THE RADIO CONTINUUM, FAR-INFRARED EMISSION, AND DENSE MOLECULAR GAS IN GALAXIES

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ABSTRACT

A tight linear correlation is established between the HCN line luminosity and the radio continuum (RC) luminosity for a sample of 65 galaxies (from Gao & Solomon’s HCN survey), including normal spiral galaxies and luminous and ultraluminous infrared galaxies (LIRGs/ULIRGs). After analyzing the various correlations among the global far-infrared (FIR), RC, CO, and HCN luminosities and their various ratios, we conclude that the FIR–RC and FIR–HCN correlations appear to be linear and are the tightest among all correlations. The combination of these two correlations could result in the tight RC–HCN correlation we observed. Meanwhile, the nonlinear RC–CO correlation shows slightly larger scatter as compared with the RC–HCN correlation, and there is no correlation between ratios of either RC/HCN–CO/HCN or RC/FIR–CO/FIR. In comparison, a meaningful correlation is still observed between ratios of RC/CO–HCN/CO. Nevertheless, the correlation between RC/FIR and HCN/FIR also disappears, reflecting again the two tightest FIR–RC and FIR–HCN correlations as well as suggesting that FIR seems to be the bridge that connects HCN with RC. Interestingly, despite obvious HCN–RC and RC–CO correlations, multi-parameter fits hint that while both RC and HCN contribute significantly (with no contribution from CO) to FIR, yet RC is primarily determined from FIR with a very small contribution from CO and essentially no contribution from HCN. These analyses independently confirm previous conclusions that it is practical to use RC luminosity instead of FIR luminosity, at least globally, as an indicator of star formation rate in galaxies including LIRGs/ULIRGs, and HCN is a much better tracer of star-forming molecular gas and correlates with FIR much better than CO.

Key words: galaxies: ISM – galaxies: starburst – infrared: galaxies – ISM: molecules – radio continuum: galaxies – radio lines: galaxies

1. INTRODUCTION

Ever since far-infrared (FIR) emission was thought to mainly originate as a result of star formation in giant molecular clouds (GMCs; e.g., Mooney & Solomon 1988), it had been used as a standard indicator of star formation rate (SFR). But until now, the spatial resolution of FIR observation has limited further detailed research, particularly in external galaxies. As another result of the formation of young massive stars, though at the end of their rapid formation and evolution, the radio continuum (RC) emission at centimeter (cm) wavelength has a completely different emission mechanism compared with that of the FIR emission. RC offers a hope, with its spatially resolved capability, to study SFR in galaxies both near (e.g., Condon et al. 1996) and far (e.g., Schinnerer et al. 2007).

The FIR emission arises from the dust heated by newborn massive stars. The young OB stars are imbedded in very tiny, yet massive and dense regions, and all of their UV/optical radiation is absorbed by dust which re-radiates mostly in mid/FIR. Though for normal disk galaxies, the situation is more complex in that the dust heating may also be contributed by older stellar population, and the optical depth of dust may not be thick enough for the FIR luminosity to truthfully measure the bolometric luminosity of entire galaxies except for the nuclear starburst regions. However, the FIR emission should provide an excellent measure of the SFR in luminous and ultraluminous infrared galaxies (LIRGs/ULIRGs), where dusty circumnuclear starbursts dominate (Kennicutt 1998a).

The RC is mainly non-thermal synchrotron emission that arises from the interaction of relativistic electrons with the ambient magnetic field in which they diffuse. The supernova remnants (SNRs) of Type II and Type Ib supernovae that are produced by massive stars ($M \gtrsim 8 M_\odot$), which have lifetimes $\lesssim 3 \times 10^7$ yr, are thought to have accelerated most of the relativistic electrons. If we take the typical spiral disk field strength $B \sim 5 \mu G$ and comparable magnetic energy density with inverse Compton radiation energy density, the synchrotron lifetime of the relativistic electrons is $\lesssim 10^8$ yr while emitting at 1.5 GHz. Therefore, RC can probe very recent star formation activity in normal star-forming galaxies whose radio emission is not dominated by the active galactic nucleus (AGN; Condon 1992).

On global scales, the FIR and RC emissions are linearly correlated over 5 orders of magnitude in luminosities for various galaxies from dwarf galaxies, normal spiral galaxies, and irregular galaxies, to starbursts, Seyferts, radio-quiet quasars (Condon et al. 1991), and local LIRGs/ULIRGs (Yun et al. 2001), out to the most extreme star-forming galaxies in the early universe, at $z = 1$ and beyond (Appleton et al. 2004). The FIR–RC correlation for the IRAS 2 Jy galaxy sample (Yun et al. 2001, including 1809 galaxies) is well described by a linear relation, and over 98% of the sample galaxies follow this tight correlated relation. This correlation offers a potential method of deriving the SFR using the measured RC luminosity (Yun et al. 2001) even if the FIR luminosity is unknown, and the RC images could potentially be used to judge how the FIR distribution would look on detailed small scales in galaxies (Condon et al. 1996). With the high resolution capability of Spitzer (and now Herschel), detailed local FIR–RC correlation is also shown to be valid (e.g., Murphy et al. 2006, 2008).

