SPATIALLY RESOLVED DENSE MOLECULAR GAS AND STAR FORMATION RATE IN M51

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ABSTRACT

We present the spatially resolved observations of HCN $J = 1–0$ emission in the nearby spiral galaxy M51 using the IRAM 30 m telescope. The HCN map covers an extent of 4′ × 5′, which is, so far, the largest in M51 with a spatial resolution of 28″. There is a correlation between infrared emission (an indication of star formation rate (SFR)) and HCN (1–0) emission (a dense gas tracer) on a kiloparsec scale in M51, a natural extension of the proportionality between the SFR and the dense gas mass established globally in galaxies. Within M51, the relation appears to be sub-linear (with a slope of 0.74 ± 0.16) as $L_{IR}$ rises less quickly than $L_{HCN}$. We attribute this to a difference between center and outer disk such that the central regions have stronger HCN (1–0) emission per unit star formation. The IR–HCN correlation in M51 is further compared with global ones from the Milky Way to high-z galaxies and bridges the gap between giant molecular clouds and galaxies. Like the centers of nearby galaxies, the $L_{IR}/L_{HCN}$ ratio measured in M51 (particularly in the central regions) is slightly lower than what is measured globally in galaxies, yet is still within the scatter. This implies that though the $L_{IR}/L_{HCN}$ ratio varies as a function of physical environment in the different positions of M51, IR, and HCN indeed show a linear correlation over 10 orders of magnitude.

Key words: galaxies: individual (M51, NGC 5194) – galaxies: ISM – ISM: molecules – radio lines: galaxies

1. INTRODUCTION

The molecular gas in galaxies is organized in giant molecular clouds (GMCs). Within these clouds, denser regions, often called clumps and cores, are found and this is where star formation takes place. Star formation rate (SFR) is linearly correlated with the amount of molecular gas (Kennicutt 1989; Bigiel et al. 2008) except in infrared (IR) luminous galaxies whose SFR is higher than would be expected from their CO emission (a molecular gas tracer). The SFR and total gas (H$_2$ and HI) surface densities are correlated (Kennicutt 1998), typically with power-law exponents greater than one when the HI dominates, i.e., in the lower column density regions generally located in the outer disk, and approaching one in the H$_2$-dominated regions (Buat et al. 1989; Buat 1992; Bigiel et al. 2008). Thus, on a galaxy scale, the important link is between the SFR and molecular gas content, particularly the mass of dense gas. The star formation efficiency (SFE; SFR/CO) is higher in galaxies with a higher fraction of dense gas (Gao & Solomon 2004a). Lada et al. (2012) suggested that the SFR and molecular gas correlation is always linear with the same fraction of dense gas found in clouds to galaxies.

A few environments exist in which the dense gas fraction, typically the HCN/CO intensity ratio, is clearly different from the average large-scale value of normal galaxies (~1/30, Gao & Solomon 2004a). Ultraluminous IR galaxies have a higher dense gas fraction (Gao & Solomon 2004a), while environments that have undergone a gas–gas collision typically have a lower dense gas fraction (e.g., Braine et al. 2003, 2004).

The physical conditions of active star-forming GMC cores are revealed by emission from high-$J$ $(> 3)$ rotational transition CO lines and large dipole-moment molecules like CS, HCO$^+$, and HCN (Evans 1999). The HCN $J = 1–0$ transition traces denser gas ($> 3 \times 10^3$ cm$^{-3}$) than CO $J = 1–0$ ($> 300$ cm$^{-3}$) because of its larger dipole moment. From a HCN emission survey of 65 galaxies, Gao & Solomon (2004a) find a tight linear correlation between the SFR, traced by IR luminosity ($L_{IR}$), and dense gas mass ($M_{dense}$), traced by the HCN luminosity ($L_{HCN}$), with an almost constant average ratio $L_{IR}/L_{HCN} = 900L_{IR}/(K$ km s$^{-1}$ pc$^2$), whereas the IR–CO correlation is clearly nonlinear. Wu et al. (2005, 2010) extended this correlation to Galactic GMCs in the Milky Way. The HCN–IR correlation appears to be valid at high redshift as well (Gao et al. 2007), but a large gap is present between global galaxies and Galactic GMCs (see Figure 2 in Lada et al. 2012).

