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THE STAR FORMATION RATE–DENSE GAS RELATION IN GALAXIES AS MEASURED BY HCN(3–2) EMISSION

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ABSTRACT

We present observations made with the 10 m Heinrich Hertz Submillimeter Telescope of HCN(3–2) emission from a sample of 30 nearby galaxies ranging in infrared luminosity from 10^{10} to $10^{12.5} L_{\odot}$ and HCN(3–2) luminosity from 10^6 to 10^9 K km s^{−1} pc². We examine the correlation between the infrared luminosity and HCN(3–2) luminosity and find that the best-fit linear regression has a slope (in log-log space) of 0.74 ± 0.12 . Including recently published data from Graciá-Carpio et al. tightens the constraints on the best-fit slope to 0.79 ± 0.09 . This slope below unity suggests that the HCN(3–2) molecular line luminosity is not linearly tracing the amount of dense gas. Our results are consistent with predictions from recent theoretical models that find slopes below unity when the line luminosity depends on the average gas density with a power-law index greater than a Kennicutt-Schmidt index of 1.5.

Subject headings: galaxies: evolution — galaxies: ISM — submillimeter

Online material: color figures

1. INTRODUCTION

For decades, it has been known that the star formation rate (SFR) in galaxies is intimately related to the gas reservoir from which stars are formed (Schmidt 1959). Observations of the galactic-averaged surface density of H I and CO gas indicate that the SFR increases with total gas surface density (H I + H₂ measured by CO $J = 1-0$) according to $\Sigma_{\text{SFR}} \sim \Sigma_{\text{gas}}^N$, where $N = 1.4 \pm 0.15$ (Kennicutt-Schmidt law, hereafter KS law; Kennicutt 1998b). Recent studies have focused on dense molecular gas tracers [e.g., HCN(1–0), CO(3–2)] and have found a tight, linear correlation between the SFR, traced by infrared (IR) luminosity (L_{IR}), and the mass of dense gas, traced by molecular line luminosity, L_{mol} (Gao & Solomon 2004a, 2004b; Narayanan et al. 2005). The surface density relation and the SFR- L_{mol} relation (for dense gas tracers) appear to predict different behaviors for the underlying star formation law in galaxies.

The linear relationship between L_{IR} and HCN(1–0) luminosity over three decades in L_{IR} found by Gao & Solomon (2004a, 2004b) in local star-forming galaxies has been interpreted as a constant star formation efficiency (SFR/ M_{H_2}) traced by dense molecular gas. Wu et al. (2005) extended the observed linear relationship between L_{IR} and HCN(1–0) luminosity to Galactic clumps, positing that if HCN(1–0) emission faithfully traces dense molecular core mass (above a cutoff luminosity of $L_{\text{bol}} > 10^{4.5} L_{\odot}$), then constant SFR per unit mass is a result of a dense molecular clump comprising a “fundamental unit” of star formation. The observed extragalactic linear correlation is a natural extension of the constant SFR per unit mass ob-

served toward dense molecular clumps in the Milky Way (Plume et al. 1997; Shirley et al. 2003, 2007). In this picture, ultraluminous IR galaxies such as Arp 220 that lie on the linear SFR-HCN(1–0) relation simply contain more cluster-forming units and a higher fraction of dense molecular gas.

The interpretation outlined in Wu et al. (2005) predicts a linear relation between SFR and tracers of even higher critical (n_{crit}) density than HCN(1–0). However, recent theoretical models from Narayanan et al. (2008, hereafter N08) and Krumholz & Thompson (2007, hereafter KT07) predict that the power-law index between the SFR and higher critical density tracers such as HCN(3–2) should in fact be below unity. The physical explanation for this behavior is that in systems with predominantly low-density gas, emission from high critical density lines originates in the extreme tails of the density distribution, resulting in a $L_{\text{mol}}-\langle n \rangle$ relation with a slope greater than unity. This effect drives an SFR- L_{mol} relation with a slope below unity for tracers with higher n_{crit} than that of HCN(1–0). To test this prediction, we have measured the HCN(3–2) line luminosity ($L'_{\text{HCN}(3-2)}$) from a sample of 30 galaxies and compared our results with recently published data from Graciá-Carpio et al. (2008, hereafter GC08). Both data sets show a $L_{\text{IR}}-L'_{\text{HCN}(3-2)}$ slope that is significantly below unity, in agreement with the model predictions.

