EMPIRE: The IRAM 30 m Dense Gas Survey of Nearby Galaxies

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Abstract

We present EMPIRE, an IRAM 30 m large program that mapped λ = 3–4 mm dense gas tracers at ∼1–2 kpc resolution across the whole star-forming disk of nine nearby massive spiral galaxies. We describe the EMPIRE observing and reduction strategies and show new whole-galaxy maps of HCN(1–0), HCO+(1–0), HNC(1–0), and CO(1–0). We explore how the HCN-to-CO and IR-to-HCN ratios, observational proxies for the dense gas fraction and dense gas star formation efficiency, depend on host galaxy and local environment. We find that the fraction of dense gas correlates with stellar surface density, gas surface density, molecular-to-atomic gas ratio, and dynamical equilibrium pressure. In EMPIRE, the star formation rate per unit dense gas is anticorrelated with these same environmental parameters. Thus, although dense gas appears abundant in the central regions of many spiral galaxies, this gas appears relatively inefficient at forming stars. These results qualitatively agree with previous work on nearby galaxies and the Milky Way’s Central Molecular Zone. To first order, EMPIRE demonstrates that the conditions in a galaxy disk set the gas density distribution and that the dense gas traced by HCN shows an environment-dependent relation to star formation. However, our results also show significant (±0.2 dex) galaxy-to-galaxy variations. We suggest that gas structure beyond the scale of our observations and dynamical effects likely also play an important role.

Key words: galaxies: ISM – galaxies: star formation – ISM: molecules – radio lines: galaxies

Supporting material: machine-readable tables

1. Introduction

We present the survey called EMIR Multiline Probe of the ISM Regulating Galaxy Evolution (EMPIRE; PI: F. Bigiel). EMPIRE used the IRAM 30 m telescope to map multiple molecular lines in the 3–4 mm atmospheric window across the whole star-forming area of nine nearby, massive spiral galaxies. The lines covered include the highly critical density transitions HCN(1–0), HCO+(1–0), and HNC(1–0), which are frequently referred to as “dense gas tracers.” Thanks to the wide bandwidth of the EMIR receiver, we simultaneously cover the CO isotopologues 13CO and 18CO and a number of fainter lines (e.g., the low-lying transitions of SiO, C2H, and N2H+).

The ratios among the lines that are mapped by EMPIRE constrain the density distribution and other physical conditions in the molecular gas. The faintness of these transitions at extragalactic distances has prevented previous large-scale mapping efforts. EMPIRE overcomes this obstacle by leveraging the wide bandwidth and excellent sensitivity of EMIR on the IRAM 30 m telescope. The result is the first resolved (1–2 kpc resolution), wide-area-mapping survey of density-sensitive molecular lines in the 3–4 mm atmospheric window.

EMPIRE has two core goals. First, to constrain the density distribution within the molecular gas and to measure the dependence of the gas density distribution on galactic environment. Second, to measure how the star formation efficiency (SFE) per unit molecular gas mass depends on the density distribution within the molecular gas and environment. More colloquially, EMPIRE aims to answer the questions of where gas in galaxies is dense, and how dense gas relates to star formation.

This paper describes the survey and addresses these two core questions. Here, we focus on the HCN-to-CO and IR-to-HCN line ratios as observational proxies for the dense gas fraction and dense gas SFE, respectively. We measure how these quantities depend on local conditions within galaxy disks.

Our results build on previous observations: the pointed HCN survey by Usero et al. (2015), full-disc HCN mapping of M51 by Bigiel et al. (2016), and the ALMA+IRAM study of four galaxies by Gallagher et al. (2018a). J. Puschnig et al. (2019, in preparation)
will extend our analysis to leverage the full suite of EMPIRE line ratios, which we only briefly discuss here.

In addition to these studies, EMPIRE has already been used to study physical conditions in the molecular gas in a series of related papers. Jiménez-Donaire et al. (2017a) derived constraints on the optical depth of dense gas tracers by studying their less abundant isotopologues (H\(^{13}\)CN and H\(^{12}\)\(^{13}\)CO\(^+\)). Jiménez-Donaire et al. (2017b) showed that the \(^{13}\)CO-to-\(^{12}\)CO line ratio increases systematically with radius in our targets. Cormier et al. (2018) measured the \(^{13}\)CO-to-\(^{12}\)CO ratio across our targets and showed how it depends on physical conditions. They also calculated a spatially resolved \(^{13}\)CO-to-H\(_2\) conversion factor, and found that \(^{13}\)CO may be a better tracer of the molecular gas mass than \(^{12}\)CO in galaxy centers. Gallagher et al. (2018b) combined EMPIRE with higher resolution ALMA maps to show that on average, the spectroscopic dense gas fraction, traced by HCN-to-CO, correlates with the cloud-scale molecular gas surface density.

We give the scientific background for the survey in Section 1.1. We describe our IRAM 30 m observations, data reduction, and data processing in Section 2. In Section 3 we summarize key supporting multiwavelength data, and in Section 4 we explain how we convert these into physical quantities. Section 4.7 describes the stacking techniques that we use to improve the signal-to-noise ratio (S/N) of our measurements. We present our results in Section 5. In Sections 5.1–5.2 we analyze the spatial extent of dense gas emission and compare it to the distribution of the CO emission. In Section 5.3 we compare our measurements to star formation scaling relations obtained from previous observations. We investigate the systematic variations of the star formation efficiencies and the dense gas fractions in Section 5.4. Section 6 discusses our findings. We compare our observations to other recent results and discuss plausible physical drivers that could explain our observations. Finally, Section 7 presents a summary of the survey and our key findings.

1.1. Background

The low-J \(^{12}\)CO emission lines have been used to map the molecular ISM in the Milky Way and many external galaxies. CO is the second most abundant molecule after H\(_2\), and has been calibrated as a proxy to trace the distribution of H\(_2\) mass (e.g., Bolatto et al. 2013). Given the low “effective” critical density required to excite the J = 1–0 transition and its low-excitation temperature, CO emission traces the bulk molecular medium. However, stars are thought to form preferentially in the densest regions of molecular clouds. Studies of the Milky Way (Heiderman et al. 2010; Lada et al. 2010, 2012; Evans et al. 2014; Vutsalchavakul et al. 2016) and external galaxies (Gao & Solomon 2004; García-Burillo et al. 2012) have highlighted the role of dense gas as the immediate site of star formation. Thus, knowing the prevalence and star-forming ability of this dense gas is crucial to understanding how gas is converted into stars in a galactic context.

Line emission from molecules with higher dipole moments than that of CO, such as HCN or HCO\(^+\), has a higher critical density than CO. This critical density represents the density for which the total radiative decay rate between an upper and lower rotational level equals the rate of collisional deexcitation out of the upper level (see, e.g., Shirley 2015). For an optically thin line, the emissivity (line emission per unit mass, as defined in Leroy et al. 2017b) of the gas reaches a maximum at this value. In reality, radiative trapping effects can lead to a lower “effective critical density.” Moreover, because the emissivity of gas below the critical density is low but not zero, high masses of low-density gas can produce significant emission even from high-dipole moment molecules (e.g., Shirley 2015; Leroy et al. 2017b). Despite these important caveats, the effective mean densities probed by low-J HCN and HCO\(^+\) lines are still notably higher than those accesses by low-J CO lines. As a result, we expect these lines to trace gas that is more closely linked to star formation.

In a seminal paper, Gao & Solomon (2004) observed the ground-state transition of HCN emission from 53 entire galaxies and bright galaxy centers across a large range of galaxy types, from normal spirals to (ultra)luminous infrared galaxies (L\(_\text{IR}\) \(\geq 10^{11}\) L\(_\odot\), hereafter (U)LIRGs). They observed a strong linear relationship between the recent star formation rate (SFR), as traced by the total infrared emission, and the HCN luminosity. Such a linear relationship does not hold for CO, because IR-bright starburst galaxies, LIRGs, and ULIRGs show a higher ratio of IR-to-CO emission than normal galaxies. Similar results were found by several subsequent studies of nearby galaxies (e.g., Graciá-Carpio et al. 2006; Juneau et al. 2009; García-Burillo et al. 2012). If the conversion from line luminosities into gas masses is the same for all galaxies, these results imply that the SFE of the molecular gas as traced by CO (SFE\(_\text{mol} = \text{SFR/}\text{M}_{\text{mol}}\)) is higher in more luminous systems, while the SFE of the dense molecular gas (SFE\(_\text{dense} = \text{SFR/}\text{M}_{\text{dense}}\)) as traced by HCN is approximately constant.

Observations isolating clouds and star-forming clumps in the Milky Way (e.g., Wu et al. 2005; Heiderman et al. 2010; Lada et al. 2010, 2012; Evans et al. 2014) have extended the extragalactic IR-to-HCN correlation down to individual molecular clouds and dense cores. This suggests that the SFR per unit dense gas mass is nearly constant across many scales. These studies also found a good correspondence between the SFR in individual clouds (by counting young stellar objects) and the dense gas mass (by using extinction measurements). This suggests that dense gas mass is a strong predictor of how much star formation is occurring in a cloud.

As a result of these studies, a constant dense gas SFE, SFE\(_\text{dense} = \Sigma_{\text{dense}}\), above some critical surface density, \(\Sigma_{\text{dense}}\), has been hypothesized (e.g., Lada et al. 2010, 2012; Evans et al. 2014). These density threshold models for star formation assume a constant SFE of dense molecular gas, and the overall SFR would then be regulated by the amount of dense gas that is available above this threshold. Lada et al. (2013) and Evans et al. (2014) discussed in detail the limitations of this column density threshold idea and its applicability to Galactic molecular clouds. In particular, Lada et al. (2013) argued that a Kennicutt–Schmidt-type scaling relation is not enough to completely describe star formation in a cloud, and as a consequence, the observed scaling relation in unresolved galaxies is likely a consequence of unresolved observations of individual clouds (an idea also explored in Bigiel et al. 2008; Leroy et al. 2008).

By contrast, turbulence-regulated whole-cloud models for star formation postulate that the global properties of turbulent clouds set their density distribution and SFE (e.g., Padoan & Nordlund 2002; Krumholz & Thompson 2007; Federrath & Klessen 2012). In this scenario, the fraction of star-forming
dense gas, \( f_{\text{dense}} = M_{\text{dense}}/M_{\text{mol}} \), and its efficiency, \( \text{SFE}_{\text{dense}} \), depend on cloud parameters such as cloud mean density, virial parameter, and Mach number.

Observations of nearby galaxies, however, suggest that a constant \( \text{SFE}_{\text{dense}} \) for star-forming regions across different galactic environments may be insufficient to explain the observations. García-Burillo et al. (2012) used the IRAM 30 m telescope to observe a sample of 19 LIRGs in the \( J = 1-0 \) lines of CO, HCN, and HCO\(^+\). Combined with literature data, they assembled a sample of \( \sim 100 \) normal and (UL)IRLIRQ galaxies. Their observations, averaged across entire galaxies, largely obeyed the IR-to-dense gas power-law correlation found in previous Galactic and extragalactic work. However, the sample of LIRGs and ULIRGs deviates from this power law. The authors measured \( L_{\text{IR}}/L_{\text{HCN}} \) ratios as a proxy for \( \text{SFE}_{\text{dense}} \) and found that these luminosity ratios are a factor of 2–3 higher in LIRGs and ULIRGs than those measured in normal galaxies. These variations in the efficiency of star formation in dense gas suggest that real physical effects are still at play in different galactic environments and agree better with turbulence-regulated models.

Observations of entire galaxy disks at kiloparsec scales bridge the gap between cloud-scale studies and galaxy-scale surveys, which provide a large number of systems but the resolution is too low to connect to local ISM physics. These observations reveal systematic variations in the overall linear correlation between dense gas tracers and SFR tracers seen in global measurements of entire galaxies. Usero et al. (2015) used the IRAM 30 m telescope to survey HCN(1–0) emission from 62 regions across 29 nearby star-forming galaxies. The resolution they achieved (\( \sim 1–2 \) kpc) allowed them to investigate the properties of the dense gas as a function of local conditions in galaxy disks. Their results show that the dense gas fraction \( (f_{\text{dense}}) \) as traced by the HCN/C0 ratio strongly depends on location in the disk: it increases with stellar surface densities \( (\Sigma_*) \) and molecular-to-atomic gas ratios \( (R_{\text{mol}}) \). On the other hand, the authors found that the SFE of dense molecular gas \( \text{SFE}_{\text{dense mol}} \) as traced by the IR/HCN ratio is systematically anticorrelated with those same parameters: it is \( \sim 6–8 \) times lower near galaxy centers than in the outer regions of the galaxy disks.

Similar results have been found by Bigiel et al. (2016) and Chen et al. (2015) across the full disk of NGC 5194 (M51); while there is an overall correlation between SFR tracers and HCN emission at kiloparsec resolution, the efficiency of dense gas to form stars drops at small galactocentric radii (taking the observables at face value). Gallagher et al. (2018a) presented new ALMA dense gas observations combined with IRAM 30 m short spacing, mapping the inner \( \sim 3–5 \) kpc of four local galaxies (NGC 3351, NGC 3627, NGC 4254, and NGC 4321). They found the same correlations between dense gas fraction, SFR, and local environment, and expressed them in terms of the dynamical equilibrium pressure needed to support the weight of a gas disk in a galaxy region (e.g., Elmegreen 1989; Helfer & Blitz 1997; Wong & Blitz 2002; Blitz & Rosolowsky 2006). Querejeta et al. (2019) found similar results in resolved regions of the spiral arms in M51 with high angular resolution observations from IRAM/NOEMA. Recent findings by Benss & Wilson (2019) in the Antennae galaxy system also resemble these results. The two nuclei, NGC 4038 and NGC 4039, show the largest dense gas fractions, but the lowest SFE per unit dense gas mass.

Correspondingly, multiple observations in our own Milky Way have revealed that the SFR in the inner \( \sim 500 \) pc of the Galaxy (Central Molecular Zone, CMZ) appears strongly suppressed relative to its dense gas content (e.g., Jones et al. 2012; Longmore et al. 2013; Barnes et al. 2017; Mills & Battersby 2017). This reinforces the trends discussed above. Dense gas in regions with high mean density appears to be inefficient at forming stars. Interpreting the observables at face value, these results may suggest changing density distributions and changing SFRs per unit dense gas. The latter would be at odds with models that use a fixed density threshold. Exploring these trends further across whole galaxy disks to understand the role of dense gas in galaxy-scale star formation requires wide-field mapping of the main dense gas tracers across full galaxy disks.

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### Table 1

| Galaxy       | R.A. (EQ 2000) hh mm ss.s | Decl. (EQ 2000) dd mm ss.s | \( i \) | P.A. (°) | \( r_{25} \) | \( D \) | \( V_{\text{hel}} \) (km s\(^{-1}\)) | Metal. | Morph. | \( \langle \Sigma_{\text{SFR}} \rangle \) | \( \log_{10}(M_\odot) \) |
|--------------|---------------------------|---------------------------|-------|-------|--------|-----|-----------------|-------|-------|----------------|------------------|
| NGC 628      | 01:36:41.8                | 15:47:00                  | 7     | 20    | 4.9    | 9.0 | 659.1           | SAc   | 4.0  | \( 4 \times 10^{-3} \) | 10.0             |
| NGC 2903     | 09:32:10.1                | 21:30:03                  | 65    | 204   | 5.9    | 8.5 | 556.6           | SABc  | 5.7  | \( 7 \times 10^{-3} \) | 10.1             |
| NGC 3184     | 10:18:17.0                | 41:25:28                  | 16    | 179   | 3.7    | 13.0| 593.3           | SABc  | 20   | \( 2 \times 10^{-3} \) | 10.2             |
| NGC 3627     | 11:20:15.0                | 52:39:30                  | 62    | 173   | 5.2    | 16.8| 2407.0          | SABc  | 9.0  | \( 9 \times 10^{-3} \) | 10.6             |
| NGC 4254     | 12:18:0.0                 | 14:24:59                  | 32    | 55    | 2.5    | 16.8| 714.3           | SABc  | 4.1  | \( 1 \times 10^{-3} \) | 10.5             |
| NGC 4321     | 12:22:55.0                | 15:49:19                  | 30    | 153   | 3.0    | 15.2| 1571.0          | SABc  | 20   | \( 2 \times 10^{-3} \) | 10.5             |
| NGC 5055     | 13:15:49.2                | 42:01:45                  | 59    | 102   | 5.9    | 8.9 | 499.3           | SABc  | 8.0  | \( 1 \times 10^{-3} \) | 10.5             |
| NGC 5194     | 13:29:52.7                | 47:11:43                  | 20    | 172   | 3.9    | 8.4 | 456.2           | SABc  | 20   | \( 2 \times 10^{-3} \) | 10.5             |
| NGC 6946     | 20:34:52.2                | 60:09:14                  | 33    | 243   | 5.7    | 7.0 | 42.4            | SABc  | 21   | \( 2 \times 10^{-3} \) | 10.5             |

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Notes: Galaxy names (1), adopted coordinates (2–3), and morphological types (10) are taken as listed in NED, the NASA Extragalactic Database. The orientation parameters inclinations (4), position angles (5), and radius of the B-band 25th magnitude isophote (6) are taken from the HyperLeda database (Makarov et al. 2014). Distances (7) are adopted from the Extragalactic Distance Database (EDD, Tully et al. 2009). Heliocentric central velocities (8) are taken from Walter et al. (2008). Globally averaged metallicities (9) are taken from Moustakas et al. (2010), except for NGC 2903 (Engelbracht et al. 2008). The average SFR surface density (11) inside 0.75 \( r_{25} \) is adopted from Leroy et al. (2013). The integrated stellar mass (12) of the entire galaxies based on 3.6 \( \mu \)m emission is taken from Dale et al. (2007, 2009).
2. Observations and Data Processing

2.1. Sample Selection

Table 1 lists the EMPIRE targets. All targets are nearby \((d \leq 15\text{\,Mpc})\) face-on \((i \leq 65^\circ)\) spiral galaxies that are also large on the sky \((\gtrsim 2')\).

We chose our targets from the HERA CO-Line Extragalactic Survey (HERACLES, Leroy et al. 2009). Because HERACLES builds on SINGS (Kennicutt et al. 2003), THINGS (Walter et al. 2008), and KINGFISH (Kennicutt et al. 2011), this ensures high-quality and homogeneous multiwavelength data. We selected CO-bright and actively star-forming targets, allowing us to detect the faint lines that trace dense gas. We also required that the galaxies be viewed relatively face on and lie close enough so that the IRAM 30 m beam \((\sim 30''\) at \(\sim 90\text{\,GHz})\) translates into physical scales of \(\sim 1-2\text{\,kpc}\).

Finally, we aimed to cover a range of morphological and dynamical features. The sample contains galaxies that show a strong spiral-arm structure (NGC 628, NGC 3184, and NGC 5194). It also covers strongly barred galaxies (NGC 2903 and NGC 3627), flocculent disks (NGC 5055 and NGC 6946), strong nuclear bursts (NGC 2903, NGC 4321, and NGC 6946), Virgo cluster members (NGC 4254 and NGC 4321), and interacting galaxies (NGC 3627 and NGC 5194).