Few HCN maps of external galaxies are available (e.g., Nguyen et al. 1992; Gao & Solomon 2004b; Kepley et al. 2014) because the HCN emission in normal spiral disks is weak, such that little is known about the dense gas distribution outside the central regions in external galaxies. Except for a few high-resolution HCN maps (Kohno et al. 1996; Helfer & Blitz 1997; Krips et al. 2007; Schinnerer et al. 2007; Levine et al. 2008; Muraoka et al. 2009; Leroy et al. 2015) of the central kiloparsec and a few single-dish maps of IC 342 (40″ × 60″), M83 (40″ × 50″), and M51 (1.5′ × 2′, Nguyen et al. 1992), few HCN observations exist toward the outer disks. More observations of HCN emission in nearby galactic disks are necessary in order to properly interpret whole-galaxy data which is a mixture of nucleus and disk emission.

M51 is an ideal target for studying the spatially resolved IR–HCN correlation across galactic disks. It is a large local spiral galaxy ($D \sim 7.6$ Mpc, Ciardullo et al. 2002) seen nearly face-
on (i \sim 22^\circ, Colombo et al. 2014). The Herschel\(^8\) Very Nearby Galaxy Survey (VNGS) mapped M51 at wavelengths of 70, 160, 250, and 350 \(\mu\)m (Mentuch Cooper et al. 2012). CO emission has been mapped over the entire galaxy by Koda et al. (2011, CO 1–0), Schuster et al. (2007, CO 2–1), and Vlahakis et al. (2013, CO 3–2). The PdBI Arcsecond Whirlpool Survey (Schinnerer et al. 2013) observed the CO 1–0 emission in the central 9 kpc of M51 at 1\(''\) resolution. HCN emission in the central disk (1.5 \times 2\) has been mapped by Nguyen et al. (1992). The correlations between SFR and H\(_2\) on a kiloparsec scale in M51 were explored by Kennicutt et al. (2007) and Bigiel et al. (2008).

In this paper, we present a map of M51 in the HCN \(J = 1–0\) line at 88.6 GHz with the IRAM 30 m telescope to obtain a spatially resolved HCN image of a nearby spiral galaxy covering 4\('\) \times 5\('\). The IRAM 30 m beam corresponds to a spatial resolution of \sim 1 kpc and samples large GMC associations and individual GMCs within the beam along the spiral arms to starburst-like regions near the center. Combined with the Herschel VNGS 70 and 160 \(\mu\)m maps, we can make a detailed point-by-point comparison of the IR–HCN correlation at kiloparsec scales within a normal star-forming disk, bridging the luminosity gap between galaxies and individual GMCs.

The observations and data reduction are presented in Section 2. The HCN maps and the kiloparsec scale IR–HCN correlation are presented in Section 3. In Section 4, we compare the distribution of HCN, CO, and IR, and discuss the effect of dust temperature on the HCN emission. The IR–HCN correlation in M51 is compared with existing data for galaxies and Galactic clouds.

2. OBSERVATIONS AND DATA REDUCTION
2.1. HCN Observations

During 2004 May, 2005 June, and 2007 July, we used the IRAM 30 m telescope on Pico Veleta near Granada, Spain, to map the HCN \(J = 1–0\) emission from M51 at a rest frequency of \(\nu = 88.63185\) GHz. The angular resolution of the IRAM 30 m is 28\(''\) at 88.6 GHz, which is \sim 1 kpc at the distance of M51. The map covers 4\('\) \times 5\('\) (8 kpc \times 10 kpc) and the spectra are spaced by 15\(''\) (see Figure 1). So far, this is the largest HCN map of M51.