2. OBSERVATIONS

Observations of HCN(3–2) ($\nu_{\text{rest}} = 265.886431$ GHz) were obtained from 2007 February through 2007 June using the 10 m Heinrich Hertz Submillimeter Telescope (SMT) on Mount Graham (Arizona). Our sample includes 30 galaxies and covers a broad range of IR luminosities: $L_{\text{IR}} \sim 10^{10.2}-10^{12.5} L_{\odot}$. Central positions of all galaxies were observed in HCN(3–2). One nearby galaxy ($D < 7$ Mpc) was mapped (NGC 0253). The FWHM of the SMT at 265 GHz is $\sim 30''$, such that a single beam covers the central kpc of galaxies beyond 7 Mpc.

The observations were made using the new ALMA sideband separating receiver and the Forbes Filterbank spectrometer. This dual-polarization receiver uses image-separating superconductor-insulator-superconductor (SIS) mixers that are significantly more sensitive than conventional receiver systems using quasi-

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TABLE 1
SMT HCN(3–2) DATA

Source	$L_{\text{HCN}(3-2)}$ (K km s ⁻¹)	$L'_{\text{HCN}(3-2)}$ (10 ⁶ K km s ⁻¹ pc ²)	L_{IR} (10 ¹¹ L _⊙)
Arp 193	0.36 ± 0.11	82 ± 25	5.1 ± 1.0
Arp 220	4.51 ± 0.90	634 ± 127	18.3 ± 3.7
Arp 55	<0.23	<147	5.2 ± 1.0
IC 342 ^a	1.76 ± 0.37	0.25 ± 0.05	0.13 ± 0.03
IRAS 10565	<0.19	<148	11.0 ± 2.2
IRAS 17208	<0.27	<203	29.1 ± 5.8
IRAS 23365	<0.18	<293	14.2 ± 2.8
M82 ^a	6.21 ± 1.26	2.7 ± 0.6	0.53 ± 0.11
Mrk 231	<0.15	<108	26.5 ± 5.3
Mrk 273	<0.13	<77	15.6 ± 3.1
NGC 0253 ^b	13.67 ± 2.85	8 ± 2	0.25 ± 0.05
NGC 0520	0.55 ± 0.13	14 ± 3	0.8 ± 0.2
NGC 0660	1.19 ± 0.29	4 ± 1	0.31 ± 0.06
NGC 0695	<0.13	<56	4.0 ± 0.8
NGC 1068	6.01 ± 1.22	38 ± 8	1.0 ± 0.2
NGC 1614	<0.21	<23	3.5 ± 0.7
NGC 2146	0.68 ± 0.15	2.6 ± 0.6	1.1 ± 0.2
NGC 2903	0.61 ± 0.16	0.9 ± 0.2	0.15 ± 0.03
NGC 3079	2.58 ± 0.53	16 ± 3	0.6 ± 0.1
NGC 3628	1.04 ± 0.22	3.6 ± 0.8	0.18 ± 0.04
NGC 3690	0.83 ± 0.19	39 ± 9	7.1 ± 1.4
NGC 3893	<0.23	<1	0.16 ± 0.03
NGC 4414	<0.19	<5	0.35 ± 0.07
NGC 6240	0.88 ± 0.19	225 ± 49	7.0 ± 1.4
NGC 6701	0.36 ± 0.10	27 ± 8	1.1 ± 0.2
NGC 7331	<0.16	<0.5	0.37 ± 0.07
NGC 7469	0.57 ± 0.14	65 ± 16	3.3 ± 0.6
NGC 7771	0.75 ± 0.17	66 ± 15	2.2 ± 0.4
UGC 051017	<0.11	<74	9.6 ± 1.9
VII Zw 31	<0.32	<373	9.0 ± 1.8

^a Lower limits due to spatial undersampling.