2.2. IRAM 30 m Observations

The observations for EMPIRE were carried out at the IRAM 30 m telescope located at Pico Veleta, Spain. Most of the data were taken from 2014 December through 2016 December for \(\sim 440\text{\,h}\) over the course of 16 runs. We refer to the EMPIRE survey website\(^\text{15} \) for additional information. A link to the official polarization EMIR receiver (Carter et al. 2012), which yields an instantaneous bandwidth of 15.6 GHz per polarization. The data were recorded using the fast Fourier transform spectrometers (FTS), with a spectral resolution of 195 kHz, corresponding to \(\sim 0.5\text{\,km s}^{-1}\) for the E090 band. We tuned EMIR with a local oscillator frequency of \(\sim 98.6\text{\,GHz}\). This allowed us to simultaneously observe the bright high critical density tracers HCN \((1-0),\) HCO\(^+\)(1-0), and HNC (1-0) and the optically thin molecular column tracers \(^{13}\text{CO}(1-0)\) and \(^{13}\text{CO}(1-0)\). In addition, many fainter transitions of other molecules are also present in the band (see Table 2). These are mostly not detected in individual lines of sight. In future work we will explore whether these are accessible by means of spectral stacking.

For the remainder of the paper we refer to HCN \((1-0)\) emission as HCN and proceed analogously for the other molecular lines.

In every target galaxy, we defined a rectangular field that encompassed the area where \(^{12}\text{CO}(2-1)\) emission is detected in the HERACLES maps (Table 3). We mapped these fields using the on-the-fly (OTF) mapping mode with emission-free reference positions close to the galaxies. We scanned each galaxy at \(8''\) per second in multiple paths offset by \(8'',\) parallel to the major axis of the scanned field to cover the entire molecular disk. While scanning, we read out one dump every \(4''\) (every 0.5 s) to ensure Nyquist sampling. To avoid remnant scan patterns in the final data products, we also scanned the same area in perpendicular (minor axis) direction, with the orientation of the cross-hatched pattern set by the position angle of the galaxy. See Figure 1 for an example. Additionally, we shifted the grid center by \(N \times \sqrt{2}\) with \(N = 0, 2, 4, 6\) along the diagonal of the grid cell to obtain a finer \(2''\) grid (Figure 1 shows the case of \(N = 0\)). The observing dates for the individual galaxies, area covered, and the orientation of the OTF scans are shown in Table 3.

NGC 5194 (M51) was observed in July and August 2012 as a precursor program to EMPIRE. For this galaxy a slightly different E090 tuning was used, where the local oscillator frequency was set to \(\sim 88.7\text{\,GHz}\). This configuration allowed capturing the isotopologues from the main dense gas tracers, \(^{12}\text{CO},\) \(^{13}\text{CO},\) and HN\(^{13}\text{C}\) (see Jiménez-Donaire et al. 2017a), leaving \(^{13}\text{CO}\) and \(^{12}\text{CO}\) unobserved for this galaxy. The \(^{12}\text{CO}\) data for NGC 5194, however, was observed as part of the PAWS survey (Schinnerer et al. 2013). We refer to Bigiel et al. (2016) for an analysis of this galaxy and details of the observations.

At the beginning of each observing session the focus of the telescope was set using observations of planets or bright quasars and then observed and corrected again every \(\sim 3\text{\,hr}\) as well as at sunset and sunrise. The telescope pointing was corrected every 1–1.5 hr using a point-like source (quasar or planet) close to the target galaxy. Chopper-wheel calibrations were performed every \(\sim 10–15\) minutes employing standard hot-/cold-load absorber and sky measurements; these are used to perform the first basic calibration and to convert the data into corrected antenna temperature scale \(T_A^\circ\). Line calibrators were observed as part of EMPIRE once a day during the observing runs, and the measured velocity-integrated intensities varied by only \(\sim 3\%–8\%\) between different runs (see Figure 18), implying a stable relative calibration in EMPIRE.

2.3. New \(^{12}\text{CO}(1-0)\) Observations

A key goal of EMPIRE is to measure variations in the dense gas fraction and relate them to local ISM conditions. The ratio of high critical density \((>10^4\text{\,cm}^{-3})\) tracers like HCN \((1-0)\) to

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\(^{15}\) https://empiresurvey.webstarts.com
tracers of total molecular material ($>10^2$ cm$^{-3}$) such as CO(1−0), hereafter CO, is sensitive to changes in gas density (Leroy et al. 2017b). Thus, e.g., the HCN-to-CO ratio is one immediately accessible observational diagnostic of the dense gas fraction. High-quality and uniform $^{12}$CO(1−0) data thus play a key role for such measurements. Although ancillary CO(2−1) data exist for the EMPIRE galaxies (Leroy et al. 2009), no uniform high-quality single-dish CO(1−0) data set existed for all targets. Therefore, we also obtained new maps of the CO(1−0) line emission from each target using EMIR on the IRAM 30 m (PI Jiménez-Donaire, projects 061-15 and 059-16; PI Cormier, project D15-12; NGC 5194 has 30 m EMIR CO(1−0) data from PAWS). These ancillary data cover a larger region matched to the HERACLES coverage in $^{12}$CO(2−1).

For these observations, the upper 8 GHz sub-band of EMIR was set at 3 mm to cover the $^{12}$CO(1−0) line and the isotopologues $^{13}$CO(1−0) and C$^{18}$O(1−0). We centered the remaining 8 GHz bandwidth at 212.98 GHz to capture the $J = 2−1$ transition lines of $^{13}$CO and C$^{18}$O. The new CO data set was obtained and processed in the same way as the other EMPIRE data.

### 2.4. Data Reduction and Processing

We use the multichannel imaging and calibration software for receiver arrays (MIRA) to perform the basic calibration and data reduction. This software is part of the Grenoble image and line data analysis software (GILDAS) package.\(^{18}\) We first convert each spectrum into the antenna temperature scale by combining it with the nearest chopper-wheel calibration scan. Then we subtract the closest OFF measurement from the calibrated spectrum. After this basic calibration, the data for each observed line are written out using the continuum and line analysis single-dish software (CLASS) package. At every position where a data dump is taken, we extract a spectrum for each individual line of interest, subtract a zeroth-order baseline

\[^{18}\text{http://www.iram.fr/IRAMFR/GILDAS; see Pety (2005) for more detailed information.}\]
from this spectrum, and regrid the spectrum to have channel width \(4 \text{ km s}^{-1}\) across a \(1500 \text{ km s}^{-1}\) bandpass. Then these spectra are written out into FITS tables.

After this, we read the spectra into a custom IDL pipeline (based on, but improved from, the HERACLES data reduction pipeline; Leroy et al. 2009). Here, we identify pathological data showing spikes or platforming effects (intensity offsets in the observed spectra) before fitting any baselines. In order to fit baselines to each spectrum, we wish to avoid the expected velocity range of the line, which we determine from CO\((1-0)\) emission. For every spectrum we define a window ranging between 50 and 300 \(\text{km s}^{-1}\), centered around the galactic mean CO\((1-0)\) velocity. After this, we define two additional windows adjacent to the central one and with the same width, which we use to fit a second-order polynomial baseline. This fit is then subtracted from the entire spectrum.

In order to filter remaining pathological spectra, we sort all spectra according to their root-mean-square (rms, calculated after subtracting the baselines on the line-free windows) relative to the expected value from the radiometer equation and reject the highest 10%. In addition, we exclude spectra or parts of spectra in velocity, time or polarization, where careful inspection reveals remaining platforming or other issues.

Finally, the data for each spectral line are gridded into a cube, which is later convolved with a Gaussian kernel to a common working resolution of 33\(\prime\) for the purposes of this work. We employed forward and beam efficiencies available from the IRAM documentation\(^{19}\) in order to convert the temperature scales, \(T_A^*\), into main beam temperature (\(T_{\text{MB}}\)):

\[
T_{\text{MB}} = \frac{F_{\text{eff}}}{B_{\text{eff}}} T_A^*. \tag{1}
\]

For the 2013 campaign, the typical \(T_{\text{MB}}/T_A^*\) ratios at 88.6 and 115.3 GHz are 1.17 and 1.21, respectively. For the remainder of the paper, we work in units of \(T_{\text{MB}}\).

### 2.5. Final Data Products

Because low-\(J\) CO lines are much easier to excite and generally much brighter than those from the dense gas tracers HCN, HCO\(^+\), and HNC, and CO isotopologues, we use our new CO\((1-0)\) data to construct masks for the dense gas tracers in position and velocity. For this, we select the regions in each galaxy with a \(^{12}\text{CO}(1-0)\) S/N > 4 in at least two coincident pixels, and we then expand these by incorporating adjacent pixels with S/N \(> 2\). In all cases, the dense gas emission appears well contained within these masks.

Maps of integrated intensity for each emission line are created by integrating the masked data cubes along every line of sight. We use the regions outside the bright CO\((1-0)\) mask (free of signal) to estimate the rms noise in individual channels as the standard deviation in line-free parts of each spectrum in our data cubes. To generate uncertainty maps of the integrated intensity, we multiplied the derived rms noise by the channel width (4 km s\(^{-1}\)) in velocity and by the square-root of the number of channels used to compute the integrated intensity along the line of sight. We find an rms noise range of 1.8–2.9 mK (\(T_{\text{MB}}\)), with an average of \(\sim 2.4\) mK for HCN(1–0). These values are slightly higher in the case of our HCO\(^+\)(1–0) observations, where the typical rms noise varies within 2.0–3.0 mK, with an average of 2.6 mK. We find our HNC(1–0) cubes to be the noisiest within the studied dense gas tracers, where the calculated rms noise ranges from 2.7 mK to 5.0 mK, with an average of 3.5 mK. Within our sample, we consistently find the data cubes for NGC 628 and NGC 5194 to be the noisiest, whereas NGC 4254 shows the lowest rms noise. Regarding our complementary CO\((1-0)\) data taken at \(\sim 115\) GHz, we typically find a much higher rms noise level of \(\sim 18\) mK (within the range of 15–20 mK) due to the much shorter integration times needed to detect this line (see Table 3), although the S/N achieved is much higher than for the dense gas lines. This translates into uncertainties on the integrated intensities on the order of 0.07 K km s\(^{-1}\) for the dense gas tracers, about 0.09 K km s\(^{-1}\) for the CO isotopologues (\(^{13}\)CO and C\(^{18}\)O), and 0.50 K km s\(^{-1}\) for CO.

### 3. Ancillary Data

The EMPIRE targets are some of the best-studied nearby galaxies. They all have existing data across the electromagnetic spectrum that provide an excellent characterization of the distribution of gas, stars, dust, and recent star formation.

The atomic gas content is measured using data from The H I Nearby Galaxy Survey (THINGS, Walter et al. 2008). This VLA large program mapped 34 galaxies, including 7 of the 9 EMPIRE galaxies, in the 21 cm line with high angular (~10\(\prime\)) and velocity (~5 km s\(^{-1}\)) resolution and sensitivity. NGC 4254 and NGC 4321 were not covered by THINGS, therefore we used archival VLA maps (from Schruba et al. 2011; Leroy et al. 2013).

We employ broadband IR photometry in the 3.6–500 \(\mu\)m range, from the Spitzer Infrared Galaxies Survey (SINGS, Kennicutt et al. 2003) and the Key Insights on Nearby Galaxies: a Far-Infrared Survey with Herschel survey (KINGFISH, Kennicutt et al. 2011). This broadband IR emission is then used to estimate the total infrared emission following Galametz et al. (2013) and SFR surface densities (\(\Sigma_{\text{SFR}}\)), as described in Section 4. NGC 2903 and NGC 5194 lack KINGFISH coverage, therefore we use Spitzer 24 \(\mu\)m emission maps (Local Volume Legacy, LVL, from Dale et al. 2009) for NGC 2903 and other Herschel data for NGC 5194 (Very Nearby Galaxy Survey, VNGS, from Bendo et al. 2012). We use the Spitzer Survey of Stellar Structure in Galaxies (S4G) processing of the IRAC data (Sheth et al. 2010) and LVL processing of the MIPS data (Dale et al. 2009; Lee et al. 2009) to compute stellar surface densities (\(\Sigma_\star\)) in our targets.

### 4. Estimating Physical Parameters and Spectral Stacking

Converting observed intensities into physical quantities is subject to assumptions and hence is somewhat uncertain (e.g., Kennicutt & Evans 2012; Bolatto et al. 2013; Sandstrom et al. 2013; Usero et al. 2015). We therefore choose in the following to report our results using direct observables (e.g., intensities \(I_{\text{HCN}}\)) in addition to reporting physical quantities (e.g., \(\Sigma_{\text{dense}}\)). These are derived from linear transformations following Usero et al. (2015) as detailed below.

#### 4.1. Molecular Gas Surface Density

We estimate the mass surface density of molecular gas using our new maps of CO\((1-0)\) line emission (Section 2.3) to trace the molecular hydrogen (H\(_2\)) content. The molecular surface
density can be derived as
\[ \Sigma_{\text{mol}} = \alpha_{\text{CO}} I_{\text{CO}} \cos(i). \] (2)

The \( \cos(i) \) factor corrects for inclination, and \( \alpha_{\text{CO}} \) is the CO-to-H\(_2\) conversion factor. We assume this value to be Milky Way-like throughout the sample (\( \alpha_{\text{CO}} = 4.4 M_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1} \), i.e., including the 1.36 factor for helium), which is commonly adopted for massive solar metallicity galaxies (see Bolatto et al. 2013). Although variations from galaxy to galaxy and within galaxies are present, the most up-to-date values calculated in the disks of nearby galaxies largely agree with the Galactic value (Sandstrom et al. 2013; Cormier et al. 2018). Galaxy centers show the largest differences, with systematically lower values, and the scatter per radius is only a factor of 2 (Bolatto et al. 2013; Sandstrom et al. 2013; Cormier et al. 2018). Provided that our focus is on kiloparsec-size regions and late-type normal spirals, we do not expect large variations across the disks. In fact, the average disk metallicities only range from 12 + log O/H of 8.34 to 8.68 (about a factor of two) in our target galaxies (see Table 1). Despite these observed variations of \( \alpha_{\text{CO}} \) in galaxy centers, for simplicity and lacking a detailed physical understanding, we adopt the fixed Milky Way conversion factor and discuss its implications in Section 6.

4.2. Dense Gas Surface Density

As for the dense gas surface densities, a conversion factor (\( \alpha_{\text{HCN}} \)) can also be defined to calculate the mass surface density of dense molecular gas, \( \Sigma_{\text{dense}} \), from the HCN(1-0) integrated intensity:
\[ \Sigma_{\text{dense}} = \alpha_{\text{HCN}} I_{\text{HCN}} \cos(i). \] (3)

Gao & Solomon (2004) estimated \( \alpha_{\text{HCN}} = 10 M_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1} \) as a typical value for the disks of normal star-forming galaxies based on virial theorem and radiative transfer arguments. For this, they assumed self-gravitating dense gas clumps with typical \( n \sim 3 \times 10^4 \text{cm}^{-3} \) and brightness temperatures of 35 K. Wu et al. (2010) found higher values of \( \sim 20 M_\odot \text{ pc}^{-2} (\text{K km s}^{-1})^{-1} \) with a 0.54 dex scatter in a more complete study of resolved dense clumps, for which the mass was determined through the virial method. However, this dense gas conversion factor is not as well characterized as \( \alpha_{\text{CO}} \) and should thus be considered at least as uncertain as the latter (see Section 6.4). For consistency with previous extragalactic work, we use the conversion factor estimated in Gao & Solomon (2004) to calculate dense gas surface densities.

A number of caveats are associated with using HCN emission as a dense gas tracer. We review these in detail in Section 6.4, but also mention them briefly here. First, the mean density traced by any molecular line reflects the convolution of an underlying density distribution with a density-dependent emissivity. As a consequence, in the common case where low-density gas is more abundant than high-density gas, significant emission can also arise from gas density below the critical density. Second, the optical depth, and so the strength of radiative trapping, associated with HCN is not strongly constrained. Neither are the HCN abundance or excitation known perfectly. While a detailed assessment of HCN emissivity and intensity, dense gas mass, and effective density with the available data is not possible, the strongly different effective critical densities of low-J HCN and CO lines render, e.g., the HCN-to-CO ratio a good first-order proxy for changing mean gas density on kiloparsec scales (this is also supported by radiative transfer modeling; Leroy et al. 2017b). Several other processes such as UV, X-ray, or cosmic-ray heating can also alter the emissivity of HCN via chemistry. These issues are likewise impossible to address with only the EMPIRE data. We indirectly address this issue using different line ratios (e.g., HCO\(^+\)-to-CO), and we expect chemistry effects to average out at least to some degree on kiloparsec scales. However, because of these caveats, we present and analyze our results using direct observables and recommend caution regarding their interpretation (see Section 6).

4.3. Atomic Gas Surface Density

We calculate the atomic gas mass surface density, \( \Sigma_{\text{HI}} \), from the 21 cm line integrated-intensity maps obtained by THINGS (Walter et al. 2008) via
\[ \frac{\Sigma_{\text{HI}}}{M_\odot \text{ pc}^{-2}} = 0.020 \frac{I_{\text{HI}} \text{ cm}^{-2}}{\text{K km s}^{-1}} \cos(i). \] (4)

This conversion assumes optically thin emission and takes any missing zero-spacing correction to be negligible. These are reasonable assumptions for the THINGS data set provided the good agreement found between interferometric-only and single-dish measurements inside the THINGS 30′ primary beam (see Walter et al. 2008). In addition, it includes a factor of 1.36 to reflect the presence of helium.

4.4. Stellar Surface Density

The stellar structure observed in galaxy disks can provide an interesting insight into the distribution of dense gas: gas follows the stellar gravitational potential, and hence the stellar distribution in the galaxy disk can be an important driver of the local dynamical equilibrium pressure. Usero et al. (2015) and Bigiel et al. (2016) employed the Spitzer 3.6 \( \mu \text{m} \) maps (Dale et al. 2009) to derive the stellar surface density, \( \Sigma_\ast \), because photospheric emission from old stars is responsible for most of the emission seen in the 3.6 \( \mu \text{m} \) band. However, there can be contamination from dust heated by young stellar populations. Therefore we follow the approach used by Gallagher et al. (2018a), and use contaminant-corrected maps from Querejeta et al. (2015). They employed reprocessed 3.6 and 4.5 \( \mu \text{m} \) photometry as part of S\(^2\)G, and used the independent component analysis (ICA) method presented in Meidt et al. (2012) to separate the contribution from the dust emission heated by young stars in the 3.6 \( \mu \text{m} \) band (about 10%–30%). Finally, we derive stellar surface densities by assuming a mass-to-light ratio of 352 \( M_\odot \text{ pc}^{-2} (\text{MJy sr}^{-1})^{-1} \), which corresponds to approximately 0.5 \( M_\odot \) per \( L_\odot \) (Meidt et al. 2014).