Pointings were checked about every 2 hr on nearby QSOs with strong millimeter continuum emission, or occasionally on

\(^8\) Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
The A100 and B100 receivers, which receive two orthogonal polarizations, were used to observe the molecular lines simultaneously. We used the 512 × 1 MHz filter bank backend, yielding a spectral resolution of 3.3 km s⁻¹. Typical system temperatures at 88.6 GHz were ∼130 K on average on the T_A* scale. To convert the observed antenna temperatures to the main beam temperature scale, we use 

\[ T_{mb} = T_A^* F_{eff} / B_{eff} \]

where the forward efficiency \( F_{eff} = 95\% \) and the beam efficiency \( B_{eff} = 78\% \). Observations focused on the spiral arms for the outer disk regions due to the limited observing time available. Some bad weather data were discarded and the total observing time of the useful data in M51 is ∼81 hr. The integration time at each position was 6–90 minutes depending on the signal strength.

All the data were reduced with the CLASS program of the GILDAS package. After eliminating bad channels, a linear baseline was fit to correct the total power variations in the receiver and atmosphere. A small fraction of the spectra were not well fit by a linear baseline. The line windows are determined from the HCN spectra themselves when the emission was strong. Where the emission was weak or not detected, we used line windows based on the CO emission, which was detected throughout the map. Individual spectra with poor baselines were discarded and spectra at each position were combined.

### 2.2. CO Data

The CO \( J = 1-0 \) total power and short spacing data were taken with the 5 × 5 Beam Array Receiver System on the Nobeyama Radio Observatory 45 m telescope (Koda et al. 2011).

All CO and the Herschel IR data (70, 160, and 250 μm) are convolved to the resolution of the HCN observations (2.8") to make a detailed point-by-point comparison with HCN.

### 3. RESULTS AND ANALYSIS

#### 3.1. HCN Line

#### 3.1.1. HCN Spectra

The HCN \( J = 1-0 \) spectra are shown in Figure 1. All spectra are plotted in main beam temperature (\( T_{mb} \)) and smoothed to 13.3 km s⁻¹ resolution for show (for some weak HCN positions, the spectra are further binned to 26.7 km s⁻¹ for display). Figure 2 shows several HCN and CO line profiles in detail. The HCN emission line is centered at 475 km s⁻¹ in the nucleus and shifted to 535 and 400 km s⁻¹ in the northern and southern regions, respectively. The peak of the HCN spectrum is 1/10 of the CO peak in the center regions while it is 1/30 in the outer disk. The zero power line width is close to 200 km s⁻¹ and decreases to 30–60 km s⁻¹ in the outer disk. The HCN line peak and profile in the center is consistent...
with those found in previous observations by Nguyen et al. (1992).

### 3.1.2. Local HCN Line Luminosities

The HCN integrated intensities were measured as $I_{\text{HCN}} = \int T_m dV$ over the emission window. For the HCN spectra with high signal-to-noise ratio ($S/N \geq 5$) in integrated intensity, we define the emission window from HCN. But for the HCN spectra with low intensity $S/N (<5)$, we define the emission window using the CO spectra, detected in all positions. As the intensity is dependent on the strength of the line relative to the zero point defined by the baseline outside the line window (Braine et al. 1993; Matthews & Gao 2001), the integrated intensity errors were estimated as

$$\delta I_{\text{HCN}} = T_{\text{rms}} \sqrt{W_{\text{HCN}} \delta c / (1 - W_{\text{HCN}}/W)},$$

where $T_{\text{rms}}$ is the rms noise fluctuation, $W_{\text{HCN}}$ is the width of the line window in km s$^{-1}$, $\delta c$ is the channel spacing in units of km s$^{-1}$, and $W$ is the entire velocity coverage (1000 km s$^{-1}$). $3\delta I_{\text{HCN}}$ upper limits were established for the weak $S/N < 3$ spectra.