^b Mapped.

optical techniques for image separation. Receiver temperatures were typically ~100 K and system temperatures ranged from 200 to 400 K. The 2048 channel, 1 MHz resolution spectrometer was split into two 1 GHz bandwidths, one for each polarization, corresponding to a velocity coverage per polarization of 1130 km s⁻¹. All of our targets were observed in beam-switching mode with a chop rate of 2.2 Hz and a beam throw of 2'. We employed a 6 GHz intermediate frequency with the HCN(3–2) line in the lower sideband. Image rejections of the upper sideband were typically 18–20 dB.

Our observing strategy involved pointing and calibration observations approximately every 2 hr using either Jupiter or Saturn when available, otherwise DR 21 or W3OH. Calibration scans were obtained in position-switch mode with reference off positions of 5' (30' for DR 21) in right ascension. We found typical pointing errors of 2''–3'' and measured the main-beam efficiency, η_{mb} , to be 0.67 ± 0.04 for filterbank A (H-polarization) and 0.80 ± 0.04 for filterbank B (V-polarization). Antenna temperatures are converted to main-beam temperatures using $T_{\text{mb}} = T_A^*/\eta_{\text{mb}}$. We assumed a systematic calibration uncertainty of ~20%. The integrated intensity of HCN(3–2) emission was calculated using velocity intervals based on the HCN(1–0) line profiles. We computed the HCN line luminosity using equation (1) in Gao & Solomon (2004b) for objects farther than 7 Mpc away and using their equation (4) for NGC 0253, the nearby galaxy that we mapped. Our mapping strategy involved five pointings along the major axis and three along the minor axis, each separated by 15''. Our results are presented in Table 1.

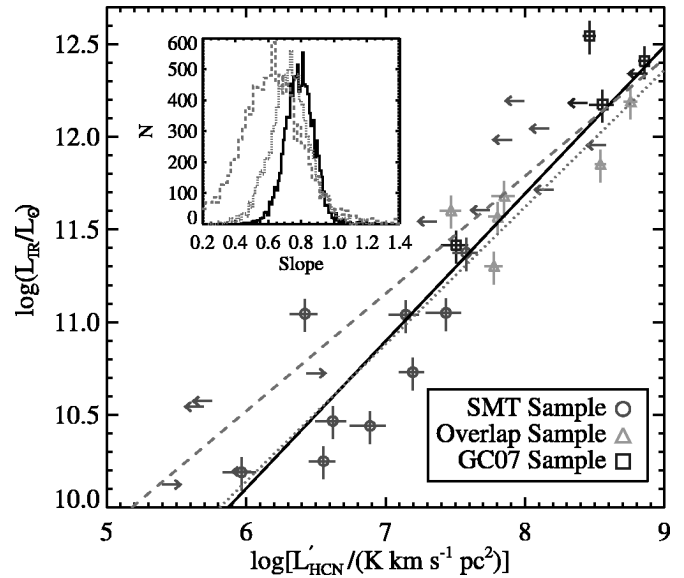


FIG. 1.— L_{IR} as a function of $L'_{\text{HCN}(3-2)}$ for the sample of extragalactic sources reported here (open circles), those observed by GC08 (blue squares), and those detected by both surveys (green triangles). Objects not detected above the 2σ level are shown as upper limits while sources within 7 Mpc that were not mapped (IC 342 and M82) are shown as lower limits. Error bars represent 1σ uncertainties. The solid line is a best-fit linear regression to the galaxies with detections from the combined sample and has a slope of 0.79. The dotted and dashed lines represent the same quantities but as applied to the SMT sample only and GC08 sample only, respectively. The inset shows the distribution of slope values returned by the fitting routine for each of these three samples. In the combined sample, a slope of unity is ruled out at the 99% confidence level. [See the electronic edition of the Journal for a color version of this figure.]