4.5. Total Infrared Intensity and SFR

Following the same approach as in our previous work (e.g., Usero et al. 2015; Bigiel et al. 2016; Jiménez-Donaire et al. 2017b; Cormier et al. 2018), we use the total infrared (TIR) surface brightness as a proxy for the local surface density of star formation. To estimate this, we combine \( \lambda = 70, 160, \) and 250 \( \mu \text{m} \) maps from Herschel (KINGFISH, Kennicutt et al. 2011). We convolve these to match the 33′ beam of our EMPIRE data using the kernels from Aniano et al. (2011), and calculate the TIR
surface brightness following Galametz et al. (2013),
\[
\Sigma_{\text{TIR}} = \sum c_i \Sigma_i,
\]
where \(\Sigma_i\) refers to the surface brightness in a given Herschel band \(i\). We then convert into SFR surface density using the prescription of Murphy et al. (2011):
\[
\frac{\Sigma_{\text{SFR}}}{M_\odot \text{ yr}^{-1} \text{kpc}^{-2}} = 1.48 \times 10^{-10} \frac{\Sigma_{\text{TIR}}}{L_\odot \text{kpc}^{-2}}.
\]

NGC 2903 lacks Herschel data, therefore we use Spitzer 24 and 70 \(\mu\)m (from LVL, Dale et al. 2009) data to estimate the TIR surface brightness, following the same method. We motivate this choice and discuss alternative SFR tracers in Appendix E. We find that our results are robust against the choice of SFR tracer, which was also the conclusion reached in a similar extensive analysis by Gallagher et al. (2018a).

In the study of \(^{13}\text{CO}(1-0)\) emission from EMPIRE, Cormier et al. (2018) compared TIR estimates for all galaxies in our sample using both spectral energy distribution (SED) modeling and the prescriptions of Galametz et al. (2013). They find differences between the two estimates on the order of 10\% when the MIPS, PACS, and SPIRE bands are combined, and about 20\% when the MIPS bands alone are used.

4.6. Hydrostatic Pressure of the ISM

The gravitational potential of a galaxy at any point in the disk is the sum of contributions from the ISM, stars, and dark matter. In hydrostatic equilibrium, the midplane pressure of the gas in a galaxy disk will adjust to support its weight in this combined gravitational potential of gas and stars. We might expect this midplane external pressure to be coupled to the mean internal pressure of molecular clouds (e.g., Ostriker et al. 2010; Hughes et al. 2013), setting its individual pressure and (surface) densities before star formation takes place. These in turn may play a key role in regulating the cloud density structure and subsequent star formation.

In this picture the hydrostatic pressure, \(P_h\), increases with gas volume density, and it would determine not only the ability of the ISM to form molecular hydrogen (Elmegreen 1989; Elmegreen & Parravano 1994), but also the initial ability of gas at any particular density to form stars (e.g., Helfer & Blitz 1997; Usero et al. 2015; Meidt et al. 2018). As \(P_h\) rises, so would the mean density of the gas in the clouds, which would lead to higher observable dense gas fractions. Thus, a number of recent works have focused on this dynamical equilibrium pressure as a key parameter related to the fraction of dense gas and star formation across large parts of local galaxies (e.g., Gallagher et al. 2018a).

Following Elmegreen (1989), Wong & Blitz (2002), and Blitz & Rosolowsky (2006), the hydrostatic pressure required to balance the gravity on the gas in the disk can be expressed as
\[
P_h = \frac{\pi}{2} G \Sigma_{\text{gas}} \left( \Sigma_{\text{gas}} + \frac{\sigma_g}{\sigma_{\tau,z}^2} \Sigma_* \right),
\]
where \(\Sigma_{\text{gas}}\) is the total atomic and molecular surface density, \(\Sigma_*\) is the stellar surface density, \(\sigma_g\) is the velocity dispersion of the gas, and \(\sigma_{\tau,z}\) is the stellar velocity dispersion in the vertical direction. While the first term in the equation expresses the gas self-gravity, the second term reflects the weight of the gas in the stellar potential well. We neglect the contribution of dark matter to the mass volume density, which in the inner parts of galaxies is dominated by the stars near the disk midplane.

Because direct measurements of stellar velocity dispersion in nearby galaxy disks are rare, we adopt a series of assumptions to obtain \(P_h\) as a function of more easily observable quantities. Following Leroy et al. (2008), we assume a self-gravitating stellar disk characterized by a scale height \(h_* = \frac{1}{2} \sqrt{\frac{\sigma_{\tau,z}^2}{2G\rho_s}}\), where \(\rho_s\) is the stellar volume density. The scale height, \(h_*\), is typically observed to be constant with radius across the star-forming disks of spiral galaxies (e.g., van der Kruit & Freeman 1981; Kregel et al. 2002; van der Kruit & Freeman 2011). The stellar surface density and the midplane stellar volume density are then related: \(\Sigma_* \approx 4 \rho_s h_*\). We adopt \(\sigma_g \approx 15 \text{ km s}^{-1}\), a value observed to be appropriate for large scales and high surface density regions of galaxy disks (e.g., Tamburro et al. 2009; Caldú-Primo et al. 2013; Leroy et al. 2016; Sun et al. 2018). We refer to Leroy et al. (2008) and Gallagher et al. (2018a) for more detailed assumptions in the hydrostatic pressure derivation. We expect this pressure estimation to be a good representation of the time-averaged hydrostatic pressure needed to balance the galaxy disk against its own self-gravity and the stellar gravitational potential well.

In the following, we refer to it as dynamical-equilibrium pressure \(P_{DE}\).

4.7. Spectral Stacking Technique

The emission coming from high critical density tracers such as HCN is faint for individual lines of sight, especially in the inter-arm regions and outer parts of galaxies. The wide coverage of EMPIRE includes significant areas where our target lines are not detected at high significance over individual lines of sight. To increase the S/N, we thus also average independent spectra over extended regions (e.g., deriving radial profiles) using a spectral stacking technique that leverages our high S/N CO data as a prior (Schruba et al. 2011; Caldú-Primo et al. 2013; Jiménez-Donaire et al. 2017a).

Specifically, we measure the mean velocity along each line of sight from the \(^{12}\text{CO}\) line, and assume that the dense gas tracer emission is distributed over similar velocities (as we do observe in HCN-bright regions). This value, which varies across galaxy disks due to rotation, is then used as a reference for the spectral stacking. The velocity axis of all our spectral lines is then aligned to the local CO mean velocity, and the spectra are then subsequently stacked. In Figures 2 and 19–26 we provide an example of the resulting HCN spectral stacks (blue lines) in radial bins of 30\' for one EMPIRE galaxy.

We fit the stacked spectrum of each molecular line with a single-Gaussian profile or a double-horn profile. The latter profile is adapted to better describe some of the galaxy centers where the observed emission lines appear broad, with a flattened peak due to spatially unresolved gas motions that coincide with central bars or molecular rings. To perform the fit, we center a 100 \(\text{km s}^{-1}\) wide window on the peak of emission to have an initial guess for the line width and use the MPFIT function in IDL. The free parameters we calculate from the fit are the line center velocity, the peak intensity, and the velocity dispersion. We compute the uncertainties on the integrated intensity as
\[
\Delta I = I_{\text{rms}} \times \Delta v_{\text{chan}} \times \frac{\text{FWHM}_{\text{line}}}{\Delta v_{\text{chan}}},
\]
where $\sigma_{rms}$ is the 1σ rms value of the noise in K, which is measured from the signal-free part of the spectrum, $\Delta v_{chan}$ is the width of each channel in units of km s$^{-1}$, and $FWHM_{line}$ is the full width at half-maximum of the line derived from the fit, also in km s$^{-1}$. When the emission lines remain undetected (below 3σ rms of the noise), we compute 3σ upper limits on the integrated intensity. These are derived by integrating over a Gaussian profile with a peak set to the 3σ rms value of the noise, and a width set to the $FWHM_{line}$ found for the high S/N CO line, stacked over the same physical region.

5. Results

5.1. Distribution of Dense Gas Emission

Figures 3–11 show integrated-intensity maps and azimuthally averaged profiles of line intensities, line ratios, and physical conditions for each EMPIRE target. The top left panel shows the infrared dust continuum at 70 μm that traces the location of recent star formation activity. The top right panel shows the line-integrated $^{12}$CO(1−0) intensity from our new maps. Gray contours in the top right panel show the HCN(1−0) line integrated intensity. The middle row includes radial profiles for the brightest lines detected in the EMPIRE survey (left); and key quantities characterizing the galactic ISM structure (right). The bottom row shows the radial profiles of the ratios of the main dense gas tracers to CO(1−0), which trace molecular gas (HCN/CO, HCO$^+$/CO and HN/C/CO, left panel), and among the dense gas tracers (HCO$^+$/HCN, HNC/HCN, HNC/HCO$^+$, right panel).

Generally, the distribution of HCN intensity matches the large-scale structure traced by CO and 70 μm emission. The HCN intensity peaks at the center of each target and then appears prominent along the spiral arms (e.g., NGC 5055, NGC 5194, and NGC 6946) and central bars (e.g., NGC 2903 and NGC 3627). Globally, we find the brightest emission in NGC 6946 and the weakest in NGC 3184.

Outside galaxy centers, we find that the HCN-integrated intensity is ~30–70 times weaker than CO on average. As a result, we only detect the brightest individual lines of sight at high S/N in HCN. The spectral stacking approach described in Section 4.7 still allows us to recover the line signal at good S/N after integrating over a larger area.

The radial profiles in Figures 3–11 illustrate the success of this stacking approach. We bin the data by galactocentric radius, using 30′′ wide bins (~1–2 kpc at the distance of our sample). Within each bin, we create stacked spectra for each dense gas tracer and CO isotopologue (e.g., see Figure 2). Despite the faintness of HCN, we detect the average signal at high significance out to galactocentric radii ~9–11 kpc in HCN. This is similar to the radius of the solar circle. We also recover the average HCO$^+$ signal out to ~7–10 kpc, and detect HNC out to ~4–6 kpc. This represents the largest collection to date of extended resolved profiles of dense gas in nearby galaxies.

5.2. Molecular Line Ratios

5.2.1. Dense Gas Tracers to CO

In Figures 3–11 the stacked intensities of all lines ($^{12}$CO, $^{13}$CO, HCN, HCO$^+$, and HNC) decrease with increasing radius. On average, the emission of the dense gas tracers decreases more rapidly than that of lower density gas tracers $^{12}$CO and $^{13}$CO. In fact, in all galaxies except for NGC 628, HCN/CO (blue in the bottom left panel) appears highest in the galaxy center and then decreases with increasing galactocentric radius.

On average, HCN/CO decreases by a factor of ~2 across the range of radii where we detect it. The decline in HCN/CO appears similar in our barred (NGC 2903, NGC 3184, NGC 3627,
Figure 3. Atlas of observations for the EMPIRE sources. Top left: Herschel 70 μm map tracing star formation at its native resolution of ~6″. Top right: HCN (1−0) contours (0.5, 0.8 and 1.0 K km s\(^{-1}\), white) over \(^{12}\)CO(1−0) integrated intensity (K km s\(^{-1}\)) at 33″ resolution. Middle left: azimuthally stacked integrated-intensity profiles for the main EMPIRE lines in 30″ radial bins. The stacks span the entire galaxy disks out to ~8 kpc. Points show secure detections (>3σ), and arrows show 3σ upper limits. Middle right: surface density profiles for tracers of atomic (H\(^{\text{I}}\)), bulk molecular (CO), stellar (Spitzer 3.6 μm), and SFR (TIR) surface density and dynamical equilibrium pressure. Bottom: ratio (K km s\(^{-1}\)) of stacked integrated intensities of main dense gas tracers and CO integrated intensity (left) and among dense gas tracers (right) as a function of radius.
NGC 4321, and NGC 6946) and unbarred (NGC 628, NGC 4254, NGC 5055, and NGC 5194) targets. We observe the largest HCN/CO declines in NGC 3627 (~0.60 dex), NGC 4254 (~0.60 dex), NGC 5194 (~0.60 dex), and NGC 6946 (~0.55 dex). Again, we see no strong morphological divide; NGC 3627 and NGC 6946 are strongly barred galaxies with prominent dense gas emission in their centers and bars, while NGC 4254 and NGC 5194 are unbarred galaxies rich in molecular gas.

We quantify differences between the central pointing and the rest of each galaxy, which we refer to as the “disk.” Following Cormier et al. (2018), we take the “center” to have a radius of

Figure 4. Continued for NGC 2903. Spitzer 24 μm data are used in the case of NGC 2903 as an SFR tracer because no Herschel data are available. The HCN(1−0) contours employed are 0.5, 0.8 and 1.7 K km s⁻¹.
16'' ≈ 0.8 kpc (i.e., one resolution element). The disk includes all other emission above a low-intensity threshold (∼2 K km s$^{-1}$) and excludes center. For each galaxy center and each disk region, we create stacked spectra for each emission line. We use them to measure average intensities and line ratios. We calculate the mean ratios for barred galaxies and unbarred galaxies separately, as well as for the entire sample, and report them in Table 4 and Figure 12. We also note the implied dense gas fractions, adopting the fiducial conversion factors.$^{20}$

$^{20}$ We apply our adopted HCN conversion factor to HCO$^+$ and HNC. The dense gas fractions inferred from these lines should be taken as more approximate than that from HCN.
From HCN/CO, we estimate dense gas fractions \( f_{\text{dense}} \) as described in Section 4 of 6%–10% for the EMPIRE galaxy centers. They show twice as much dense gas than galaxy disks, where \( f_{\text{dense}} \approx 5\% \). We also find similar HCN/CO, HCO\(^+\)/CO, and HNC/CO ratios by comparing barred and unbarred galaxies.

While we do not find a clear link to bars, the concentration of gas at the galaxy center does appear to drive high HCN/CO ratios. Figure 12 shows that high HCN/CO, HCO\(^+\)/CO, and HNC/CO values tend to appear in regions with high CO intensity. Modulo conversion factor effects, these high CO intensities indicate high concentrations of gas in the galaxy.
Achieving a high dense gas fraction at the galaxy center appears to require concentrating a large amount of gas at the galaxy center. We return to this point in Section 5.4.

Figure 12 shows similar trends in HCN/CO, HCO⁺/CO, and HNC/CO. The similarity among all three lines suggests that the results do reflect a changing gas density. However, a changing density may not be the only effect. Galaxy centers also host conditions that can lead to increased HCN excitation at fixed density. Increased gas temperatures by excitation by electrons, UV, X-rays, cosmic rays, and mechanical heating have all been suggested to increase HCN emission (see, e.g., Kohno et al. 2001; Izumi et al. 2013; Bisbas et al. 2015; Goldsmith & Kauffmann 2017). We return to this in Sections 5.4 and 6.4.

Figure 7. Continued for NGC 4254. The HCN(1–0) contours employed are 0.3, 0.7, and 1.0 K km s⁻¹.
Our dense gas fractions estimated from HCN/CO agree well with recent literature measurements in nearby galaxies. The recent higher resolution ($8'' \sim 500$ pc) study of nearby galaxies presented by Gallagher et al. (2018a) shows that a median value of 10% is characteristic of the inner kiloparsec of four nearby galaxy disks (NGC 3351, NGC 3627, NGC 4254, and NGC 4321). Our EMPIRE central dense gas fractions are 9%, 7%, and 10% for NGC 3627, NGC 4254, and NGC 4321, respectively. These are in good agreement with the results in Gallagher et al. (2018a). The small differences are likely due to the larger beam size in EMPIRE, which will encompass more extended emission. We find very similar $f_{\text{dense}}$ values to those from Usero et al. (2015; median values of 8% in all disk pointings and 5% excluding the centers) and slightly lower
values than those from Gao & Solomon (2004; 12%). This is most likely attributable to the fact that EMPIRE median values are dominated by disk positions with overall lower $f_{\text{dense}}$, while Gao & Solomon (2004) measured galaxy averages (with total luminosities dominated by the central enhancements) and focused on IR-bright and starburst galaxies. All of these studies also adopted our fiducial $\alpha_{\text{HCN}}$.

5.2.2. Ratios Among Dense Gas Tracers

Table 4 also provides the average line ratios among our high-density tracers HCO$^+$/HCN and HNC/HCN. We find average HCO$^+$/HCN values of $\sim$0.8 and HNC/HCN values of $\sim$0.5 across the disks of our targets. These measurements agree with observations of the Milky Way CMZ and Galactic GMCs (e.g.,

Figure 9. Continued for NGC 5055. The HCN(1−0) contours employed are 0.3, 0.9, and 1.6 K km s$^{-1}$. 

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Jones et al. 2012, ~0.6), nearby galaxies (such as M51, NGC 253, and NGC 6946; Meier et al. 2014, 2015; Chen et al. 2015, ~0.6–1.1), and a number of LIRGs (e.g., Loenen et al. 2008; Privon et al. 2015, ~0.5–2.0).

We plot profiles of HCO\(^+\)/HCN, HCO\(^+\)/HNC, and HNC/HCN in the bottom right panels of Figures 3–11. The behavior of the HCO\(^+\)/HNC and HNC/HCN profiles is only weakly constrained due to our lower HNC detection rate. On the other hand, HCN and HCO\(^+\) exhibit almost identical profiles in NGC 3627, NGC 4254, NGC 4321, NGC 5194, and NGC 6946. In these targets we only observe significant differences in the galaxy centers and at large radii. This resembles the results seen at

Figure 10. Continued for NGC 5194. The HCN(1−0) contours employed are 0.3, 0.9, 2.1, and 3.3 K km s\(^{-1}\).
higher resolution over a smaller field of view by Gallagher et al. (2018a). The authors find almost identical radial profiles for the two lines in the inner ∼4 kpc of their five targets.

The HCO$^+$/HCN line ratios measured across our galaxy sample are close to unity and change little over the galaxy disks. This suggests that HCN and HCO$^+$ lines might be slightly subthermal across the galaxy disks (Knudsen et al. 2007; Meier et al. 2015) if both are optically thick, as shown in, e.g., Jiménez-Donaire et al. (2017a).

Two targets, NGC 4254 and NGC 6946, show HCO$^+$-to-HCN profiles that are a function of increasing radius, where the typical ratio reaches values up to ∼1.5. These values are higher than those

Figure 11. Continued for NGC 6946. The HCN(1−0) contours employed are 0.4, 1.4, and 4.7 K km s$^{-1}$.
found in their central regions (\( \sim -0.8 \)). Because HCO\(^+\) has a lower critical density than HCN (see Table 2), the changing HCO\(^+\)/HCN values could simply be attributed to a changing gas density across these disks. Higher HCO\(^+\)/HCN values are also found in lower metallicity systems such as IC 10 (1.1–2.8, Nishimura et al. 2016; Braine et al. 2017; Kepley et al. 2018), M31 (1.2, Brouillet et al. 2005), M33 (1.1–2.5, Buchbender et al. 2013; Braine et al. 2017), or the Magellanic Clouds (1.8–3, Chin et al. 1997, 1998), possibly because less nitrogen is produced by massive stars (Vincenzo et al. 2016). However, the slightly rising HNC/HCN profiles in these two targets prevent us from concluding whether the higher HCO\(^+\)-to-HCN ratios can be associated with the reduction of nitrogen-bearing molecules such as HCN or HNC. Alternatively, the HNC/HCN abundance ratio could increase at lower temperatures because the chemical balance between the two species is relatively more favorable to HNC. This would also cause the HCO\(^+\)/HCN profiles to increase in these regions.