The HCN luminosity in each observed region is calculated as:

$$L_{\text{HCN}}(K \text{ km s}^{-1} \text{ pc}^2) = 23.5\Omega d_L^2 (\text{Mpc}) I_{\text{HCN}}(K \text{ km s}^{-1}),$$

where $\Omega$ is the solid angle of the regions covered by the telescope beams in arcsec$^2$ (Solomon et al. 1997) and $d_L$ is the
luminosity distance. The local CO luminosity is calculated with the same formula (switching HCN with CO).

3.1.3. HCN Distribution

Figure 3 shows the CO, HCN, and 70 μm integrated intensity maps, respectively. The HCN integrated intensity peak is 5.54 ± 0.04 K km s⁻¹, located at 15″ west of the optical nucleus and about 15″ north of the CO peak (relative to the HCN resolution). The HCN map reproduces the large-scale structure traced by CO fairly well. The northern and southern CO arms are detected in HCN. 70 μm images (tracing SFR) show the same structure with HCN and CO. The high-resolution 70 μm peaks in spiral arms are tightly related to the HCN peaks.

3.2. Correlation between HCN and IR

3.2.1. \( L_{\text{IR}} \) from 70 and 160 μm Fluxes

In order to compare the IR and HCN point by point, we need to calculate the IR luminosity of each HCN beam. The Herschel PACS observations at 70 and 160 μm bracket the peak of the thermal dust emission and so provide an excellent estimate of the dust luminosity (Boquien et al. 2011). Following Galametz et al. (2013), we calculate the total IR luminosity from the convolved 70 and 160 μm images as:

\[
\log L_{\text{IR}} = [(0.973 \times \log \nu L_{\nu}(70) + 0.567) + (1.024 \times \log \nu L_{\nu}(160) + 0.176)]/2.
\]

3.2.2. Correlation between HCN and IR

Figure 4 shows \( L_{\text{IR}} \) versus \( L_{\text{HCN}} \) for all of the points with HCN detection (S/N ≥ 3). The HCN emission is correlated tightly with IR over 1.5 orders of magnitude in HCN intensities (correlation coefficient \( R = 0.87 \)). The least-square fits yield a slope of 0.74 such that the SFR varies less than the dense gas mass. The best-fit (logarithmic) relation is:

\[
\log \left( \frac{L_{\text{IR}}}{L_{\odot}} \right) = (0.74 \pm 0.16) \times \log \left( \frac{L_{\text{HCN}}}{K \text{ km s}^{-1} \text{ pc}^{-2}} \right) + (4.28 \pm 0.95).
\]

The uncertainties given in the equation refer to the fitting errors responding to the uncertainty of \( L_{\text{HCN}} \). The dense gas SFE \( (L_{\text{IR}}/L_{\text{HCN}}) \) of the central regions (filled triangles, with an average \( L_{\text{IR}}/L_{\text{HCN}} \) ratio of 388 ± 47 \( L_{\odot} \) (K km s⁻¹ pc⁻²); only the HCN luminosity errors are taken into account) is systematically lower than that of the outer disk regions (open triangles, with an average \( L_{\text{IR}}/L_{\text{HCN}} \) ratio of 691 ± 156 \( L_{\odot} \) (K km s⁻¹ pc⁻²)).

3.2.3. Comparison of the HCN–IR and CO–IR Correlations

The relation between CO and IR luminosity of the same regions in M51 is also shown in Figure 4. The least-square fit yields a slope of 1.07 ± 0.28 (correlation coefficient \( R = 0.78 \)), such that the HCN varies more than the IR and CO for the same regions. The correlation coefficient between HCN and IR (0.87) is better than that of the CO–IR correlation (0.78). The fitting error for the slope of IR–CO (0.28) is much larger than that of IR–HCN (0.16). The most obvious difference occurs at the high \( L_{\text{IR}} \) end, dominated by the central region, similar to the situation for galaxies as a whole. In Figure 4, lines of constant IR/HCN and IR/CO ratios fit the outer disk regions, but the constant IR/HCN line lies above most of the central regions, while the constant IR/CO line does not.

