections, which yields 0.15 dex lower HCN/CO and 0.08 dex higher SFR/HCN across galaxy discs, which are affected by S/N-clipping (and similar values in centres, which have S/N $\geq$ 3 for 29 out of 31 galaxies).