5.3. IR-HCN Scaling Relations

In Figure 13 we plot the IR luminosity, tracing the SFR, as a function of the HCN luminosity, which traces the dense gas content. Light red dots show lines of sight from EMPiRE with S/N > 3 HCN detections. We also show an integrated measurement for each EMPiRE target as a filled gray circle.

We compare EMPiRE to an extensive compilation of literature measurements. This includes measurements of Galactic dense gas cores (Wu et al. 2010; Stephens et al. 2016), individual giant molecular clouds (GMCs) in the SMC, LMC, and other low-metallicity galaxies (Chin et al. 1997, 1998; Braine et al. 2017), giant molecular associations in nearby galaxies (Brouillet et al. 2005; Buchbender et al. 2013; Chen et al. 2017), resolved nearby galaxy disks (Kepley et al. 2014; Bigiel et al. 2015; Chen et al. 2015; Usero et al. 2015; Gallagher et al. 2018), and whole galaxies and galaxy centers (Gao & Solomon 2004; Gao et al. 2007; Krips et al. 2008; Graciá-Carpio et al. 2008; Juneau et al. 2009; García-Burillo et al. 2012; Crocker et al. 2012; Priyv et al. 2015). In total, we plot 225 data points for resolved cores and GMCs, 194 data points correspond to observations of entire galaxies or bright galaxy centers, and 415 data points (including the high S/N EMPiRE detections) for resolved (\( \sim -0.3–2\) kpc) galaxy disks. This literature collection is available in Table 11. The plots also include data for the Milky Way CMZ (i.e., the inner \( \sim -500\) pc; Jones et al. 2012). The ensemble of data in Figure 13 follows the same relationship as was found by Gao & Solomon (2004), who related IR and HCN emission in starbursts and IR-bright whole galaxies. As shown before (e.g., Wu et al. 2005), this scaling relation spans almost 10 orders of magnitude in IR and HCN luminosity. Moreover, the relationship appears approximately linear. Gray lines in Figure 13 show the mean IR-to-HCN ratio found across the entire data set (including EMPiRE). In Table 5 we report the mean IR-to-HCN ratios for each type of data in the plot.

Table 4

| Table 4 | Average Dense Gas Line Ratios (Observed Integrated Intensities, Excluding Upper Limits), Separated into Central Pointings and Disks, for the EMPiRE Spiral Galaxies |
|--------|---------------------------------------------------------------|
| Ratio   | Center (Inner 30° \( \sim -1–2\) kpc) | Disk (Excl. Center) | All |
| --------|---------------------------------------------|-----------------------------|------|
| HCN/CO  | 0.030(2) (6.8 ± 0.5%) | 0.034(2) (7.7 ± 0.5%) | 0.018(2) (4.0 ± 2.0%) |
| HCO\(^+\)/CO | 0.024(2) (5.4 ± 0.5%) | 0.025(2) (5.7 ± 0.5%) | 0.014(5) (3.2 ± 1.0%) |
| HNC/CO  | 0.013(2) (2.9 ± 0.5%) | 0.014(2) (3.2 ± 0.5%) | 0.010(3) (2.3 ± 0.8%) |
| HCO\(^+\)/HCN | 0.8 ± 0.1 | 0.7 ± 0.1 | 0.8 ± 0.2 |
| HNC/HCN | 0.4 ± 0.1 | 0.4 ± 0.1 | 0.6 ± 0.2 |

Note. The percentage numbers in parenthesis show the dense gas fractions (\( J_{\text{h2}} \)) computed using the fiducial conversion factors from Section 4. The quoted uncertainties are estimated as weighted means of the uncertainties derived as indicated in Section 4.7.

\( \text{Figure 12. Ratio of high to low critical density tracers for the central pointing (circles) and rest of the disk (squares) of the EMPiRE galaxies. The exact values and uncertainties are described in Table 4. Upper limits to the stacked line ratios are represented by open symbols. Symbols corresponding to barred galaxies are outlined with black contours.} \)
Our new EMPIRE measurements and the other resolved kiloparsec-scale data partly fill the gap between the resolved cores (∼0.5 pc), individual clouds (∼10–100 pc), and the integrated emission from whole galaxies. We caution that while this represents an appealing way to visualize our data, the luminosity of a pointing in an EMPIRE disk is somewhat arbitrary. We could define larger or smaller regions and so shift the data in luminosity. As emphasized in the previous and next sections, the key physics in EMPIRE comes from resolved ratios of lines and tracers of recent star formation.

In that sense, the key point for Figure 13 is the good agreement between the IR-to-HCN ratio in EMPIRE and that from previous work. The bottom panels in Figure 13 plot this L_{IR}/L_{HCN} ratio, which has been widely used as a tracer of the SFR per unit dense gas (SF_{dense}). We find a mean ratio of ∼776 L_{⊙}/(K km s^{-1} pc^{2}) throughout our whole compilation (Table 5).
Notes. We include the 1σ rms scatter found for each sample. The \(L_{IR} \rightarrow L_{HCN}\) Spearman’s rank correlation coefficients and their \(p\)-values (in parenthesis) are also indicated in the table.

### Table 5

| Sample            | \(\log_{10}(L_{IR}/L_{HCN})\) | Scattering | Spearman’s Rank Corr. |
|-------------------|-------------------------------|------------|-----------------------|
| Unresolved galaxies | 2.99                          | ±0.30 dex  | 0.91 (<0.01)          |
| Resolved galaxy disks | 2.85                          | ±0.24 dex  | 0.79 (<0.01)          |
| MW cores and nearby clouds | 2.85                          | ±0.47 dex  | 0.85 (<0.01)          |
| Combined          | 2.89                          | ±0.37 dex  | 0.96 (<0.01)          |

### Table 6

![Table 6](source)

Rank Correlation Coefficients of HCN/CO (Proxy for Dense Gas Fraction) and TIR/HCN (Proxy for Star Formation Efficiency of Dense Gas) as a Function of Galactocentric Radius, Stellar Surface Density, Molecular Gas Surface Density, Ratio of Molecular-to-atomic Gas, and Local Dynamical Equilibrium Pressure

**Notes.**

- \(^{a}\) Unbarred galaxies.
- \(^{b}\) Barred galaxies. The numbers in parentheses indicate the corresponding \(p\)-values.

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Figure 13 also illustrates the significant scatter in IR-to-HCN in our data, which we also report in Table 5. We find an rms scatter of 0.37 dex for all objects. We find a smaller but still significant value of \(\sim 0.3\) dex for whole galaxies and \(\sim 0.25\) dex for resolved regions in nearby galaxies (see Appendix F for a detailed estimation of the physical scatter in EMPIRE measurements).

Some of this scatter reflects measurement uncertainty, and on small scales, stochasticity may play an important role. On the scale of resolved galaxy disks, much of this scatter has a physical origin. We see below that in EMPIRE, the IR-to-HCN ratio shows systematic trends as a function of environment (following Usero et al. 2015; Bigiel et al. 2016; Gallagher et al. 2018a). As discussed in Section 1.1, the Milky Way and other galaxy centers show low ratios of star formation to dense gas. This also points to a physical origin for much of the scatter in Figure 13.

#### 5.4. Dense Gas Fraction and SFE\(_{\text{dense}}\)

We designed EMPIRE to measure how the dense gas fraction, \(f_{\text{dense}}\), and the SFE of dense gas, \(SFE_{\text{dense}}\), depend on location and local conditions inside a galaxy disk. Here, we address these questions using our brightest dense gas tracer, HCN(1\( \rightarrow \)0).

Figure 14 plots \(f_{\text{dense}}\) and \(SFE_{\text{dense}}\) as likely functions of galactocentric radius and local conditions relevant to the formation and behavior of dense gas: stellar surface density (\(\Sigma_\star\)), molecular gas surface density (\(\Sigma_{\text{mol}}\)), the ratio of the ISM in a molecular phase (\(R_{\text{mol}} = \Sigma_{\text{mol}}/\Sigma_{\text{H}_2}\)), and the pressure...
To construct these plots, we define bins in stellar surface density, molecular-to-atomic gas fraction, and dynamical equilibrium pressure. We sort each galaxy by each quantity, identifying all lines of sight in each bin. Then, we stack all CO and HCN spectra and TIR intensities in each bin. We used these stacked CO, stacked HCN, and stacked TIR measurements to compute the average HCN-to-CO fraction and IR-to-HCN ratio in every bin. The error bars that we report in the plots include uncertainties from the statistical noise and from the spectral fitting.

In the main text, we focus on these stacked profiles to reveal the underlying physical trends in the data. This averaging technique is a core part of the EMPIRE experiment design and allows us to explore whole galaxy disks. In the Appendices...
(see Figures 27, 29, 33, and 35), we present measurements of the same trends by plotting each individual line of sight.

5.4.1. Dense Gas Fraction

The left panels of Figure 14 show the variation in HCN-to-CO ratio, which traces \( f_{\text{dense}} \), as a function of galactocentric radius, stellar surface density, molecular-to-atomic gas fraction, and \( P_{\text{DE}} \). In all targets, \( f_{\text{dense}} \) increases toward the galactic centers. We see similar stacked trends in the stellar surface density \( (\Sigma^* \text{ up to } 10^3 - 10^4 M_\odot \text{ pc}^{-2}) \), molecular-to-atomic gas fractions \( (R_{\text{mol}} \sim 10^2) \), and equilibrium pressure \( (P_{\text{DE}}/k_B \sim 10^6 - 10^7 \text{ Kcm}^{-3}) \). HCN-to-CO correlates positively with all of these quantities. Individual galaxies do show distinct relationships, so that the stacked trends appear offset in the galaxies.

The positive correlations of HCN-to-CO with \( \Sigma^*, f_{\text{mol}}, \) and \( P_{\text{DE}} \) agree with previous observations of kiloparsec-size regions in nearby galaxies (e.g., Usero et al. 2015; Chen et al. 2015; Bigiel et al. 2016; Gallagher et al. 2018a). The stacked trends in Figure 14 cover the whole area of active star formation across a significant sample of whole galaxies. As a result, Figure 14 represents the best systematic characterization to date of the dependence of \( f_{\text{dense}} \) on local conditions. Physically, all of the trends convey that \( f_{\text{dense}} \) appears higher at higher stellar surface densities, higher molecular-to-atomic ratios, and higher midplane pressures.

We measure the strength of the correlation between \( f_{\text{dense}} \) and our environmental measurements using the Spearman rank correlation coefficient, \( \rho \). Table 6 reports \( \rho \) for each environmental measure, each target, and all targets together. The \( \rho \) coefficient quantifies the degree to which \( f_{\text{dense}} \) and the other quantity track one another monotonically in our binned measurements. To assess the uncertainty in our measured \( \rho \), we repeatedly add noise to our measurements; the magnitude reflects the associated uncertainties. We take the scatter across 1000 such Monte Carlo realizations to be the uncertainty in \( \rho \). We caution that because our bins have not been chosen for the purpose of rigorous statistical comparison, \( \rho \) should only be qualitatively compared between quantities.

We also quantify the relationship between HCN-to-CO and local conditions using power-law fits (Figure 14). We fit lines to the stacked trends in log–log space, neglecting upper limits (i.e., the bins with stacked \( S/N < 3 \) for HCN). We weight all bins equally. While these fits capture general trends, large galaxy-to-galaxy scatter remains in each scaling relation. This implies that for each of these fits, significant additional physics beyond only the two variables we considered affects the observed relation. As a complement, we provide weighted averages of fit parameters for each galaxy trend and discuss the scatter introduced by galaxy variations below.

**Galactocentric radius:** HCN-to-CO is anticorrelated with galactocentric radius. The following power law describes our
data:
\[ \log_{10} \frac{\text{HCN}}{\text{CO}} = (-1.5 \pm 0.2) - (0.8 \pm 0.2) \log_{10} \frac{r}{r_{25}}, \] (9)

where \( r_{25} \) is the 25th magnitude \( B \)-band isophotal radius from LEDA (Paturel et al. 2003). Our data mostly lie in the range 0–0.6 \( r_{25} \), and the fit should apply over this range. Individual binned measurements scatter by \( \pm 0.20 \) dex about this fit, with most scatter driven by galaxy-to-galaxy variations. Our central measurements out to \( \sim 2 \) kpc in radius (confined to the inner two bins) show even more scatter, \( \pm 0.35 \) dex.

It is easy to understand an anticorrelation of galactocentric radius and \( f_{\text{dense}} \): Bars, interactions, and the inner parts of strong spiral arms can drive significant masses of gas toward the inner parts of disks (e.g., Athanassoula 1992; Kormendy & Kennicutt 2004; Sormani et al. 2018). As a result, galaxy centers tend to show higher gas surface densities than the rest of the disk. The central parts of galaxies also have the highest stellar surface densities in the disk. Thus there tends to be more gas and a deeper potential well in the inner parts of galaxies. These two factors should lead to higher gas densities at smaller radii. In turn, this leads us to expect both higher HCN intensities and higher HCN-to-CO ratios in the inner parts of galaxies.

Individual galaxies show distinct trends in Figure 14. Barred galaxies show stronger anticorrelations (\( \rho \sim -0.7 \)) between \( f_{\text{dense}} \) and radius than unbarred galaxies (\( \rho \sim -0.3 \)). Galaxies also appear offset from one another at fixed radius, reflecting that the same radius may correspond to different physical conditions in different galaxies. In the next few panels we plot \( f_{\text{dense}} \) as a function of gas or stellar surface density, and we see greater similarity among all galaxies.

**Stellar surface density:** We expect high \( f_{\text{dense}} \) where the gravitational potential is deeper (e.g., Helfer & Blitz 1997). Stars represent the dominant mass component in the inner part of most galaxy disks. Therefore, following Usero et al. (2015), Bigiel et al. (2016), and Gallagher et al. (2018a), the stellar surface density should be a good predictor of \( f_{\text{dense}} \) at least in regions with abundant gas.

Figure 14 and Table 6 indeed show a strong trend in each galaxy that also appears similar among galaxies. Our best-fit power law relating \( I_{\text{HCN}}/I_{\text{CO}} \) to \( \Sigma_* \) is

\[ \log_{10} \frac{\text{HCN}}{\text{CO}} = (-2.7 \pm 0.2) + (0.4 \pm 0.1) \log_{10} \frac{\Sigma_*}{M_\odot \, \text{pc}^{-2}} . \] (10)

This is valid at \( \sim 1–2 \) kpc resolution and mostly over the range \( \Sigma_* \sim 100–1000 \, M_\odot \, \text{pc}^{-2} \). Individual bins show a scatter of \( \sim 0.2 \) dex about this line, again driven mostly by galaxy-to-galaxy variations.

Our best-fit relation agrees well with that found by Usero et al. (2015). The slope is slightly shallower and offset by 0.6 dex than the relation found in the resolved inner regions of nearby galaxies by Gallagher et al. (2018a).

**Molecular gas surface density:** In Section 5.2 we saw that high HCN-to-CO ratios correlate with the intensity of CO in galaxy centers. The higher concentrations of denser gas in regions with higher mean gas surface density arise for the simple reason that these high surface densities indicate a large amount of gas that is concentrated in a small area. Gallagher et al. (2018a) found that HCN/CO correlates with \( \Sigma_{\text{mol}} \) at \( \sim 500 \) pc scales as well as with \( \Sigma_{\text{mol}} \) on cloud scales (Gallagher et al. 2018b).

We plot the observable ratio HCN/CO as a function of \( \Sigma_{\text{mol}} \) in Figure 14 and fit the following scaling relation:

\[ \log_{10} \frac{\text{HCN}}{\text{CO}} = (-2.4 \pm 0.2) + (0.5 \pm 0.1) \log_{10} \frac{\Sigma_{\text{mol}}}{M_\odot \, \text{pc}^{-2}} . \] (11)

This holds at \( \sim 1–2 \) kpc resolution over the range \( \Sigma_{\text{mol}} \sim 1–400 \, M_\odot \, \text{pc}^{-2} \). We find \( 0.18 \) dex scatter about the fit. We recall that we adopt a fixed \( \alpha_{\text{CO}} = 4.4 \, M_\odot \, \text{pc}^{-2} \, (\text{K km s}^{-1})^{-1} \) and do not implement any environment-dependent conversion factor. Therefore, Equation (11) formally captures the scaling between HCN-to-CO and \( I_{\text{CO}} \).

Thus HCN/CO, which traces the fraction of dense gas, correlates well with both stellar and gas surface densities in EMPIRE. More gas and a deeper stellar potential well imply higher gas densities. Our targets mostly show a common behavior; the main outlier is NGC 6946. This galaxy appears moderately displaced toward lower HCN-to-CO ratios at a fixed \( \Sigma_{\text{mol}} \) or \( \Sigma_* \). NGC 6946 also shows evidence of a radius-dependent conversion factor (Sandstrom et al. 2013). When this effect is accounted for, the points from this galaxy are expected to be moved into better agreement with the rest of our data, provided that the variations in HCN conversion factor are milder.

**Molecular-to-atomic gas ratio:** The local ratio of molecular to atomic gas reflects the interstellar density and pressure. A greater fraction of gas in denser pressure environments is in the molecular phase (e.g., Wong & Blitz 2002; Blitz & Rosolowsky 2006; Leroy et al. 2008), although factors such as the radiation field and dust abundance also play a role (e.g., Pellegrini et al. 2009; Wolfire et al. 2010; Sternberg et al. 2014). Usero et al. (2015) showed that \( f_{\text{dense}} \) correlates with the molecular-to-atomic gas ratio. This implies that the same facts that cause gas to become molecular may also drive gas to higher densities.

We fit the following relation:

\[ \log_{10} \frac{\text{HCN}}{\text{CO}} = (-1.8 \pm 0.1) + (0.42 \pm 0.04) \log_{10} R_{\text{mol}} . \] (12)

The relationship holds at \( 1–2 \) kpc resolution and over the range \( R_{\text{mol}} \sim 0.5–100 \). We again find \( \pm 0.2 \) dex scatter from galaxy to galaxy at fixed \( R_{\text{mol}} \). NGC 6946 appears offset from the relations we found for the rest of galaxy disks, probably because the CO-to-molecular gas surface density conversion factor is variable.

**Dynamical equilibrium pressure:** The correlations with surface density and \( R_{\text{mol}} \) could be expected if the mean turbulent interstellar pressure is closely coupled to the gas density distribution (see Helfer & Blitz 1997; Usero et al. 2015; Gallagher et al. 2018a). When we assume vertical hydrostatic equilibrium, the mean interstellar pressure must balance the weight of the gas in the potential well (see references and discussion in Section 4.6). We plot \( f_{\text{dense}} \) as a function of pressure in Figure 14. There we do observe a clear correlation, but again with some notable outliers.
We fit the following power law relating $I_{\text{HCN}}/I_{\text{CO}}$ to $P_{\text{DE}}$:

$$\log_{10} \frac{I_{\text{HCN}}}{I_{\text{CO}}} = (-4.9 \pm 0.4) + (0.6 \pm 0.1) \log_{10} \left[ \frac{P_{\text{DE}}}{k_B \, \text{cm}^{-3} \text{K}} \right].$$  (13)

This holds at 1–2 kpc resolution over the range $\log_{10} P_{\text{DE}}/k_B [\text{K cm}^{-3}] \sim 4.5$–6.5. Again, our individual binned stacks scatter by $\pm 0.2$ dex rms about the measurement.