4. DISCUSSION

4.1. Comparison of the HCN, CO, and IR Distribution

The azimuthal averages are calculated to investigate the radius distribution of CO, HCN, and IR, as shown in lines as in Figure 5. We average over rings of 15″ width (regions within the intervals \( r = n \times 15\arcsec + 75\arcsec \pm 75\arcsec \), \( n = 0, \ldots, 10 \)), comparable to the angular resolution of our data. All the intensities of CO, HCN, and IR decrease rapidly with radius in the central 45″ (1.66 kpc) and then more slowly at larger radii. HCN decreases faster than IR, and IR decreases faster than CO along with radius. The HCN emission is more confined to the inner regions than IR and CO.

The HCN/CO, IR/HCN (SFEdense), and IR/CO (SFE) distributions are shown in Figure 6. The HCN/CO and IR/CO ratios are much higher in the center than in the outer disk, but IR/HCN is lower. The IR/HCN ratio is 388\( L_{\odot} \) (K km s⁻¹ pc⁻²) on average in the central 45″ (1.66 kpc), while it is 691\( L_{\odot} \) (K km s⁻¹ pc⁻²) in the outer disk, illustrating that the physical conditions in the center are quite different from the outer disk.

A pattern of high \( L_{\text{IR}}/L_{\text{CO}} \) (SFE) and \( L_{\text{IR}}/L_{\text{HCN}} \) (SFEdense) can be seen in some regions of the outer spiral arms (Figure 6). GMA cores in the spiral arm are found to have nearby star-forming regions (Egusa et al. 2011) which suggests that star formation can be triggered in the spiral arm. Koda et al. (2012) studied CO lines in M51 and found that the CO(2−1)/CO(1−0) ratio is enhanced in the spiral arms, especially downstream of the molecular arms. Higher resolution and sensitivity HCN observations are needed to study the effect of spiral arms on the HCN–IR correlation.
4.2. Mass of Dense Molecular Gas Traced by HCN

As the measured IR–HCN correlation physically comes from the connection between star formation activity and dense molecular gas, it should be noted that the mass of molecular gas estimated from HCN includes considerable uncertainties because HCN emission is optically thick. Sandstrom et al. (2013) find that in the HERACLES sample the CO emission to H$_2$ factor ($M_{\text{IR}}/L_{\text{CO}}$) increases from the central kiloparsec to regions farther out in the disk, in agreement with earlier work (e.g., Nakai & Kuno 1995; Sodroski et al. 1995; Braine et al. 1997). This suggests that $M_{\text{dense}}/L_{\text{HCN}}$ may vary linearly with galactocentric radius as well. In this situation, the SFR–$M_{\text{dense}}$ correlation may be linear while $L_{\text{IR}}$–$L_{\text{HCN}}$ may not, requiring a varying $M_{\text{dense}}/L_{\text{HCN}}$ factor to convert from $L_{\text{HCN}}$ to $M_{\text{dense}}$.

Figure 6. (a) HCN $J = 1-0$ integrated intensity map ($K$ km s$^{-1}$) of the detected regions (S/N $\geq$ 3). (b), (c), (d) are, respectively, maps of $L_{\text{HCN}}/L_{\text{CO}}, L_{\text{IR}}/L_{\text{HCN}}$ [$L_{\text{CO}}/(K$ km s$^{-1}$ pc$^2$)], and $L_{\text{IR}}/L_{\text{CO}}$ [$L_{\text{IR}}/(K$ km s$^{-1}$ pc$^2$)] of the same region. Contours are the same as those in Figure 3(a). The black circle shows the assumed center occupying the central 45′ (1.66 kpc).