3. RESULTS

In Figure 1, we show the $L_{\text{IR}}-L'_{\text{HCN}(3-2)}$ relation using the data from Table 1 and from GC08. Although in principle both star formation and active galactic nuclei (AGN) processes heat the dust in a galaxy, the IR luminosity from our sample of nearby galaxies is largely uncontaminated by AGN, and so we use L_{IR} as a proxy for the SFR. Some exceptions are two objects presented in this Letter (NGC 1068 and NGC 7469) as well as two objects from Graciá-Carpio et al. (2008): Mrk 231 and Mrk 273. Excluding these sources from the fit does not significantly alter our results (a more detailed investigation into the role of AGN will be presented in a companion paper; S. Juneau et al., in preparation). Furthermore, these results (particularly our best-fit slope values) do not change significantly if one extrapolates from the FIR luminosity to estimate L_{IR} . We conservatively assume a 20% uncertainty in the correction factor needed to generate a L_{IR} value from the *IRAS* flux densities (Table 1 in Sanders & Mirabel 1996), which ends up dominating the total error budget. Adjusting this uncertainty from 10% to 30% does not have a significant effect on the resulting best-fit slope.

We use the publicly available Bayesian Monte Carlo Markov chain routines of Kelly (2007) to compute the linear regression between $\log(L_{\text{IR}})$ and $\log(L'_{\text{HCN}(3-2)})$. This routine assumes that the distribution of the independent variable can be well described by a mixture of Gaussian functions and accounts for heteroskedastic errors in both L_{IR} and $L'_{\text{HCN}(3-2)}$. The posterior distributions of possible slopes and y-intercepts are sampled. We define the best fit using the median slope and intercept values. The dotted gray line in Figure 1 is the best fit to those

galaxies observed by the SMT with $>2\sigma$ detections (excluding IC 342 and M82, for which we have only lower limits on $L'_{\text{HCN}(3-2)}$) and is described by the following equation:

$$\begin{aligned} \log L_{\text{IR}} = & (0.74 \pm 0.12) \times \log L_{\text{HCN}(3-2)} \\ & + (5.7 \pm 0.9). \end{aligned} \quad (1)$$

A slope of unity is inconsistent with the data at the 98% confidence level. However, we caution that the formal uncertainty is large enough to encompass a slope of unity at the 2σ level. We note that using a simple least-squares fit routine (SVDFIT in IDL) instead of the linear regression code from Kelly (2007) produces a slope of 0.73.

We can expand our sample by including data from GC08. These authors observed HCN(3–2) emission from a sample of 13 galaxies with the IRAM 30 m telescope, of which 10 were significantly detected. We observed nine of these sources and were able to detect six of them.

Combining our sample with that from GC08, we can place an even stronger constraint on the value of the slope. For the sources marked as green triangles, we use the average $L'_{\text{HCN}(3-2)}$ value of the two surveys (measurements of the overlapping objects were in agreement to within 20%) but the L_{IR} value as given in GC08, since they use a more accurate prescription for computing the total IR luminosity.

We note that a similar sample of nearby galaxies has been observed by Paglione et al. (1997). Unfortunately, a direct comparison between their sample and ours is problematic because they employed a dual-sideband receiver system and did not measure the sideband gain ratio, which can vary by a factor of 2. We examined the integrated intensities of the seven galaxies appearing in both samples and found the values to be consistent within this factor of 2. HCN(3–2) luminosities have been published for the nuclear region of a set of nearby galaxies by Krips et al. (2008). However, these observations were conducted with the IRAM 30 m telescope (with a beam size a factor of 3 smaller than the SMT) and therefore provide only lower limits to the full $L'_{\text{HCN}(3-2)}$ emission. For the purposes of this Letter, the best comparison sample is that of GC08, so we place our focus there for the remainder of the discussion.

We compute the distribution of best-fitting slopes when considering only the published detections in GC08. This is shown with the gray dashed line in the inset of Figure 1, where the median and standard deviation are 0.63 ± 0.20 . The best-fit linear regression is shown with the dashed line. The next step we take is to combine all available data and recompute the best-fit slope and y -intercept. This results in a narrower distribution of slope values with a median below unity: 0.79 ± 0.09 . The distribution is shown as the solid black line in the inset of Figure 1, and the best-fit line is shown in the full plot. Using the full, combined data set, a slope of unity is ruled out at the 99% confidence level (the median value is 2.5σ from unity). Using IDL’s SVDFIT, we find a slope of 0.79 using the full combined data set. One of the objects in our sample (NGC 2146) lies significantly off the best-fit relation, in the sense of either a lower $L'_{\text{HCN}(3-2)}$ value or a greater L_{IR} . To explore the extent to which this affects the resultant best-fit slope, we remove this object from the sample and recompute the slope, finding a larger slope with a smaller dispersion: 0.84 ± 0.07 . This remains significantly below unity and within 1 standard deviation of the result using the full sample. Finally, GC08 find evidence for a change in the $L_{\text{IR}}-L'_{\text{HCN}(1-0)}$ relation