Similar to our results for $R_{\text{mol}}$, $I_{\text{HCN}}/I_{\text{CO}}$ correlates strongly with $P_{\text{DE}}$ in each individual galaxy. This appears true for both barred ($\rho \sim 0.9$) and unbarred galaxies ($\rho \sim 0.8$). These correlations show similar slopes (within 10%) for different galaxy disks. However, the overall correlation appears weaker because the stacked relations show considerable offset from one another. Again, NGC 6946 appears to be a significant outlier, possibly due to conversion factor effects. In this plot, NGC 4254 also appears to be a significant outlier.

In theory, $P_{\text{DE}}$ represents the most direct physical driver of density that we test. If $I_{\text{HCN}}/I_{\text{CO}}$ traces $f_{\text{dense}}$, and we estimate $P_{\text{DE}}$ correctly, then our observations imply that while the $\sim 1$–2 kpc mean pressure scales with $f_{\text{dense}}$, other physics also play an important role. In addition to the conversion factor effects discussed above, we might also expect the structure of the gas within our large beam to play a role. Our observations do not distinguish between gas that is concentrated in a few massive dense clouds and gas that is spread through a diffuse layer. Comparisons to higher resolution CO mapping of our targets (e.g., Gallagher et al. 2018b; Sun et al. 2018) will help to clarify the role of the detailed ISM structure in producing this galaxy-to-galaxy scatter.

**Dense gas fraction and environment:** The measurements in this section represent the most thorough view to date of the dependence of the HCN-to-CO ratio, which traces $f_{\text{dense}}$, on the environment in nearby galaxies. Our results agree well with previous work by Usero et al. (2015), Bigiel et al. (2016), and Gallagher et al. (2018a), but they extend these studies to a wider area and offer a more complete coverage of a sample of galaxies. EMPIRE recovers HCN emission out to radii similar to the solar circle and spanning a wide range of local conditions: out to $\sim 8$–10 kpc in galactic radius, $\Sigma_\ast$ ranging from $\sim 30$ to $3200 \, M_\odot \, \text{pc}^{-2}$, molecular gas surface densities up to $\Sigma_{\text{mol}} \sim 300 \, M_\odot \, \text{pc}^{-2}$, three orders of magnitude in $R_{\text{mol}}$ (typical ratios range from $\sim 0.1$ to 2), and more than two orders of magnitude in $P_{\text{DE}}$. The correlations, fits, and stacked profiles that we present should provide a basic reference for how the HCN-to-CO ratio behaves across galaxies.

We find $f_{\text{dense}}$ traced by HCN-to-CO to vary significantly as a function of local environment. $f_{\text{dense}}$ appears higher in regions with high stellar and gas surface densities, high interstellar pressures, and high molecular gas fractions. These conditions tend to occur more in the inner parts of galaxies, and we also observe that $f_{\text{dense}}$ appears to be anticorrelated with galactocentric radius. These correlations are often very strong for individual galaxies and appear almost monotonic in our binned data. However, the relationship between $f_{\text{dense}}$ and each of these quantities still shows significant galaxy-to-galaxy scatter; the typical rms scatter is $\pm 0.2$ dex. This exceeds our measurement errors and highlights that additional physics are still at play. In addition to uncertainties in physical parameter estimation, we highlight an important possible role for the ISM structure below the 1–2 kpc resolution of our data (i.e., beam filling factor variations). We also emphasize that the role of galactic dynamics (other than vertical force balance) remains relatively unexplored so far (but see Meidt 2016; Meidt et al. 2018).

### 5.4.2. Star Formation Efficiency of Dense Gas

At face value, the ratio of TIR-to-HCN emission traces the SFE of dense gas, $\text{SFE}_{\text{dense}} \equiv \text{SFR}/M_{\text{dense}}$. In the right panels of Figure 14, the lower part of Table 6, and the fits in this section, we measure the dependence of $\text{SFE}_{\text{dense}}$ on environment in EMPIRE. In the main text, we again focus on stacked trends. In the appendix, we show every individual kiloparsec measurement (Figures 28, 30, 34 and 36).

Figure 14 shows that $\text{SFE}_{\text{dense}} \propto \text{TIR}/\text{HCN}$ generally increases toward large galactocentric radii, and systematically decreases toward regions of high stellar surface density, high molecular gas surface density, high molecular fraction, and high pressure. These trends all contrast with what we observed for $f_{\text{dense}}$, where the systematic behavior has the opposite sense. The clear correlation of $\text{SFE}_{\text{dense}}$ with environment shows that the observed scatter about the $L_{\text{IR}}–I_{\text{HCN}}$ scaling relation (Section 5.3) reflects real correlations of $\text{SFE}_{\text{dense}}$ with local environment.

**Galactocentric radius:** $\text{SFE}_{\text{dense}}$ tends to rise with increasing galactocentric radius, but with large galaxy-to-galaxy scatter. Our best fit of $I_{\text{TIR}}/I_{\text{HCN}}$ and galactocentric radius is

$$\log_{10} \frac{I_{\text{TIR}}}{I_{\text{HCN}}} = (2.8 \pm 0.3) + (0.6 \pm 0.2) \frac{r}{r_{25}},$$  (14)

with an overall scatter of $\pm 0.30$ dex from galaxy to galaxy at fixed radius. We quote the fit here in terms of the TIR-to-HCN ratio, which has units of $L_{\odot}/(K \, \text{km s}^{-1} \text{pc}^2)$.

$\text{SFE}_{\text{dense}}$ increases with increasing galactocentric radius in most of our targets. The large galaxy-to-galaxy scatter means, however, that radius alone does not predict the TIR-to-HCN ratio well. As with $f_{\text{dense}}$, the same radius in different galaxies corresponds to different physical conditions in a way that affects $\text{SFE}_{\text{dense}}$.

The increase in $\text{SFE}_{\text{dense}}$ with radius appears in both barred ($\rho \sim 0.7$) and unbarred ($\rho \sim 0.6$) galaxies. We observe some difference in the shape of the profile between these two groups, however. For unbarred galaxies the $I_{\text{TIR}}/I_{\text{HCN}}$ profile often appears quite flat across most of the galaxy disk, with a lower value in the inner $\sim 2$ kpc of the galaxy. In barred galaxies, the profiles appear smoother, and TIR-to-HCN steadily increases with increasing radius.

We note that with the resolution of the EMPIRE data, we cannot rule out the effects of galaxy dynamics in these radial trends. More specifically, barred galaxies in which bars are smaller than their corotation regions often show pile-ups of gas in the leading edges of the bar (e.g., Downes et al. 1996; Sheth et al. 2005; Beuther et al. 2016). This particular orbit structure creates shear motions in the molecular gas, and little star formation occurs, thus the SFE is lower, which is typically restricted to the resonances of the bar. In addition to this, nuclear bars such as those present in NGC 4321 (Sakamoto et al. 1995; García-Burillo et al. 1998) may also be responsible for this orbit structure and contribute to the lower SFE observed in barred galaxy centers.

**Stellar surface density:** The middle right panel of Figure 14 demonstrates an overall anticorrelation of $I_{\text{TIR}}/I_{\text{HCN}}$ and stellar surface density. In fact, all individual galaxies show an
anticorrelation between IR/HCN and $\Sigma_*$, and all but three galaxies show a strong anticorrelation (see Table 6). A good fit to our data is given by

$$\log_{10} \frac{TIR}{HCN} = (4.0 \pm 0.3) - (0.4 \pm 0.1) \log_{10} \left( \frac{\Sigma_*}{M_\odot \, pc^{-2}} \right).$$

(15)

This fit holds for disk galaxies at $\sim$1–2 kpc resolution over the range $\Sigma_* \sim 100$–1000 $M_\odot \, pc^{-2}$. Individual binned measurements show an rms scatter of $\pm 0.26$ dex about the fit.

These trends with stellar surface density resemble those seen by Usero et al. (2015), Bigiel et al. (2016), and Gallagher et al. (2018a). The same conditions that cause the gas to become denser on average also appear to drive SFE$_{dense}$ to lower values.

**Molecular gas surface density:** Above, we find higher $f_{dense}$ in regions with higher $\Sigma_{mol}$. Considering SFE$_{dense}$, the trend reverses. We find lower $I_{IR}/I_{HCN}$ in regions of high $\Sigma_{mol}$. Similar to the case for $\Sigma_*$, the entire sample shows an overall strong anticorrelation ($\rho = -0.64$) between $\Sigma_{mol}$ and $I_{IR}/I_{HCN}$. This anticorrelation appears even stronger in many individual galaxies, again reflecting offset trends among galaxies.

Our EMPIRE data are well-described by

$$\log_{10} \frac{TIR}{HCN} = (3.5 \pm 0.7) - (0.4 \pm 0.1) \log_{10} \left( \frac{\Sigma_{mol}}{M_\odot \, pc^{-2}} \right).$$

(16)

The fit holds over $\Sigma_{mol} \sim 10$–100 $M_\odot \, pc^{-2}$ at 1–2 kpc resolution. The individual measurements scatter by $\pm 0.22$ dex scatter about the global fit. As in the $f_{dense}$-$\Sigma_{mol}$ correlation, NGC 6946 appears moderately displaced toward higher TIR-TOHCN ratios at fixed $\Sigma_{mol}$. This could be related to the radius-dependent conversion factor seen in Sandstrom et al. (2013).

To explain similar trends, Usero et al. (2015), Bigiel et al. (2016), and Gallagher et al. (2018a) suggested a context-dependent role for the dense gas traced by HCN. In this scenario, which we discuss in more detail below, the anticorrelations observed between SFE$_{dense}$ and $\Sigma_*$ or $\Sigma_{mol}$ may occur because the mean density of the ISM rises in regions with high $\Sigma_*$ and high $\Sigma_{mol}$ (this appears to be the case in EMPIRE and Gallagher et al. 2018b). In this case, the HCN may trace gas at lower density than the local density required for gas to collapse and subsequently form stars.

**Molecular-to-atomic gas ratio:** Given that SFE$_{dense}$ is anticorrelated with $\Sigma_*$ and $\Sigma_{mol}$, we also expect an anticorrelation with the ratio of molecular to atomic gas, $R_{mol}$. We observe an anticorrelation in most targets, but the scatter among galaxies is larger than the dynamic range of the observations.

We find a best-fit relation

$$\log_{10} \frac{TIR}{HCN} = (3.1 \pm 0.1) - (0.30 \pm 0.06) R_{mol},$$

(17)

which holds over the range $R_{mol} \sim 0.3$–10 at $\sim$1–2 kpc resolution. Compared to the trends with $\Sigma_*$, $\Sigma_{mol}$, the correlation of SFE$_{dense}$ shows a significantly weaker correlation coefficient of $-0.38$, and the data scatter about the fit with rms $\pm 0.28$ dex. Again, most of this scatter is due to offsets among galaxies. The typical $R_{mol}$ varies by more than an order of magnitude across our sample, and binning by $R_{mol}$ does not appear to reveal a strong common underlying relation. $R_{mol}$ alone seems insufficient to predict the SFE$_{dense}$ with high precision.

**Dynamical equilibrium pressure:** If SFE$_{dense}$, traced by TIR-to-HCN, is anticorrelated with the mean ISM density, then it should be anticorrelated with $P_{DE}$, our environmental measure that is directly related to the mean midplane density. We observe a clear anticorrelation between SFE$_{dense}$ and $P_{DE}$, although we again find significant galaxy-to-galaxy scatter.

A least-squares minimization of our data yields

$$\log_{10} \frac{TIR}{HCN} = (4.7 \pm 0.4) - (0.3 \pm 0.1) \frac{P_{DE}}{k_B \, cm^{-3} K},$$

(18)

which is valid at 1–2 kpc resolution over the range $\log_{10} P_{DE}/k_B$ [K cm$^{-3}$] $\sim$4.5–6.5. Individual data show $\pm 0.24$ dex scatter about the fit at fixed $P_{DE}$.

SFE$_{dense}$ is anticorrelated with $P_{DE}$ in the expected sense, but does not offer a better predictor of SFE$_{dense}$ than $\Sigma_{mol}$ or $\Sigma_*$ (similar to the finding by Gallagher et al. 2018a), although it shows a clearer relation than $R_{mol}$ or $f_{gas}$.

We note that this spread in pressures is correlated with the total IR emission: for a fixed TIR-TOHCN ratio, galaxies with higher SFR on average (see middle right panel in Figures 3–11) show much higher characteristic $P_{DE}$ values in their centers.

**Star formation efficiency of dense gas:** Taking the TIR-TOHCN ratio to trace SFE$_{dense}$, we observe a systematic dependence of SFE$_{dense}$ on environment in the EMPIRE sample. This dependence manifests itself in that the inner regions of galaxy disks with high pressure and high gas surface density appear to be the most inefficient at forming stars out of dense molecular gas. These results also demonstrate that the scatter in the $L_{IR}$-4$_{HCN}$ scaling relation (Section 5.3) has a physical origin. Using the scaling relations in this section, one could predict whether an EMPIRE data point would on average fall above or below the scaling relation.

Our results agree well with previous observations of dense gas in nearby galaxy disks (see Chen et al. 2015; Usero et al. 2015; Bigiel et al. 2016; Gallagher et al. 2018a). As we emphasize above, EMPIRE represents the best systematic measurement to date. The combination of whole-galaxy mapping and a significant sample mean that our results can serve as a reference for the behavior of nearby disk galaxies at $\sim$1–2 kpc resolution. In this sense, our observations help establish that the SFE$_{dense}$ variations observed in previous studies are not restricted to the nucleus of galaxies, nor are they the result of biased sampling.

Gallagher et al. (2018a) speculate that the behavior that we see could be expected if environment affects the mean density of molecular clouds (which does appear to be the case, e.g., Sun et al. 2018) and star formation occurs in regions of local overdensity. In this case, in regions with high mean cloud densities, e.g., high-pressure regions such as galaxy centers, the gas traced by HCN represents increasingly less of an overdensity relative to the mean. This scenario (see also Krumholz & Thompson 2007; Narayanan et al. 2008; Usero et al. 2015) would qualitatively explain our results, but it raises some other issues in turn. We return to this in Section 6.

We show that while SFE$_{dense}$ is anticorrelated with $\Sigma_*$, $\Sigma_{mol}$, $R_{mol}$, and $P_{DE}$, none of these quantities places all of the EMPIRE targets on a single scaling relation. This suggests that several of these variables need to be taken into account, or that there must be additional physics at play that regulate SFE$_{dense}$.

We highlight the likely role of the sub-beam structure, i.e.,
Figure 15. \( \Sigma_{SFR}/\Sigma_{mol} \) ratio (left) as a proxy for the SFE of the bulk molecular gas, and the \( \Sigma_{SFR}/\Sigma_{dense} \) ratio (right), as a proxy for the SFE of the dense gas, vs. the \( \Sigma_{dense}/\Sigma_{mol} \) ratio, for a proxy for the dense gas fraction. In gray circles we display the EMPIRE disk measurements, and we compare them with the samples from Usero et al. (2015), García-Burillo et al. (2012), and Gao & Solomon (2004), which are shown as green, red, and dark blue circles, respectively. We include observations for the CMZ in CO (Dame et al. 2001), HCN (Jones et al. 2012), and TIR (Barnes et al. 2017) for a comparison with a well-studied extreme environment.

Different gas structure within our 1–2 kpc beams and dynamics. Querejeta et al. (2019) show a strong relationship between \( SFE_{dense} \) and velocity dispersion in M51, and kinematics in M51 also strongly correlate with the SFE of the total molecular gas (see Meidt et al. 2013; Leroy et al. 2017a). Comparing EMPIRE-based \( SFE_{dense} \) to kinematic information will be an important next step.

Finally, we emphasize that our fitted scaling relations should not be extrapolated far outside the regime where we measure them. Gao & Solomon (2004), García-Burillo et al. (2012), and Usero et al. (2015) have all shown that the TIR-to-HCN ratio in (U)LIRGs is not heavily suppressed relative to that in disks (see Section 5.3). Extrapolating our relationships to arbitrarily high \( P_{DE}, \Sigma_{mol} \), or \( \Sigma_{dense} \) would thus yield incorrect results.

5.5. The Relation between \( f_{dense} \) and \( SFE_{mol} \)

At face value, our EMPIRE results show a variable \( SFE_{dense} \) as traced by the observable TIR-to-HCN ratio across and within galaxies. These results are difficult to explain within the framework of density threshold models. As noted by Usero et al. (2015) and Gallagher et al. (2018a), among others, in a density threshold model variations in the SFE of the total molecular gas, \( SFE_{mol} \), are expected to track \( f_{dense} \), with no change in \( SFE_{dense} \) (e.g., see Gao & Solomon 2004; Lada et al. 2012).

Following Gallagher et al. (2018a), Usero et al. (2015), and Gao & Solomon (2004), we test the density threshold hypothesis by measuring the strength of the correlation between \( SFE_{mol} = \Sigma_{SFR}/\Sigma_{mol} \), as traced by the TIR-to-CO ratio, and the dense gas fraction (\( f_{dense} = \Sigma_{dense}/\Sigma_{mol} \)) indicated by HCN/CO. EMPIRE allows us to test this hypothesis in the whole area of nearby galaxies, and in the process, to extend to lower \( \Sigma_{dense}/\Sigma_{mol} \) and \( \Sigma_{SFR}/\Sigma_{mol} \) than previous tests.

The left panel in Figure 15 displays \( \Sigma_{SFR}/\Sigma_{mol} \) as a function of \( \Sigma_{dense}/\Sigma_{mol} \). EMPIRE > 3σ disk measurements appear as gray points. For a comparison, we show the Usero et al. (2015) pointed observations (green points), integrated galaxy measurements from García-Burillo et al. (2012; red points) and Gao & Solomon (2004; dark blue points), data from the Milky Way CMZ\(^\text{22} \) (light blue, data from Jones et al. 2012; Barnes et al. 2017), and data from other galaxy centers from Gallagher et al. (2018a; orange points).

The plot clearly indicates a relationship between \( SFE_{mol} \) and \( f_{dense} \). The thick black line indicates an ordinary least-squares bisector fit to the significant EMPIRE measurements (gray points). This fit has the form

\[
\log_{10} \frac{\Sigma_{SFR}}{\Sigma_{mol}} = -2.07 + 0.93 \log_{10} \frac{\Sigma_{dense}}{\Sigma_{mol}},
\]

where \( \Sigma_{SFR}/\Sigma_{mol} \) has units of Myr\(^{-1} \). The accompanying black dashed lines show the ±1σ scatter about the relation. This relation applies at 1–2 kpc resolution mainly over the range \( \log_{10} f_{dense} \sim -1.5 \) to \( -1.0 \) and \( \log_{10} SFE_{mol} \) [Myr\(^{-1} \)] \sim -3.5 to \( -3.0 \) (i.e., molecular gas depletion times of \( \sim 1–3 \) Gyr). We caution that our fit does not extend to the starburst regime that is included in the samples of García-Burillo et al. (2012) and Gao & Solomon (2004).