Gao & Solomon (2004b) suggest that $M_{\text{dense}}/L_{\text{HCN}}$ may vary linearly with the gas excitation temperature. They estimate that for an excitation temperature of 35 K, $M_{\text{dense}}/L_{\text{HCN}} \sim 10M_\odot (K$ km s$^{-1}$ pc$^2$)$^{-1}$. The temperature-dependent $M_{\text{dense}}/L_{\text{HCN}}$ conversion can then be estimated as: $M_{\text{dense}}/L_{\text{HCN}} = 10 \times (35/T) M_\odot (K$ km s$^{-1}$ pc$^2$)$^{-1}$. Since we have no means of estimating the excitation temperature, we assume that the dust temperature is representative of the temperature of the gas in dense regions. This is probably not entirely unreasonable as the dust and gas exchange energy fairly quickly at high density. The dust temperatures are estimated from the Herschel 160 and 250 μm fluxes assuming an emissivity index of $\beta = 2$. While most spirals show a clear decrease in dust temperature with radius, in M51 we do not find a radii trend and the dust temperature varies little (24–28 K) in...
the central disk and outer spiral arm regions, resulting in little change in $M_{\text{dense}}/L_{\text{HCN}}$.

There are still some weaknesses for our estimation of $M_{\text{dense}}/L_{\text{HCN}}$. The gas excitation temperature may be different from the dust temperature in GMC cores and we do not consider the decreasing of HCN abundance which may be the primary cause of the apparent increase of $M_{\text{dense}}/L_{\text{HCN}}$ with radius. Another possible cause for the higher average IR/HCN ratio in the outer disk is that some of the IR emission may come from the general interstellar radiation field, which probably contributes proportionally more to the outer disk IR than to the center IR (Calzetti et al. 2005).

4.3. Spatially Resolved Star Formation Laws

The spatially resolved star formation laws quantify the relationship between the SFR and molecular gas in nearby galaxies at scales of $\sim$1 kpc or less. The SFR–$H_2$ relation shows various power-law indices, ranging from $<1$ (e.g., Shetty et al. 2013), $\sim$1 (Bigiel et al. 2008), $\sim$1.1–1.5 (Kennicutt et al. 2007; Schruba et al. 2010). A single linear spatially resolved SFR–$H_2$ relationship cannot describe the relation between star formation and molecular gas for the large scatter from galaxy to galaxy (Saintonge et al. 2011; Schruba et al. 2011; Rahman et al. 2012; Leroy et al. 2013).

Correlations between SFR and dense molecular gas tracers, such as HCN 1–0 (Liu et al. 2015b), HCN 4–3, HCO$^+$ 4–3, CS 7–6 (Zhang et al. 2014), and high-J CO (Liu et al. 2015a), show a tight linear correlation in global galaxies. However, IR–HCN shows a sub-linear relation in M51 on a kiloparsec scale which is likely biased by the limited dynamical range, particularly the high IR central regions. It is possible that the galaxy variations may dominate this inconsistency as shown in the SFR–$H_2$ relation. More HCN surveys toward the galaxy are needed to explore the spatially resolved IR–HCN relation.

4.4. $L_{\text{HCN}}$ Versus $L_{\text{IR}}$: Correlation from GMCs to High-$z$ Galaxies