at $L_{\text{IR}} \sim 10^{11} L_{\odot}$. Restricting our sample to galaxies above this IR luminosity, we find a slightly shallower best-fit slope of 0.64 ± 0.13 .

4. DISCUSSION

The subunity slope observed in the $L_{\text{IR}}-L'_{\text{HCN}(3-2)}$ relation presents a challenge to our understanding of the molecular SFR law. If the constant SFR per unit dense gas mass applies to observations of HCN(3–2) emission, then a linear relationship between L_{IR} and $L'_{\text{HCN}(3-2)}$ should be observed. One underlying assumption is that the HCN(3–2) molecular line luminosity is linearly tracing the dense gas mass. This may not be valid when observing unresolved galaxies that include large quantities of subthermally excited gas. Recent theoretical models from N08 and KT07 suggest that the index between the SFR and higher critical density tracers such as HCN(3–2) should in fact be below unity. N08 used hydrodynamical simulations of isolated galaxies and equal-mass galaxy mergers coupled with a 3D non-LTE radiative transfer code to probe the relationship of the dense molecular gas phase in galaxies with HCN and CO emission across a variety of rotational transitions. Meanwhile, KT07 use escape probability radiative transfer simulations coupled with models of turbulence-regulated giant molecular clouds. While their work did not specifically explore the potential relations between SFR and higher critical density lines such as HCN(3–2), fundamentally their conclusion behind the physical driver of the $L_{\text{IR}}-L'_{\text{HCN}(1-0)}$ relation is similar to that of N08, and thus similar results for higher lying transitions are expected.

According to N08 and KT07, the SFR-HCN ($u-l$) index is parameterized in terms of how the molecular line luminosity, L_{mol} , is related to the mean molecular gas density, $\langle n \rangle$, of a given galaxy. If L_{mol} grows as $\langle n \rangle$, the SFR- L_{mol} relation will have an index of ~ 1.5 (e.g., the observed $L_{\text{IR}}-L'_{\text{CO}(1-0)}$ index). On the other hand, a $L_{\text{mol}}-\langle n \rangle$ power-law index equal to the KS index produces a linear SFR- L_{mol} relationship. In this picture, the fundamental relationship is the volumetric version of the KS relation, and the observed linear SFR-HCN(1–0) relationship in galaxies results from the HCN(1–0) luminosity on average being related to the mean molecular gas density by an index similar to the KS index (i.e., $L \sim \langle n \rangle^{1.5}$). Since $L'_{\text{HCN}(1-0)}$ rises linearly with L_{IR} , HCN(1–0) emission is a useful proxy for the total SFR, once the effects of AGN have been properly taken into account.

Alternatively, if the $L_{\text{mol}}-\langle n \rangle$ power-law index is greater than the KS index, the SFR- L_{mol} index will be below unity. Physically, this can be understood as resulting from high critical density lines originating in extreme tails of the density distribution and causing a steepening of the $L_{\text{mol}}-\langle n \rangle$ power-law index compared to lower critical density lines. N08 predict that the SFR will be related to the HCN(3–2) luminosity from galaxies by an index of ~ 0.7 . Figure 2 is a reproduction of Figure 8 in N08, but with new constraints our data—as well as the data from GC08—place on the SFR-HCN power-law index. The scatter in the predicted slope is represented by the horizontal gray lines and is computed by randomly drawing a sample of 19 galaxies (which is the size of our combined data set) out of a set of 100 model galaxies 1000 times. The yellow shaded region shows the range of expected results from KT07 utilizing their publicly available code with parameters appropriate for “normal,” “intermediate,” and “starburst” galaxies. In the KT model, the SFR-HCN(3–2) relation is predicted to have a slope