For comparison, we plot fits using the same methodology as was applied to samples of Gallagher et al. (2018a; all data, not only the plotted galaxy centers). Usero et al. (2015), García-Burillo et al. (2012), and Gao & Solomon (2004), shown as orange, green, red, and blue lines, respectively. In Table 7 we report the fits, rank correlation coefficients, and their significance relating \( \Sigma_{SFR}/\Sigma_{mol} \) and \( \Sigma_{dense}/\Sigma_{mol} \) in each sample. We also note the scatter in \( SFE_{dense} \) for each sample in parentheses.

All the data sets in Figure 15 show some correlation of \( SFE_{mol} \) and \( SFE_{dense} \). The choice of data sets can significantly alter the best-fit scaling relation, however (a conclusion also emphasized by Gallagher et al. 2018a). Our best fit to EMPIRE appears almost

\(^{22}\) We define the CMZ region as a rectangle centered on \( l = 0°:545, b = -0.035 \) with width \( = 151° \) and height \( = 29° \). This width corresponds to a linear size of \( \sim 500 \) pc.
are one of the most popular reasons (e.g., large velocity fields, turbulence or large-scale breathing modes; see Benincasa et al. (2016); Battersby et al. (2017); Kauffmann et al. (2017)). Similar processes seem likely to be at play in the central regions of these other nearby galaxy disks, and perhaps to operate at a lower level to create the scatter in the EMPIRE data.

5.5.1. Scatter in SFE\textsubscript{dense} and SFE\textsubscript{mol}

Vutisalchavakul et al. (2016) compared the SFR per mass of molecular gas (SFE\textsubscript{mol}) and the SFR per mass of dense gas (SFE\textsubscript{dense}) to the molecular gas mass and dense gas mass (which they call “aggregate mass” in the case of external galaxies). They studied a sample of molecular clouds from high-mass star-forming regions in the Galactic Plane and compared their results to other nearby clouds from Evans et al. (2014), MS1 (Chen et al. 2015), and a sample of unresolved starburst galaxies (Liu et al. 2015). Vutisalchavakul et al. (2016) concluded that the mass of dense gas appears to be a better predictor of SFE than the total molecular gas mass in all environments. Treating the scatter in the SFE as a figure of merit, they found that dense gas predicted the SFE with roughly one-third of the scatter found when the entire molecular gas mass was used.

In Figure 16 we replicate the calculation of Vutisalchavakul et al. (2016). We plot SFE\textsubscript{mol} as a function of molecular gas mass in the left panel and SFE\textsubscript{dense} as a function of dense gas mass in the right panel. In addition to the measurements by Vutisalchavakul et al. (2016), we show the EMPIRE disk measurements (gray), the samples of resolved and unresolved extragalactic systems used in Figure 15, and measurements from the Milky Way CMZ.

When we follow Vutisalchavakul et al. (2016) and treat the scatter in SFE\textsubscript{mol} or SFE\textsubscript{dense} as the figure of merit, we reach similar conclusions to the paper. We find a mean SFE\textsubscript{dense} of $-1.97 \pm 0.22$, which is very similar to the average value found in Vutisalchavakul et al. (2016). The scatter we find in SFE\textsubscript{dense} ($\pm 0.22$ dex) is smaller than what we find for SFE\textsubscript{mol} ($\pm 0.31$ dex). This also closely resembles the original arguments made by Gao & Solomon (2004) regarding HCN and CO. In the most basic terms, HCN emission does appear to represent a more basic predictor of the SFR than CO. However, note that the SFR-CO relation is nonlinear for starbursts galaxies and UlIRGs at kiloparsec scales, as observed by Gao & Solomon (2004), García-Burillo et al. (2012), and Usero et al. (2015). This nonlinearity contributes to the higher spread of points that is observed in the SFE–$M_{mol}$ Relation in the left panel of Figure 16. If a linear relation is required and the absolute scatter in SFE\textsubscript{mol} or SFE\textsubscript{dense} is treated as the figure of merit, then the arguments of Vutisalchavakul et al. (2016) hold. When a nonlinear relation is adopted to allow for CO, however, the situation becomes more complex.

We caution that the absolute molecular and dense gas masses for parts of galaxies plotted in Figure 16 have limited physical meaning. The integrated mass in one of our EMPIRE measurements depends on a number of quantities (e.g., inclination and distance) in addition to the physical properties of that part of the galaxy.

5.5.2. Scatter within Individual EMPIRE Galaxies

As discussed and seen in the figures in Section 5.4, much of the dispersion in SFE\textsubscript{dense} and $f_{dense}$ that we find with EMPIRE appears as offsets among galaxies in the scaling relations. In

| Data Set          | $\rho$ | $\log_{10} \Sigma_{SFR}/\Sigma_{dense}$ |
|-------------------|--------|----------------------------------------|
| EMPIRE (this work)| 0.33 (0.02) | $-1.98 \pm 0.20$ |
| Gallagher et al. (2018a) | 0.15 (0.003) | $-1.96 \pm 0.33$ |
| Usero et al. (2015) | 0.42 (0.005) | $-1.73 \pm 0.20$ |
| García-Burillo et al. (2012) | 0.35 (0.07) | $-1.62 \pm 0.20$ |
| Gao & Solomon (2004) | 0.65 (0.001) | $-1.88 \pm 0.25$ |

Note. Rank correlation coefficients, $\rho$, and $p$-value in parentheses. We quote the median of the logarithm of the ratio $\Sigma_{SFR}/\Sigma_{dense}$, as well as its 1σ rms scatter in units of $\log_{10}(\text{Myr}^{-1})$.
Figure 16. SFR per mass of molecular gas (left) as a function of the mass of molecular gas, and SFR per mass of dense gas (right) as a function of the mass of dense gas. In gray circles we display the EMPIRE disk measurements, and we compare them with the extragalactic samples from Usero et al. (2015), García-Burillo et al. (2012), Gao & Solomon (2004), and Gallagher et al. (2018a) (same as Figure 15). We also included the data from Vutisalchavakul et al. (2016) for a comparison with Galactic molecular clouds.

Figure 16 the scatter in the gray points mixes both galaxy-to-galaxy offsets and the intrinsic scatter within individual galaxies.

To better quantify the relative importance of these contributions, we calculated the 1σ dispersion in SFE\textsubscript{dense} for each individual galaxy (σ – SFE\textsubscript{dense}). We find an average of σ – SFE\textsubscript{dense} = 0.12 ± 0.02 dex in our sample. We caution that this value includes only regions with significant detections and so suffers from some bias. Taken at face value, this scatter is comparable to the lowest values found for SFE\textsubscript{mol} in individual galaxies (e.g., see Figure 12 in Leroy et al. 2013). This again highlights a tighter local correlation between HCN and SFR than CO and SFR, although a rigorous statistical analysis will require either careful statistical modeling or data with individually higher S/N than EMPIRE. Again, treating the scatter in the simplest terms, we can subtract this local scatter in quadrature from the global 1σ dispersions in SFE\textsubscript{dense} for each individual galaxy (σ – SFE\textsubscript{dense}). We quote the mean of the logarithm of SFE\textsubscript{mol} and SFE\textsubscript{dense}, as well as its 1σ rms scatter (in parentheses) in units of log\textsubscript{10}(Myr\textsuperscript{–1}).

6. Discussion

EMPIRE reveals a systematic dependence of \( I_{\text{HCN}}/I_{\text{CO}} \) and \( I_{\text{TR}}/I_{\text{HCN}} \) on local conditions. These variations appear in all EMPIRE targets, with magnitude ~0.2 dex up to one order of magnitude, depending on the trend in question. At face value, \( I_{\text{HCN}}/I_{\text{CO}} \) traces the fraction of dense gas, while \( I_{\text{TR}}/I_{\text{HCN}} \) traces the SFR per unit dense gas mass. Both interpretations have important caveats, however. In this section we discuss the implications of our observations in the context of galactic star formation and then lay out some key caveats regarding the translation of observed intophysical quantities.

6.1. The Gas Density Distribution Depends on Environment

Our observations of \( I_{\text{HCN}}/I_{\text{CO}} \) indicate that the density distribution in molecular gas depends on local environment and changes across galaxy disks. Given the large difference in effective critical density between the two species, the ratio HCN-to-CO will certainly be sensitive to density variations, although there are important subtleties (Section 6.4). Two important pieces of evidence support the idea that HCN-to-CO traces density variations. First, we see qualitative agreement among different dense gas tracers (J. Puschnig et al. 2019, in preparation, will present a quantitative comparison). In both this paper and Gallagher et al. (2018a), the radial profiles of HCO\textsuperscript{+} agree well with those of HCN. To a lesser degree, the profiles of HNC (here) and CS (Gallagher et al. 2018a) also show the same shape, but these are limited by S/N and lack of short spacing correction for Gallagher et al. (2018a). Qualitative agreement among the high critical density lines of species that are not chemically coupled suggests that variations in HCN abundance are not the main driver for our results. Second-order variations in excitation and chemical abundances certainly remain important topics, however (Section 6.4).

Second, Gallagher et al. (2018b) used EMPIRE and ALMA data to show that the HCN-to-CO ratio measured at kiloparsec scales correlates on average with the mass-weighted average of the 120 pc resolution molecular gas surface density, which is traced by CO(2–1) emission, inside the beam. That is, changes in the HCN-to-CO ratio correlate with changes in the apparent surface density of molecular clouds. Regions with high HCN-to-CO also show high surface brightness CO emission and apparently dense clouds at 120 pc (FWHM) resolution.

| Table 8 | Mean SFE\textsubscript{mol} and Mean SFE\textsubscript{dense} |
|---------|-------------------------------------------------------------|
| Average | Vutisalchavakul et al. (2016) | This Paper |
| SFE\textsubscript{mol} | ~2.83 ± 0.42 | ~3.09 ± 0.31 |
| SFE\textsubscript{dense} | ~1.82 ± 0.19 | ~1.97 ± 0.22 |

Note. We quote the mean of the logarithm of SFE\textsubscript{mol} and SFE\textsubscript{dense}, as well as its 1σ rms scatter (in parentheses) in units of log\textsubscript{10}(Myr\textsuperscript{–1}).
These arguments give us good reason to expect that HCN-to-CO traces the gas density distribution to first order. We have phrased the associated physical quantity as $f_{\text{dense}}$, but we also expect that HCN-to-CO traces the mass-weighted mean density. For any somewhat universal gas density distribution, e.g., the lognormal density distribution expected for isothermal turbulence (e.g., Vazquez-Semadeni 1994; Padoan & Nordlund 2002) or a power law, the two properties will correlate. The Gallagher et al. (2018b) results suggest a close association.

Our results indicate that the gas density probability distribution function (PDF) changes across galaxy disks. The trend of the variations is that regions with more gas and deeper potential wells (as traced by $\Sigma_*$) on average also show denser gas on small scales.

Following Helfer & Blitz (1997) and Gallagher et al. (2018a), one useful way to express this dependence is that $f_{\text{dense}}$ appears to be correlated with the dynamical equilibrium pressure, $P_{\text{DE}}$, estimated from hydrostatic equilibrium (see Section 4.6). The $f_{\text{dense}}$–$P_{\text{DE}}$ correlation is not the tightest correlation that we observe, but it has a solid physical underpinning: when we look at parts of a disk with higher mean pressure, we find higher density gas. We do still observe significant galaxy-to-galaxy scatter in each scaling relation. We suggest that galactic dynamics and ISM structure below the scale of our beam (e.g., flows along bars, and spiral arms) represent the natural next environmental factors to consider.

Our results relate directly to the evolving literature relating molecular cloud properties to local environment. If the sub-beam gas density distribution, which is traced by the HCN-to-CO ratio, reflects environment, then the gas density at intermediate scales, which is traced by the properties of giant molecular clouds, likely does as well. Molecular clouds in high-pressure environments should have higher mean densities, and this should relate to their internal gas density distribution, which is traced by our spectroscopic measurements.

Recent work on this topic has suggested that molecular cloud masses and surface densities are correlated with environment (e.g., Hughes et al. 2013; Colombo et al. 2014; Leroy et al. 2016; Sun et al. 2018; A. Schruba et al. 2019, in preparation; J. Sun et al. 2019, in preparation). The sense of the observed correlations agrees with what we find here: higher mass galaxies and the centers of galaxies host more massive clouds with higher surface density. The internal pressure of molecular clouds appears to be correlated with the mean pressure in the environment (Hughes et al. 2013). The observed CO line widths within molecular clouds also increase in higher pressure environments (Sun et al. 2018). These observed larger line widths are directly related to larger Mach numbers, which are a measure of the intracloud turbulence. Thus, in turbulent models for star formation, this would also lead to denser gas because the Mach number drives the width of the density distribution (e.g., see Padoan & Nordlund 2002).

One next major step on this topic will involve a detailed comparison of the molecular cloud structure to spectroscopic observations such as are made with EMPIRE. Gallagher et al. (2018b) take an important first step here, showing that cloud-scale gas properties are correlated with our EMPIRE HCN-to-CO ratios.

Another key next step will be to constrain the shape of the density distribution using the full suite of molecular line data available from EMPIRE and other surveys. We mainly focus on HCN-to-CO. The combination of all EMPIRE lines allows the prospect of measuring the relative amounts of low-, intermediate-, and high-density gas, although abundance variations remain a key concern (e.g., see Leroy et al. 2017b). This work is ongoing in EMPIRE and will be presented in J. Puschign et al. (2019, in preparation).

Finally, these results have the prospect of providing information for and testing turbulent models of star formation (e.g., Padoan & Nordlund 2002; Krumholz & Thompson 2007; Federrath & Klessen 2012). In these models, the mean density, virial parameter, Mach number, and other properties of clouds affect the gas density PDF and star formation in the cloud. When we combine these models, our measurements of density and star formation to cloud-scale molecular gas properties can test these models. A comparison of all three types of measurements to key environmental factors, e.g., $\Sigma_*$, $\Sigma_{\text{mol}}$, and $P_{\text{DE}}$, allows the prospect of a holistic disk-to-core model of star formation.

6.2. An Environment-dependent Role for Gas Density in Star Formation?

In agreement with Usero et al. (2015), Bigiel et al. (2016), and Gallagher et al. (2018a), we find that $I_{\text{TR}}/I_{\text{HCN}}$, which traces the efficiency of dense gas to form stars, is anticorrelated with the surface density of stars and molecular gas, $P_{\text{DE}}$, and $R_{\text{mol}}$. These same quantities are correlated with $f_{\text{dense}}$, so that as gas becomes denser, the dense gas traced by HCN also appears less efficient at forming stars. This observation agrees with recent work targeting the Milky Way CMZ (Longmore et al. 2013; Barnes et al. 2017; Mills & Battersby 2017).

As above, the use of HCN for tracing dense gas is pivotal to this interpretation. We review caveats on this below (Section 6.4). The arguments above hold here as well. Other dense gas tracers yield a qualitatively similar picture, and comparison to cloud-scale gas properties suggests that the HCN-to-CO ratio traces density. Moreover, the Galactic center work has employed a variety of gas tracers, not only HCN, to reach qualitatively similar conclusions in the Milky Way (e.g., Battersby et al. 2017; Walker et al. 2018). Usero et al. (2015) present a detailed discussion of plausible scenarios for $\alpha_{\text{HCN}}$ variations and conclude that the observed trends are unlikely to be exclusively driven by conversion factor effects.

Previous studies of dense gas in nearby galaxies (Usero et al. 2015; Bigiel et al. 2016; Gallagher et al. 2018a) interpreted similar observations as evidence that density plays a context-dependent role for star formation. The simplest interpretation would be that star formation occurs in the densest parts of clouds, so that contrast with the mean density, not absolute density, represents the key quantity. This might be expected if the mean dynamical state of clouds is approximately universal (e.g., clouds are all virialized on average), but the mean density of clouds varies due to changes, reflecting the mean density and pressure in the disk. To first order, HCN traces only a fixed density where the freefall time should not change significantly. In low-pressure regions, this density may capture star-forming overdensities. In higher pressures regions, such as galactic centers, HCN may trace a larger fraction of the emission that extends into the bulk molecular material. In practice, this would translate into a lower apparent SFE of dense gas, in line with the increasing HCN-to-CO and decreasing TIR-to-HCN ratios observed in individual EMPIRE galaxy disks. Aspects of this argument have been made by Krumholz & Thompson (2007), Narayanan et al. (2008), Usero et al. (2015), Bigiel et al. (2016), and Gallagher et al. (2018a).
Higher pressures, and on average, they seem less dense gas. From Table 1, galaxy centers from highly star-forming galaxies appear at Figure 17. The IR-to-HCN ratio, which traces the SFE of the dense gas, as a function of the mean pressure. We show the average observed TIR-to-HCN ratio as a function of the mean $P_{\text{DE}}$ in the same region. The centers of our EMPIRE galaxies are characterized by their high pressures, but the exact central dynamical equilibrium pressure for the EMPIRE galaxy centers varies from galaxy to galaxy by more than one order of magnitude. Figure 17 shows that the centers with the highest $P_{\text{DE}}$ appear on average to form fewer stars per unit dense gas mass.

This simple view clashes with the popular claim that the SFE per freefall time is approximately $\frac{1}{2}$ kpc. If this were true, then HCN-emitting gas would show approximately the same SFE$_{\text{dense}}$ everywhere, regardless of whether HCN traced bulk or star-forming gas.

In practice, most turbulent models of star formation contain additional physical parameters related to dynamics, e.g., the Mach number and virial parameter, which can affect the density distribution and SFE. Considering the models of Krumholz & McKee (2005) and Krumholz & Thompson (2007), Usero et al. (2015) showed that the observed IR, CO, and HCN data for nearby galaxies and starburst galaxies could all be explained by allowing Mach number and density to vary. Our observations agree well with those of Usero et al. (2015), and a similar case should hold for these data as well. A key next test will be to infer the Mach number and mean density from high-resolution observations (e.g., Gallagher et al. 2018b; Sun et al. 2018; Querejeta et al. 2019) and test for consistency with these models when the physical parameters are constrained.

As with $f_{\text{dense}}$, significant galaxy-to-galaxy scatter remains in all of our observed SFE$_{\text{dense}}$ scaling relations. The strong correlations between the HCN-to-CO ratio and the local $P_{\text{DE}}$ seen in every individual galaxy disk suggest that the ambient pressure (set by the hydrostatic midplane pressure of a galaxy disk) plays a key role by setting the natal density distribution of molecular clouds, which initially are in hydrostatic equilibrium. Recent semianalytic modeling by Rahner et al. (2017, 2019) has shown exactly this effect: ensembles of identical clouds can evolve differently when they are initially set in different pressure environments. In addition to dynamics and ISM structure, timescale effects should also play an important role. Recent modeling by Rahner et al. (2017) and Grudić et al. (2019) shows that larger and more massive star-forming clouds evolve and expand more slowly with high internal pressures. High SFR regions, formed out of larger and more massive clouds, would typically show much higher internal cloud pressures. This could contribute to the horizontal shift seen in the global EMPIRE trends with respect to pressure in Figures 14 and 17. If this evolutionary sequence is slow and individual galaxies are dominated by only a handful of clouds, then the scatter among galaxies might capture evolutionary effects. Alternatively, if large-scale dynamics synchronizes star formation in some way, then these timescale effects might play a key role. Such “breathing modes” have been suggested based on simulations by Benincasa et al. (2016) and Orr et al. (2019), although it is possible that the short dynamical timescale associated with dense gas might wash these effects out.