One of the motivations for studying HCN in M51 comes from the intimate link between star formation and dense gas in galaxies and in individual GMC cores in the Milky Way. In Figure 7, we show plots of $L_{\text{IR}}$ versus $L_{\text{HCN}}$ and $L_{\text{IR}}/L_{\text{HCN}}$ (an indicator of SFE$_{\text{dense}}$) versus $L_{\text{IR}}$ measured locally in M51 (center, filled black triangles; outer disk, open triangles) compared with the observations of individual GMC cores in the Milky Way (open squares; Wu et al. 2010), M31 (filled black squares; Buchbender et al. 2013), M33 (filled blue squares; Brouillet et al. 2005), nearby galactic centers (filled blue triangles; Krips et al. 2008), whole galaxies (open hexagons; Gao & Solomon 2004b) and high-$z$ galaxies (filled hexagons; Gao et al. 2007). For whole galaxies, the mean value of $L_{\text{IR}}/L_{\text{HCN}}$ is 900$L_\odot$ (K km s$^{-1}$pc$^2$)$^{-1}$ (shown as the solid line), while it is 629$L_\odot$ (K km s$^{-1}$pc$^2$)$^{-1}$ in M51. The $L_{\text{IR}}/L_{\text{HCN}}$ ratio in M51 is a factor 1.5 lower on average than that of most galaxies, yet is still contained in the scatter. This suggests that a linear correlation is highly applicable to different physical scales, linking GMCs to kpc local regions and whole galaxies in a single relation. The linearity of the HCN–IR correlation was interpreted as a fundamental unit of all star-forming system, thus both IR and HCN are simply accumulated by adding in more units (Wu et al. 2005).
In M33, Buchbender et al. (2013) observed seven clouds at roughly 100 pc resolution in CO, HCN, and HCO⁺. It is apparent from Figure 7 that the HCN emission for a given IR luminosity is weak in M33 (filled black squares), a factor of three on average weaker than in the disk of M51. A reason to expect the HCN line to be weak with respect to IR is the sub-solar metallicity in M33. The dust abundance is expected to vary approximately linearly with metallicity (i.e., O/H) assuming a similar fraction of heavy elements in the dust phase. Because the N abundance decreases more quickly than the O abundance (i.e., N/O ratio decreases with decreasing O/H; see Figure 18 of the review by Garnett 2002), the HCN line is expected to decrease more than IR relative to Galactic abundances in M33. The disk of M31 was observed at a similar resolution by Brouillet et al. (2005); using the IR luminosity from the Draine et al. (2014) maps, these points are also shown in Figure 7 (filled blue squares) and are in rough agreement with the M51 IR/HCN ratio. From the resolved observations, the IR/HCN ratio is low for galactic centers, moderate (i.e., following the Gao et al. relation) for the disks of M51 and M31, and high for M33. This whole range is covered by the individual galactic clouds studied by Wu et al. (2010, 2005).

The centers of nine nearby galaxies NGC 1068, 2146, 3627, 4569, 4826, 5194, 6946, M82, and Arp 220 have been observed in HCN ($J = 1–0$) with the IRAM 30 m (Kr superscript et al. 2008). These objects exhibit nuclear starburst and/or active galactic nucleus signatures. We estimate the IR luminosity of the centers from the convolved Herschel 100 μm map (Galametz et al. 2013) observed by KINGFISHsuperscript10 or the combination of the convolved Herschel 70 and 160 μm map (see Section 3.2.1) observed by VNGS. The NGC 2146 and M82 centers show higher $L_{IR}/L_{HCN}$ ratios than M51, and the other seven nearby galactic centers are consistent with the central regions of M51. The lower $L_{IR}/L_{HCN}$ ratios of nearby galactic centers compare to the mean value of whole galaxies (combination of outer disk and center) suggest that the $L_{IR}/L_{HCN}$ ratio may be higher in the outer disk than the center, which supports the increasing trend from center to outer disk in M51 and nearby disk galaxies (Us supercript ero et al. 2015). More HCN observations toward the outer disk are needed to study this trend.