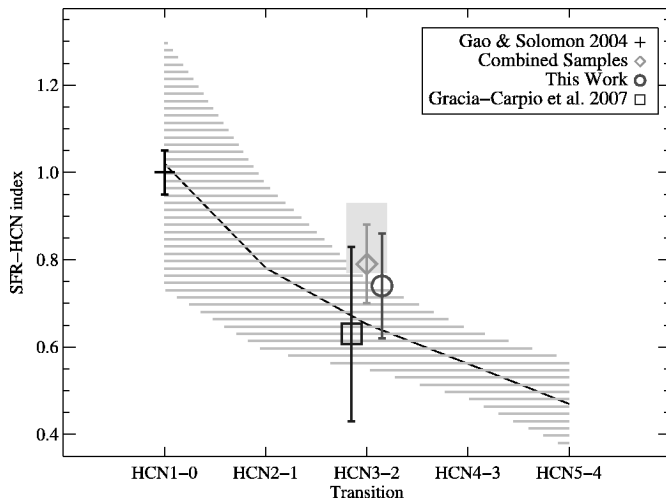


FIG. 2.—Predicted slopes in $\log(L_{\text{IR}})$ - $\log(L'_{\text{HCN}(3-2)})$ space as a function of J transition of HCN, as predicted from theoretical models by N08 (gray horizontal lines) and KT07 (yellow shaded area at the HCN(3–2) transition). Observational constraints on the slope measured from HCN(1–0) and HCN(3–2) emission are shown with their error bars. The best-fit slopes are consistent with the model predictions from both N08 and KT07. [See the electronic edition of the *Journal* for a color version of this figure.]

below unity in the range 0.77–0.93. The plotting symbols show the best-fit and 1σ range in slopes for the data sets presented here as well as that of GC08 and Gao & Solomon (2004b). All HCN(3–2) measurements are consistent with the models shown here.

It is important to note that we do not account for potential chemistry-related issues. While some evidence may exist for HCN-related chemistry in the vicinity of the hard X-ray flux associated with an AGN, both theoretical and observational investigations have found mixed results (Lintott & Viti 2006; Graciá-Carpio et al. 2006; Meijerink et al. 2007; Combes 2007; Papadopoulos 2007). Studies of the nuclear region of galaxies such as that done by Krips et al. (2007) of the Seyfert 2 galaxy

NGC 6951 will be essential to understanding all of the potentially relevant chemical processes. Finally, our sample includes only nearby galaxies; the most distant objects in our sample lie roughly 100 Mpc away (Arp 193 and NGC 6240). Among others, Gao et al. (2007) and Riechers et al. (2007) have found evidence that the $L_{\text{IR}}-L'_{\text{HCN}(3-2)}$ relation steepens at high redshift and/or high L_{IR} .

5. CONCLUSIONS

We present observations of HCN(3–2) emission from a sample of 30 nearby galaxies ranging in IR luminosity from 10^{10} to $10^{12.5} L_{\odot}$ and HCN(3–2) luminosity from 10^6 to 10^9 K km s $^{-1}$ pc 2 . We find a best-fit slope in $\log(L_{\text{IR}})$ - $\log(L'_{\text{HCN}(3-2)})$ space of 0.74 and exclude a slope of unity at the 98% confidence level (although the formal uncertainty is large enough to include a slope of unity at the 2σ level). Adding data recently published in the literature yields a slope of 0.79 and tightens the distribution of possible slopes such that a slope of unity is excluded at the 99% confidence level for this sample of galaxies. This subunity slope may be an indication that the HCN(3–2) molecular line luminosity is not linearly tracing the dense gas. Our results are consistent with predictions from recent theoretical models by N08 and KT07, who predict slopes less than unity when the line luminosity–average gas density relation has a power-law index greater than the KS index. We wish to emphasize that the results shown here are pertinent to HCN(3–2) molecular line emission and do not contradict results from previous efforts showing a tight, linear correlation between L_{IR} and $L'_{\text{HCN}(1-0)}$. Indeed, the models discussed in this Letter successfully account for this behavior as well.

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