**6.3. Relation to the $L_{\text{HCN}}$-$L_{\text{TIR}}$ Scaling Relation and SFE$_{\text{mol}}$**

The scaling relation between IR and HCN luminosity, most prominently shown by Gao & Solomon (2004), has been interpreted to indicate a universal role in star formation for the gas traced by HCN (e.g., Lada et al. 2010, 2012). Our EMPIRE data fall on this scaling relation, intermediate between individual cores and clouds and whole galaxies.

Thus, our observation of an environment-dependent TIR-to-HCN ratio should not be taken to invalidate the scaling relation. Rather, our observations show that the scatter about the relation is physical in nature. For detected regions of resolved galaxy disks, and treating each unit area the same, the rms scatter is $0.2-0.3 \text{ dex}$ and is correlated with environment as described above. In practice, the quantitative scatter about the relation depends on the adopted sampling scheme. For example, weighting equally by area tends to deemphasize galaxy centers. Weighting by luminosity deemphasizes outer disks with little star formation. In any case, we find significant physical scatter about the IR-HCN scaling relation and have quantified the dependence of the TIR-to-HCN ratio on environment.

An important corollary, already emphasized above, is that the trends that we observe in the relation of TIR-to-HCN to environment cannot be extrapolated indefinitely. Gao & Solomon (2004) and García-Burillo et al. (2012), among others, show that the TIR-to-HCN ratio in starburst galaxies with high SFE$_{\text{mol}}$ and high $P_{\text{DE}}$ is common. Galaxy centers cannot be correctly extrapolated into the (U)LIRG population, perhaps due to the different dynamics that are at play in the different environments.

Gao & Solomon (2004) and several following papers also highlighted that the HCN-to-CO ratio, $f_{\text{dense}}$, could predict the SFE of the total molecular gas, SFE$_{\text{mol}}$ or TIR-to-CO. We find that SFE$_{\text{mol}}$ correlates with $f_{\text{dense}}$. That is, variations in SFE$_{\text{dense}}$ and $f_{\text{dense}}$ are not totally offset. The exact scaling that is inferred, however, sensitively depends on the data sets that are considered because the TIR-to-HCN ratio varies. In that sense,
In this work, we focus on the content of dense gas in nearby galaxies by analyzing the emission of lines with high critical densities such as HCN(1–0). However, the interpretation of the HCN emission and thus the dense gas mass remains an open issue (see Section 6.4.1), especially in the context of clouds with varying density PDFs.

6.4. Caveats

When we assume that HCN is a good tracer of dense gas, the second major limiting factor required for a well-calibrated relationship between HCN emission, dense gas mass, and star formation is the conversion factor $\alpha_{\mathrm{HCN}}$. Thus, the observational constraints we can place on any star formation theory are sensitive to the conversion factors that translate line luminosities into masses of dense molecular gas.

The first estimation of the HCN conversion factor is detailed in the seminal work by Gao & Solomon (2004). The authors derived a dense gas conversion factor assuming virialized (self-gravitating) optically thick dense gas cores with $n \sim 3 \times 10^4 \text{cm}^{-3}$ and constant brightness temperatures of 35 K (e.g., Radford et al. 1991). In this way, they obtained a simple relation:

$$
\alpha_{\mathrm{HCN}} = 2.1 \sqrt{n(\text{H}_2)} / T_b = 10 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}. 
$$

(20)

Any conversion factor calculated under these assumptions would then depend on the gas density in molecular clouds and its temperature, which in turn depends on the gas excitation and the beam filling fraction. Later on, Wu et al. (2010) also derived a dense gas conversion factor by comparing the HCN luminosity in massive Galactic clumps to their virial mass. The authors found $\alpha_{\mathrm{HCN}} = 20 \pm 1 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$. However, the physical conditions observed in individual Galactic clumps likely differ from those of the bulk dense gas in galaxies.

Generally, $\alpha_{\mathrm{CO}}$ has been observed to increase with decreasing metallicity and to drop where the gas is more turbulent (galaxy centers and starbursts, e.g., Graciá-Carpio et al. 2008; García-Burillo et al. 2012). Moreover, excitation effects can also drive changes in the molecular gas conversion factor $\alpha_{\mathrm{CO}}$. While the dense gas conversion factor is harder to constrain because data are scarce and observations challenging, one can expect a similar dependence on turbulence and excitation.

In this regard, Shimajiri et al. (2017) estimate the mass of dense gas in Galactic clouds using dust column densities from Herschel and compare them with HCN luminosities to obtain empirical conversion factors. The authors claim that variations in $\alpha_{\mathrm{HCN}}$ in Galactic clouds could be related to variations in the far-ultraviolet (FUV) field (which is significantly stronger toward galaxy centers) and so to gas excitation and/or chemistry variations. Could the observed variations in SFE$_{\text{dense}}$ (Figure 14) be explained by gas excitation variations? Their dust temperature maps from Herschel, however, blend different ISM phases when used at extragalactic scales ($>100 \text{ pc}$), which could introduce additional uncertainty in $G_0$ and the strength of the FUV field. Thus, assessing dense gas excitation through direct observations of several rotational transitions (e.g., $J = 3–2$ to $J = 1–0$) is of crucial importance.

In terms of modeling, most estimates of dense gas conversion factors are performed using idealized clouds and density distributions (Krumholz & Thompson 2007; Leroy et al. 2017b), or simulate very small regions within molecular clouds (Onus et al. 2018), which are likely not representative of the varying conditions across galaxy disks. Recent work by Vollmer et al. (2017) on analytic modeling also considers large-scale properties of entire galaxies (e.g., surface density, turbulent velocity, and disk height) and also models the line emission from individual self-gravitating clouds using detailed chemical networks and an escape probability formalism. By comparing their calculated dense gas masses and line emission in star-forming galaxies, they predict $\alpha_{\mathrm{HCN}} = 21 \pm 6$, $33 \pm 17$, and $59 \pm 21 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$ for local spiral galaxies and ULIRGs, submillimeter galaxies, and high-z galaxies, respectively.

A more accurate determination of the dense gas conversion factor (e.g., between HCN and the dense molecular gas mass) is required for a complete understanding of the relation between HCN emission, gas density, and SFE of dense gas. This requires detailed knowledge of HCN emission in different systems (e.g., ULIRGs, starbursts, and low-metallicity galaxies) and further constraints on HCN excitation conditions. Assessing dense gas excitation using higher-$J$ lines of these molecules is possible with facilities such as ALMA, NOEMA, or the Submillimeter Array, and will be an important step forward to resolve the tension between competing star formation theories. High-resolution observations of dust continuum emission in nearby galaxies and its comparison to GMC-scale observations of CO and HCN will additionally provide insight into empirical molecular and dense gas conversion factors, as well as on its variation in different galactic environments.

6.4.2. HCN Emissivity and Critical Density

The line ratios we employ in our study (e.g., HCN/CO) are sensitive to density changes, but might also reflect opacity, chemical, or excitation effects. Thus, analyzing and interpreting line ratios arising from sub-beam density distributions requires additional knowledge to probe gas densities. In this regard, more extragalactic observations of optically thin isotopologues remain crucial to probe the optical depth, effective critical density ($n_{\text{crit}}$), and isotopic abundance of high-density tracers (Jiménez-Donaire et al. 2017a, 2017b). As detailed in Leroy et al. (2017b), differential excitation also plays an important role in determining true optical depths and characterizing the emissivity properties of gas tracers. Multi-$J$ observations of high-density tracers such as HCN, HCO$^+$, and HNC in external galaxies have the prospect of constraining $T_{\text{kin}}$ and $n$ of the gas.

Ideally, we are interested in knowing how much gas mass is emitting at a given density, and how this emissivity changes as a function of density. The HCN(1–0) transition has a higher effective critical density than the low-$J$ CO lines. The mean density of HCN-emitting gas remains uncertain, however, because even gas below the effective critical density can emit (the emission is subthermal), albeit with lower emissivity. In real molecular clouds, there is much less mass at high density than at low densities. If this imbalance is large enough, then despite the lower emissivity, the high abundance of low-density gas can lead to a case where almost all emission comes from subthermally excited gas. There is observational evidence that this subthermal emission constitutes a significant contribution to the dense gas luminosity of entire galaxies (e.g., Papadopoulos 2007; Aravena et al. 2014). Thus, knowing how much of the emission we detect...
comes from high-density gas is crucial for interpreting the observed HCN-to-CO and TIR-to-HCN variations.

Current Galactic surveys focusing on resolved subparts of star-forming regions have investigated whether commonly used dense gas tracers, including HCN(1−0), are good tracers of dense gas. One of the key results from the ORION-B survey (Pety et al. 2017) and first conclusions from the LEGO survey (Kauffmann et al. 2017) is that most of the HCN emission comes from gas densities $n < 10^{3} \mathrm{cm}^{-3}$. Pety et al. (2017) and Kauffmann et al. (2017) find that $N_{2}H^{+}(1−0)$ is the only tracer sensitive to high column densities ($>10^{22} \mathrm{cm}^{-2}$). It is important to note that their direct observables are, however, column densities (N) instead of volume densities, $n$. Additionally, they are focused on very specific physical conditions (strong interstellar radiation fields by young stars and almost no embedded stars) that are inherent to small (<10 pc in diameter) subregions within Orion. In particular, observations of prestellar cores and cold filaments in Orion A and B have shown that freeze-out of molecules onto dust grains reduces the gas phase abundance of CO and other molecules, with the notable exception of $N_{2}H^{+}$, which remains in the gas phase for a long time (e.g., Hacar et al. 2018). Along these lines, high-resolution simulations analyzed by Onus et al. (2018) also show that a significant portion of the HCN(1−0) emission comes from gas with mean densities that are a factor of 10 lower than the HCN critical density. However, most of the HCN emission originates in gas at densities $\sim 2.5−5$ times greater than the mean density of the gas (Onus et al. 2018).

Recent efforts of modeling line emission from sub-beam density distributions (e.g., Liszt & Pety 2016; Leroy et al. 2017b) show that while gas can indeed emit effectively below its effective critical density, transitions with critical densities higher than the average density of the gas show emissivities that vary strongly as the density distribution changes. Therefore the line ratios we employ as proxies (HCN-TO-CO) should be good probes of the fraction of dense gas. These models are subject to uncertain factors such as fixed $T_{\text{kin}}$ and fixed abundances, however, and they only account for one main collider.

Additionally, other physical mechanisms at play in the ISM of galaxies could increase the emissivity of HCN(1−0) at lower densities. This is mainly motivated by the fact that Pety et al. (2017) find that the spatial extent of the emission of high-density tracers such as HCN(1−0) is not correlated with the H$_2$ density that is required for collisional excitation. Two possible causes of low-density HCN(1−0) excitation are cosmic-ray heating and electron collisions. Recent work by Vollmer et al. (2017) presents an analytic model of galactic clumpy gas disks where, given physical properties of galaxies (e.g., size, rotation curve, and stellar mass profile), they are able to simultaneously calculate quantities such as the total gas mass, gas velocity dispersion, TIR luminosity, CO SLED, and HCN(1−0) luminosity. The authors show that while cosmic-ray heating does not significantly alter the CO emission, it can increase the HCN(1−0) emission by at most a factor of two. They also show that this factor is indeed necessary to reproduce the observed HCN emission in ULIRGs. Goldsmith & Kauffmann (2017) and Kauffmann et al. (2017) additionally suggest that HCN can also be excited by collisions with electrons. Goldsmith & Kauffmann (2017) compute the collisional excitation of the rotational levels of HCN, HCO$^+$, CN, and CS by electrons and H$_2$ molecules. They conclude that electron excitation of HCN(1−0) is important at densities $n < n_{\text{crit}}$ if the electron abundance is $X(e^-) > 10^{-5}$, that is, electron collisions dominate the excitation of HCN molecules in regions where most carbon is ionized but hydrogen remains molecular.

Thus, several factors are responsible for increasing the HCN emissivity (e.g., UV, X-rays, cosmic rays, and mechanical heating) that will always depend on the details of the chemistry models. While taking all these factors into account is extremely complex, a key path forward would have to involve contrasting large-scale Galactic and extragalactic observations with predictions from simulations of ensembles of molecular clouds, equipped with detailed chemistry models (Bisbas et al. 2019; Rahner et al. 2019; Seifried et al. 2019).

7. Summary and Conclusions

We presented EMPIRE, a spectral line mapping survey that targeted $\lambda = 3−4$ mm tracers of dense molecular gas (HCN, HCO$^+$, and HNC) and the bulk-gas-tracing CO isotopologues (12CO, 13CO, and C18O). EMPIRE covered the whole star-forming disk (typically out to $\sim 8–10$ kpc) of nine nearby massive galaxies and so provides the first sample of whole-galaxy-resolved (1−2 kpc resolution) dense gas maps.

Here we describe the survey products, which are publicly available from the IRAM repository and the EMPIRE website. We used these data to investigate the dependence of the dense gas fraction $f_{\text{dense}}$ as traced by the HCN-to-CO line ratio, and the efficiency with which this gas forms stars, $\text{SFE}_{\text{dense}}$ as traced by the TIR-to-HCN line ratio, on environment and host galaxy. Our main results are listed below.

1. We detect dense gas as traced by HCN(1−0), HCO$^+$(1−0) and HNC(1−0) emission across the entire galaxy sample. We employ stacking techniques to recover the emission from low S/N regions. This allows us to detect HCN out to radii of $\sim 9−11$ kpc, i.e., beyond the radius of the solar circle in the Milky Way. We detect HCO$^+$ out to $\sim 7$−10 kpc, and HNC out to $\sim 4$−6 kpc. To first order, the HCN integrated-intensity maps show similar large-scale structure to the CO and 70 $\mu$m emission.

2. Emission from the three dense gas tracers appears faint. In all EMPIRE galaxies, the HCN-to-CO line ratio on average is 0.025 and the HCO$^+$-to-CO ratio is 0.018. HNC appears fainter, with a typical HNC-to-CO ratio of 0.011. Following this, the average HCO$^+$-to-HCN is 0.7, while the average HNC-to-HCN ratio is 0.4. HCO$^+$ on average shows a similar radial profile as HCN, but we identify a few cases where the HCO$^+$-to-HCN ratio shows a systematic increase with radius. When we adopt a (highly uncertain) standard conversion from HCN-integrated intensity to dense gas, the suggestion is that on average $\sim 6\%$ of the molecular gas of the EMPIRE targets is dense HCN-emitting material.

3. EMPIRE reveals a clear dependence of the dense gas fraction, $f_{\text{dense}}$, on local conditions in a galaxy disk. $f_{\text{dense}}$ appears highest in galaxy centers and decreases with increasing galactocentric radius in all targets. At our 1−2 kpc resolution, $f_{\text{dense}}$ correlates with the local stellar mass surface density, the local molecular gas mass surface density, the molecular-to-atomic gas ratio, and the local dynamical equilibrium pressure $P_{\text{eq}}$ estimated from hydrostatic equilibrium. All of these trends convey that concentrating more gas in a deeper potential well leads to a larger fraction of dense gas. Our measurements agree well with those seen in previous work (e.g., Chen et al. 2015; Usero et al. 2015; Bigiel et al. 2016; Gallagher et al. 2018a).
With EMPIRE, we quantify the relations in the whole area of a sample of galaxies and provide the best systematic measurement to date.

4. Well-detected individual regions from EMPIRE follow the same global infrared-HCN luminosity scaling as a large compilation of literature observations that targeted Galactic cores, individual clouds, and whole galaxies (i.e., our data agree with Gao & Solomon 2004, Wu et al. 2005, and García-Burillo et al. 2012, among many others). That is, EMPIRE shows on average the same TIR-to-HCN ratio as starburst galaxies and Galactic cores. In detail, there is significant scatter about this global scaling relation. Our observations show that physical systematic variations cause this large scatter, and that it is not the result of random statistics.

5. The TIR-to-HCN ratio also shows a systematic dependence on local environment. SFE_{dense} is anticorrelated with the stellar mass surface density, molecular gas mass surface density, molecular-to-atomic gas ratio, and the dynamical equilibrium pressure. As a result, the inner regions of our targets, especially the inner 1-2 kpc, appear inefficient at forming stars relative to their (high) dense gas content. Our results agree with other recent studies of nearby galaxies (Chen et al. 2015; Usero et al. 2015; Bigiel et al. 2016; Gallagher et al. 2018a) and resemble findings for the Milky Way CMZ, which also shows low SFE_{dense} (e.g., Longmore et al. 2013; Barnes et al. 2017; Mills & Battersby 2017). These results reinforce the hypothesis that the role of gas density in star formation depends at least somewhat on context. As with f_{dense}, the wide field of view and complete coverage of EMPIRE should render our measured relationships more general than previous work.

6. We find a correlation between dense gas fraction, f_{dense}, and the overall SFE of the total molecular gas, SFE_{mol} as expected by density threshold models. However, there is considerable scatter, ~0.2-0.3 dex in the relationship between SFE_{mol} and f_{dense} caused by the systematic physical variations in SFE_{dense} described above. Thus EMPIRE shows that in normal star-forming galaxies, dense gas threshold models can only hold with an accuracy of ~0.2-0.3 dex, which is larger than the dynamic range in f_{dense}.

7. We observe significant, ~0.2 dex, galaxy-to-galaxy scatter in the scaling relations between f_{dense} and SFE_{dense} to environment. Much of this scatter appears as offsets among individual galaxies. We suggest that galactic dynamics and sub-beam gas structure may be important additional factors at play. We also highlight the importance of HCN excitation studies and of further investigations into how our adopted line ratios trace the underlying gas density distribution.

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Software: GILDAS/CLASS (Pety 2005; Gildas Team 2013).

Appendix A
Line Calibrators

Figure 18 shows the different line calibrators observed for the EMPIRE survey: W3(OH), IRC 10216, and DR21(OH). The bottom panel shows the typical system temperatures during the observations. The variations seen over the course of the observations are on the order of only 7%, which implies a very stable relative calibration of our observed lines.

| Line         | $\sigma$ = 7.0% |
|--------------|----------------|
| HCN          |                |
| calw3oh      |                |
| calirc10216  |                |
| caldr21      |                |

Figure 18. HCN(1–0) integrated intensity for each day and line calibrator, divided by the mean of all measured intensities (top panel). During the EMPIRE observing runs, three different line calibrators were used: W3(OH), IRC 10216, and DR21(OH).
Appendix B
Individual Measurements and Radial Stacks

We provide every individual line-of-sight measurements performed for the EMPIRE galaxy sample. Table 9, which appears as electronic material only, includes the integrated intensities and respective uncertainties for each molecular line we mapped (HCN(1−0), HCO+ (1−0), HNC(1−0), 12CO(1−0), 13CO(1−0), and C18O(1−0)) at each galactocentric radius.

Figures 19–26 show the result from our spectral stacking technique, applied to regions of increasing radii in the EMPIRE galaxy sample. As detailed in Section 4.7, we employed our well-detected CO(1−0) data as a prior to average independent spectra from the weaker lines at high critical density (HCN, HCO+, and HNC). We performed this averaging over extended radial regions of 30″ in angular size (∼1–2 kpc), which roughly corresponds to the angular resolution of our observations.