4.5. $L_{IR}/L_{CO}$ Versus $L_{HCN}/L_{CO}$

Figure 8 shows a correlation between $L_{IR}/L_{CO}$ (tracer of SFE) and $L_{HCN}/L_{CO}$ (tracer of dense gas fraction; $R_{HCN/CO}$). The SFE in the central regions is systematically higher than in the outer disk regions, which agrees well with Gao & Solomon’s (2004a) finding that the SFE depends on the fraction of molecular gas in a dense phase. However, the correlation between SFE and $R_{HCN/CO}$ is not linear. $R_{HCN/CO}$ in the center is higher than the linear fit determined from the mean value of the outer disk regions. Thus, either (i) $L_{IR}$ underestimates the SFR in the center (relative to the outer disk), (ii) $L_{HCN}$ overestimates $M_{dense}$ in the center (relative to the outer disk), or (iii) the central environment makes star formation less efficient. The 24 μm emission is less sensitive to the general interstellar radiation field and shows the same trends as in Figure 4, so we do not support (i). Our analysis excludes temperature as the primary cause of (ii). Abundance variations, presumably driven by nitrogen, could provide at least a partial explanation for the trends we find. Our work cannot address (iii). To further study the effect of density on starformation, we are currently observing the denser gas tracer (HCN–3) in the central disk of M51 with the JCMT telescope, potentially extended the IR and HCN4–3 relation in global galaxies.

5. SUMMARY

We present the spatially resolved observations of the HCN $J = 1–0$ transition of the nearby spiral galaxy M51 using the IRAM 30 m telescope. The map covers an extent of 4′ × 5′ with a spatial resolution of 28″ and 15″ sampling, which is, so far, the largest HCN map of M51. The HCN emission peaks 15″ west of the optical nucleus and about 15″ north of the CO peak (at the HCN resolution).

Comparing the individual observed positions, the IR emission varies less than the HCN emission, such that $L_{IR} \propto L_{HCN}^{0.74\pm0.10}$, despite the overall linear relation between HCN and IR emission from Galactic clumps to distant galaxies. While the conversion from HCN intensity to dense gas mass may vary, temperature (as traced by the dust) cannot explain the variation. It is possible that the galaxy variations may dominate this inconsistency as shown in SFR–H$_2$ relation.

$L_{IR}$ traces SFR and $L_{HCN}$ traces dense gas mass, so the ratio provides information about the efficiency of transformation of dense gas into stars. There is a clear radial trend in $L_{IR}/L_{HCN}$ decreasing with galactocentric radius. Comparing with resolved data in other galaxies, seven nearby galactic centers show a consistent $L_{IR}/L_{HCN}$ ratio (an indicator of $SFEdens$) with the central regions in M51. While the ratio measured locally in M51 is 1.5 times lower than the galactic average, it is still within the scatter. Though $L_{IR}/L_{HCN}$ may vary with physical environments in M51, HCN, and IR indeed shows a linear correlation over 10 orders of magnitude.

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REFERENCES

Bigiel, F., Leroy, A., Walter, F., et al. 2008, AJ, 136, 2846
Boquien, M., Lisensfeld, U., Duc, P.-A., et al. 2011, A&A, 533, A19
Braine, J., Combes, F., Casoli, F., et al. 1993, A&AS, 97, 887
Braine, J., Davoust, E., Zhu, M., et al. 2003, A&A, 408, L13
Braine, J., Guelin, M., Dumke, M., et al. 1997, A&A, 326, 963
Braine, J., Guelin, M., Dumke, M., et al. 1997, A&A, 326, 963
Braine, J., Davoust, E., Zhu, M., et al. 2003, A&A, 408, L13
Braine, J., Guelin, M., Dumke, M., et al. 1997, A&A, 326, 963
Braine, J., Lisensfeld, U., Duc, P.-A., et al. 2004, A&A, 418, 419
Brouillet, N., Muller, S., Herpin, F., Braine, J., & Jacq, T. 2005, A&A, 429, 153
Buat, V. 1992, A&A, 264, 444
Buat, V., Deharveng, J. M., & Donas, J. 1989, A&A, 223, 42
Buchbender, C., Kramer, C., Gonzalez-Garcia, M., et al. 2013, A&A, 549, A17
Calzetti, D., Kennicutt, R. C., Jr., & Bianchi, L. 2005, ApJ, 633, 871
Ciardullo, R., Feldmeier, J. J., Jacoby, G. H., et al. 2002, ApJ, 577, 31
Colombo, D., Meidt, S. E., Schinnerer, E., et al. 2014, ApJ, 780, 172
Egusa, F., Koda, J., & Scoville, N. 2011, ApJ, 726, 85

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