Table 10 provides the measured integrated intensities in each of the radial bins displayed in Figures 19–26 as a result of our stacking procedure. The full version of this table appears as an electronic table only.

Figure 19. Same as Figure 2, but for NGC 0628. Stacked CO(1−0), HCN(1−0), HCO+(1−0), and HNC(1−0) in 30″ (∼1.5 kpc) radial bins. Galactocentric radii are shown in units of kpc.

Table 9
Table of Individual Line-of-sight Measurements

| Galaxy | Radius r25 | IHCN (K km s⁻¹) | ΔHCN (K km s⁻¹) | IHCO⁺ (K km s⁻¹) | ΔHCO⁺ (K km s⁻¹) | IHNC (K km s⁻¹) | ΔHNC (K km s⁻¹) | IC18O (K km s⁻¹) | ΔC18O (K km s⁻¹) |
|--------|------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| NGC 628 | 0.00 | 0.21 | 0.05 | NaN | 0.14 | NaN | 0.22 | 7.67 | ... |
| NGC 628 | 0.06 | 0.14 | 0.04 | NaN | 0.13 | NaN | 0.22 | 7.12 | ... |
| NGC 628 | 0.06 | NaN | 0.14 | NaN | 0.14 | NaN | 0.23 | 6.86 | ... |
| NGC 628 | 0.06 | NaN | 0.14 | NaN | 0.15 | NaN | 0.22 | 7.04 | ... |
| NGC 628 | 0.06 | NaN | 0.16 | NaN | 0.14 | NaN | 0.21 | 6.88 | ... |
| NGC 628 | 0.06 | NaN | 0.15 | NaN | 0.14 | NaN | 0.19 | 7.05 | ... |
| NGC 628 | 0.06 | NaN | 0.16 | NaN | 0.16 | NaN | 0.24 | 6.86 | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

Note. Uncertainties: (1) Where intensity measurements are below the significance threshold (3σ rms), Columns 3–14 contain NaN for the integrated intensities and upper limits to the emission in the respective uncertainty column. (2) The data were sampled at a common angular resolution of 33″. (3) The full version of this table appears as online-only material.

(This table is available in its entirety in machine-readable form.)
Figure 20. Same as Figure 2, but for NGC 2903. Stacked CO(1−0), HCN(1−0), HCO+(1−0), and HNC(1−0) in 30″ (∼1.5 kpc) radial bins. Galactocentric radii are shown in units of kpc.

Table 10
Table of Individual Radial Profiles

| Galaxy | Radius (kpc) | \( I_{\text{HCN}} \) (K km s\(^{-1}\)) | \( \Delta I_{\text{HCN}} \) (K km s\(^{-1}\)) | \( I_{\text{HCO}^+} \) (K km s\(^{-1}\)) | \( \Delta I_{\text{HCO}^+} \) (K km s\(^{-1}\)) | \( I_{\text{HNC}} \) (K km s\(^{-1}\)) | \( \Delta I_{\text{HNC}} \) (K km s\(^{-1}\)) | \( I_{\text{CO}^{12}} \) L(Kk ms\(^{-1}\)) |
|--------|-------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------|
| NGC 628 | 1.02        | 0.08                          | 0.04                          | 0.06                          | 0.00                          | 0.04                          | 0.00                          | 0.00              |
| NGC 628 | 2.05        | 0.05                          | 0.03                          | 0.02                          | 0.00                          | 0.04                          | 0.00                          | 0.00              |
| NGC 628 | 3.27        | 0.05                          | 0.02                          | 0.02                          | 0.00                          | 0.04                          | 0.00                          | 0.00              |
| NGC 628 | 4.65        | 0.04                          | 0.02                          | 0.02                          | NaN                           | 0.04                          | 0.00                          | 0.00              |
| NGC 628 | 7.00        | 0.04                          | NaN                           | NaN                           | NaN                           | NaN                           | NaN                           | NaN               |
| NGC 2903 | 0.73        | 1.16                          | 0.04                          | 0.81                          | 0.05                          | 0.31                          | 0.06                          | 31.38             |
| NGC 2903 | 1.78        | 0.68                          | 0.02                          | 0.42                          | 0.03                          | 0.29                          | 0.02                          | 23.96             |

Note. Uncertainties: (1) Where intensity measurements are below the significance threshold (3σ rms), Columns 3–14 contain NaN for the integrated intensities, and upper limits to the emission in the respective uncertainty column. (2) The full version of this table appears as online-only material. The radius provided corresponds to the outer edge of each selected ring.

(This table is available in its entirety in machine-readable form.)
Figure 21. Same as Figure 2, but for NGC 3184. Stacked CO(1–0), HCN(1–0), HCO\(^+\)(1–0), and HNC(1–0) in 30\(\arcsec\) (~1.5 kpc) radial bins. Galactocentric radii are shown in units of kpc.

Figure 22. Same as Figure 2, but for NGC 3627. Stacked CO(1–0), HCN(1–0), HCO\(^+\)(1–0), and HNC(1–0) in 30\(\arcsec\) (~1.5 kpc) radial bins. Galactocentric radii are shown in units of kpc.
Figure 23. Same as Figure 2, but for NGC 4254. Stacked CO($1−0$), HCN($1−0$), HCO$^+$($1−0$), and HNC($1−0$) in 30″ (≈1.5 kpc) radial bins. Galactocentric radii are shown in units of kpc.

Figure 24. Same as Figure 2, but for NGC 4321. Stacked CO($1−0$), HCN($1−0$), HCO$^+$($1−0$), and HNC($1−0$) in 30″ (≈1.5 kpc) radial bins. Galactocentric radii are shown in units of kpc.
Table 11 provides a subset of the most up-to-date dense gas observations in the literature, as traced by the HCN\((1-0)\) emission line. Its full version appears as online material only. This compilation includes the data we used to construct Figure 13. When this compilation table is used, the original studies of the various data sets that are included should be referred to.

Appendix C
Literature Data

Table 11 provides a subset of the most up-to-date dense gas observations in the literature, as traced by the HCN\((1-0)\) emission line. Its full version appears as online material only. This compilation includes the data we used to construct Figure 13. When this compilation table is used, the original studies of the various data sets that are included should be referred to.
Appendix D

Individual Galaxy Trends

In this section we present the individual line-of-sight measurements of the observed HCN-to-CO and TIR-to-HCN line ratios in every galaxy disk as a function of galactocentric radius (Figures 27 and 28), stellar surface density $\Sigma_*$ (Figures 29 and 30), molecular gas surface density $\Sigma_{\text{mol}}$ (Figures 31 and 32), molecular-to-atomic gas ratio $R_{\text{mol}}$ (Figures 33 and 34) and the local dynamical equilibrium pressure $P_{\text{DE}}$ (Figures 35 and 36). In all figures the light gray data points represent the entire EMPIRE survey, while the light blue data points represent the line-of-sight measurements for each individual galaxy. Light blue points with black outlines show points in the galaxy where HCN is detected at $S/N > 3$. Dark blue points show the stacked trends shown in Figure 14, which indicate systematic variations of the HCN-to-CO (as a proxy for the dense gas fraction) and IR-to-HCN (as a proxy for the SFE of the dense gas) line ratios as a function of galactic environment.

### Table 11

| Reference                  | $\log_{10}(L_{\text{IR}})/L_e$ | $\log_{10}(L_{\text{HCN}})$ (K km s$^{-1}$ pc$^2$) |
|----------------------------|-------------------------------|-----------------------------------------------|
| Graciá-Carpio et al. (2008)| 12.26                         | 9.26                                          |
|                            | 12.24                         | 9.06                                          |
|                            | 12.18                         | 9.19                                          |
|                            | 12.07                         | 9.10                                          |
|                            | 11.99                         | 8.86                                          |
|                            | 11.98                         | 8.85                                          |
|                            | 11.88                         | 9.00                                          |
|                            | 11.86                         | 8.81                                          |
|                            | 11.66                         | 8.77                                          |
|                            | 11.61                         | 8.75                                          |
|                            | 11.54                         | 8.43                                          |
|                            | 11.53                         | 8.30                                          |
|                            | 11.41                         | 8.05                                          |
|                            | 11.23                         | 7.87                                          |
|                            | 11.36                         | 8.30                                          |

**Note.** This table is a literature compilation, and its full version appears as online-only material. Each individual study is to be cited when the contents of this table are used.

(This table is available in its entirety in machine-readable form.)
Figure 27. HCN-to-CO ratio (left axis) and $\Sigma_{\text{HCN}}/\Sigma_{\text{CO}}$ (right axis), which trace the dense gas fraction, as a function of the normalized galactocentric radius $r/r_{25}$. Each data point represents a kiloparsec-size measurement per line of sight. Gray points show all EMPIRE lines of sight. Light blue points indicate measurements for each selected galaxy. Points with black outlines show regions where HCN is detected at $S/N > 3$. Dark blue points show the stacked HCN data, which recover signal in low $S/N$ regions; downward arrows give a lower limit to the ratio in regions where HCN is not detected. The dense gas fraction in all galaxy disks appears to decrease at larger galactocentric radii. We note that the plots above are in logarithmic scale, therefore nondetections with negative values cannot be represented. They are taken into account in the stacked intensities, however.
Figure 28. IR-to-HCN ratio (left axis) and $\Sigma_{\text{SFR}}/\Sigma_{\text{HCN}}$ (right axis), which trace the efficiency of dense gas, as a function of the normalized galactocentric radius $r/r_{25}$. The description of each data point is the same as in Figure 27. The dense gas efficiency appears to decrease for higher values of $\Sigma_\star$. We emphasize that NGC 2003 lacks Herschel data, and its SFR is calculated only using the available 24 $\mu$m, which is a less accurate procedure.
Figure 29. HCN-to-CO ratio (left axis) and $\Sigma_{\text{HCN}}/\Sigma_{\text{CO}}$ (right axis), which trace the dense gas fraction, as a function of the surface density of stars, $\Sigma_*$, in galaxy disks. The dense gas fraction appears to decrease for higher values of $\Sigma_*$. The description of each data point is the same as in Figure 27.
Figure 30. IR-to-HCN ratio (left axis) and $\Sigma_{\text{SFR}}/\Sigma_{\text{HCN}}$ (right axis), which trace the efficiency of dense gas, as a function of the surface density of stars, $\Sigma_{*}$. The description of each data point is the same as in Figure 27. The dense gas efficiency appears to decrease for higher values of $\Sigma_{*}$. We emphasize that NGC 2903 lacks Herschel data, and its SFR is calculated only using the available 24 $\mu$m, which is a less accurate procedure.
Figure 31. HCN-to-CO ratio (left axis) and $\Sigma_{\text{HCN}}/\Sigma_{\text{CO}}$ (right axis), which trace the dense gas fraction, as a function of the surface density of molecular gas as traced by CO. The description of each data point is the same as in Figure 27. The dense gas fraction in all galaxy disks appears to decrease for higher values of $\Sigma_*$. 

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Figure 32. IR-to-HCN ratio (left axis) and $\Sigma_{\text{SFR}}/\Sigma_{\text{HCN}}$ (right axis), which trace the efficiency of dense gas, as a function of the surface density of molecular gas as traced by CO. The description of each data point is the same as in Figure 27. The dense gas efficiency appears to decrease for higher values of $I_{\text{CO}}$. We emphasize that NGC 2903 lacks Herschel data, and its SFR is calculated only using the available 24 $\mu$m, which is a less accurate procedure.
Figure 33. HCN-to-CO ratio (left axis) and $\Sigma_{\text{HCN}}/\Sigma_{\text{CO}}$ (right axis), which trace the dense gas fraction, as a function of the molecular-to-atomic gas ratio, $R_{\text{mol}} = \Sigma_{\text{CO}}/\Sigma_{\text{HI}}$. The description of each data point is the same as in Figure 29. The dense gas fraction in all galaxy disks appears to be correlated with the molecular gas fraction, as traced by $f_{\text{mol}}$. 

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Figure 34. IR-to-HCN ratio (left axis) and $\Sigma_{\text{SFR}}/\Sigma_{\text{HCN}}$ (right axis), which trace the efficiency of dense gas, as a function of the molecular-to-atomic gas ratio, $R_{\text{mol}} = \Sigma_{\text{CO}}/\Sigma_{\text{HI}}$. The description of each data point is the same as in Figure 29. The dense gas efficiency appears to decrease for higher values of $f_{\text{mol}}$. 

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Figure 35. HCN-to-CO ratio (left axis) and $\Sigma_{\text{HCN}}/\Sigma_{\text{CO}}$ (right axis), which trace the dense gas fraction, as a function of the local dynamical equilibrium pressure, $P_{\text{DE}}$. The description of each data point is the same as in Figure 27. The dense gas fraction in all galaxy disks appears to increase for higher ISM pressures.
Appendix E

Alternative SFR Tracers

In this paper we make use of TIR emission, calculated from a combination of $\lambda = 70, 160, \text{ and } 250 \, \mu\text{m}$ Herschel bands following the prescription from Galametz et al. (2013), as our main SFR tracer. TIR emission is a common SFR tracer in other galaxies (e.g., Gao & Solomon 2004; García-Burillo et al. 2012; Usero et al. 2015; Bigiel et al. 2016), which makes it our preferred tracer for a comparison to prior work. The method rests on probing IR emission over the full IR range from dust heated by UV emission from recent star formation. However, one of the main caveats to its usage is that TIR emission is sensitive to stellar populations up to $\sim 100 \text{ Myr}$ (Kennicutt & Evans 2012).

An alternative approach is to use a tracer that is sensitive to more recent massive star formation, such as H$\alpha$ emission ($\sim 10 \text{ Myr}$). This needs to be carefully corrected for extinction, however, which is commonly done in other galaxies by combining them with mid-IR measurements accounting for reprocessed starlight at shorter wavelengths. Here we use two of these hybrid SFR tracers to test for systematic effects in our results by our specific choice of SFR. The first calibration is a linear combination of H$\alpha$ and 24 $\mu$m emission following Calzetti et al. (2007):

$$\frac{\sum_{\text{SFR}}}{M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}} = 634 I_{\text{H}\alpha} + 0.0025 I_{24 \mu \text{m}},$$

where $I_{\text{H}\alpha}$ is in units of erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ and $I_{24 \mu \text{m}}$ in MJy sr$^{-1}$. We also employ a linear combination of FUV intensity and 24 $\mu$m emission, as proposed by (Leroy et al. 2012),

$$\frac{\sum_{\text{SFR}}}{M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}} = 0.081 I_{\text{FUV}} + 0.0032 I_{24 \mu \text{m}},$$

where $I_{\text{FUV}}$ is in units MJy sr$^{-1}$.

Figure 36. IR-to-HCN ratio (left axis) and $\Sigma_{\text{SFR}}/\Sigma_{\text{HCN}}$ (right axis), which trace the efficiency of dense gas, as a function of the local dynamical equilibrium pressure, $P_{\text{DE}}$. The description of each data point is the same as in Figure 35. The dense gas efficiency appears to decrease for higher values of the ISM pressure.
In Figures 37 and 38 we plot the SFE\textsubscript{dense}, calculated using these two SFR tracers, instead of the TIR emission, as a function of one of our environmental parameters, Σ\textsubscript{*}. We do this for all the galaxies observed in EMPIRE. Figures 37 and 38 show that there are minimal differences in our trends (up to a ∼20\% level) when compared to the trends we obtained calculating SFE\textsubscript{dense} from TIR emission (e.g., Figure 30). This suggests that most of the radiation associated with recent star formation is reprocessed by dust. The results presented in this paper therefore appear to be robust with respect to the choice of SFR tracer.

For a more detailed study of the choice of SFR tracers, we refer to the previous analyses in Usero et al. (2015) and Gallagher et al. (2018a). These authors find that the same trends exist when a selection of SFR tracers is used: TIR, H\textalpha, 24 μm, and FUV data, as well as the hybrid combinations of 24 μm and H\textalpha, and 24 μm and FUV. Gallagher et al. (2018a) additionally find that for the majority of regions of interest (inner ∼3–5 kpc) in their galaxy sample, the contribution from the unobscured FUV and H\textalpha emission is significantly lower than any estimate that involves IR emission.
Appendix F

Physical Variation in the IR-to-HCN Ratio

Our main results for SFEs in the different galaxy disks we analyzed suggest a variation in the SFE with respect to several environmental parameters that are interconnected in some way (radius, stellar surface densities, molecular-to-atomic gas ratios, and local dynamical equilibrium pressure, Figures 29–36). Before we continue to interpret the physical mechanism behind the line ratio variations, we assess whether they could be driven by the noise in the HCN data. We build a simple Monte Carlo test that includes the uncertainties on the data that can be significant. The null hypothesis of this model is that the underlying true ratios \( \frac{HCN}{TIR} \) are constant, \( C \). We compute random values that will be added to our HCN emission measurements as randomly generated values within the range of actually observed HCN uncertainties in our data. After this, we compute new synthetic ratios as

\[
\frac{HCN}{TIR} = \frac{C \times TIR + \Delta(HCN)}{IR}.
\]

As seen above, we perturb the HCN observations with different random values per data point that are realistic within our observations to determine whether the observed scatter in Figures 35–36 can be explained. We perform \(10^5\) realizations of the experiment and compute the mean IR-to-HCN ratio of them, as well as the standard deviation from the mean. We also repeat the experiment for a range of possible values of \( C \), which is initially determined from the positions in the galaxy disks where we have high S/N measurements of HCN.

Figure 39 shows the simple Monte Carlo test for the EMPIRE data set. It displays the HCN-to-TIR ratio as a function of the TIR emission computed in every individual sampling point for every particular galaxy. The EMPIRE original observations are shown as dark blue points, and the
light blue points reflect the mean value of a constant HCN/TIR model from $10^5$ realizations. In these models, as described above, the HCN value includes a random realistic perturbation within the range of the observed uncertainties. The various panels show the different cases obtained depending on the constant chosen for the model, which is initially inferred from our high S/N measurements in the galaxy. The error bars correspond to the $1\sigma$ standard deviations from the modeled points in a sample of $10^5$ realizations.

Figure 39. Monte Carlo realizations for the observed galaxies. The EMPIRE original data are shown as black points, and the perturbed points for a null hypothesis of SFE = $C$ are shown in light green areas. The different panels show the case for each galaxy for a typical $C$ value equal to the median HCN/IR value in each galaxy. The error bars correspond to the $1\sigma$ standard deviations from the modeled points in a sample of $10^5$ realizations.

Figure 40 shows that the vast majority of data in EMPIRE has a much larger scatter than expected from our Monte Carlo realizations. The only exception is NGC 3627, which shows a comparable scatter in the real and simulated data in its entire disk, except for its very central position. Therefore there are real and systematic variations beyond what we can expect from the noise; there must be physical and chemical processes that are responsible for the even larger scatter at low TIR values.
**Figure 40.** Ratio between standard deviation computed for the EMPIRE data set and the standard deviation of Monte Carlo realizations. Each color set and the standard deviation of Monte Carlo realizations. Each color horizontal black line marks the units value, where the scatter in the EMPIRE data set is similar to the one reproduced by the Monte Carlo analysis.

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