Many researchers have conducted plenty of observations of CO emission in galaxies, and the global correlations between FIR and CO (e.g., Devereux & Young 1990; Young & Scoville 1991) and between RC and CO (Rickard et al. 1977; Israel &
Rowan-Robinson 1984; Adler et al. 1991; Murgia et al. 2002) are also well established for different samples. Adler et al. (1991) and Murgia et al. (2002, 2005) found that the RC–CO correlation is linear from global scale down to ∼100 pc size scale, at which scale there is still no evidence that this correlation is going to break down, with a dispersion that is less than a factor of 2. Therefore, the mean star formation efficiency (SFE), which measures the SFR (deduced from RC) per unit mass of molecular gas available to form stars, is found to vary weakly with Hubble morphological type (among galaxies) and distances from galaxy centers (within individual galaxy disks; Murgia et al. 2002). For the HCN survey sample (Gao & Solomon 2004a, 2004b, hereafter GSo4a and GSo4b) of 65 spiral galaxies, starbursts, LIRGs, and ULIRGs, we show here that this FIR and RC correlation also holds and appears to be the best correlation among all correlations. Before the HCN survey of Gao & Solomon (GSo4b), the HCN emission in external galaxies has only been observed in less than 30 galaxies, and only a few of them are measured globally to derive the total HCN emission (e.g., Sorai et al. 2002; Shibatsuka et al. 2003). Based on this systematic HCN survey, a tight linear FIR–HCN correlation has been established (GSo4a). Most recent follow-up observations of dense molecular gas tracers, such as HCN, HCO+, HNC, etc., in galaxies (Baan et al. 2008; Gracia-Carpio et al. 2008), mostly confirm this correlation. Some theoretical models also predict such linear correlations (e.g., Krumholz & Thompson 2007). According to this linear FIR–HCN correlation, a Schmidt (1959) star formation law in terms of dense molecular gas is established with a power-law index of 1.0. Furthermore, compared with the FIR–CO correlation, the FIR–HCN is linear and tighter as the authors argued that the combination of the stronger correlations between FIR–HCN and between HCN–CO may account for this FIR–CO correlation. Based on these comparisons, they also argued that the amount of the dense molecular gas traced by HCN, but not the total amount of molecular gas traced by CO, could be a critical molecular parameter that measures SFR in star-forming galaxies (GSo4a). These new results from the HCN survey obviously invoke a question on the comparison between the correlations of RC–HCN versus RC–CO: is the RC–HCN correlation significantly better than the RC–CO correlation? How do the FIR and RC as SFR indicators relate to the star formation materials, the molecular gas (CO), and particularly the dense molecular gas (HCN)? Stars are born mainly in GMCs. The total mass of molecular gas of GMCs can be determined from the CO luminosity. However, the excesses of the CO luminosity in GMC cores where active high-mass star formation occurs are not specific enough to reveal the star formation potential of the dense cores. The physical conditions of star-forming GMC cores (Evans 1999) are better revealed by emission from high dipole-moment molecules, like HCN, whose emission traces the dense molecular gas \( n(H_2) \geq 3 \times 10^4 \text{ cm}^{-3} \) associated with the cores of the star-forming GMCs (GSo4b). FIR–HCN is shown to be linearly correlated (GSo4a). Does HCN also strongly correlate with RC? What is the role of dense molecular gas in the FIR–RC relationship?

Here, we utilize this HCN sample to analyze the various relationships among the global HCN, FIR, CO, and RC luminosities to answer some questions raised here and to further demonstrate the possibility of using the RC luminosity instead of FIR luminosity as an indicator of the SFR. The HCN sample and the total RC luminosity of the sample are presented in Section 2. Section 3 presents the results and analysis of the various correlations of these global luminosities and their ratios and shows that the global correlation between RC and HCN appears to be a combination of the two tightest correlations between FIR–RC and between FIR–HCN even though the RC–HCN correlation is significantly better than the RC–CO correlation. Discussion on the possible physical relationship between the HCN (dense molecular gas tracer) and the RC emission (the indicator of the rate of high-mass star formation) in galaxies is presented in Section 4, followed by the main points of this study in Section 5.

2. THE RADIO CONTINUUM SAMPLE

Our RC sample is drawn entirely from the HCN sample of Gao & Solomon (GSo4a and GSo4b). The sample includes almost all galaxies with strong CO and FIR emission in the northern sky (53 in total, GSo4b) and 12 additional galaxies (mostly LIRGs/ULIRGs) from the literature, mainly from Solomon et al. (1992). Details about the sample properties and the measurements of the total HCN emission in galaxies can be found in GSo4b.

The RC flux is mainly obtained from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), which covers the sky north of J2000.0 decl. = −40° at 1.4 GHz (Condon et al. 1998), whereas for some large sources with diameter \( D_{25} \) larger than \( \sim 8' \), we adopted the fluxes given in previous RC surveys (e.g., Segalovitz 1977; Condon 1987; Condon & Broderick 1988; Condon et al. 1990, 1996) to avoid the missing flux problem that NVSS suffers for sources with diameters larger than \( \sim 8' \).

The flux of NGC 4945, which is a southern galaxy not covered by NVSS, is taken from the Parkes catalogue as listed in the NED.3

The derived global luminosity of RC at 1.4 GHz and HCN, FIR, and CO (from GSo4a and GSo4b) luminosities of galaxies in this sample are listed in Table 1 (here we make no distinction between the total IR and FIR emission, though the total IR luminosity defined in Sanders & Mirabel 1996 is used). A few sensitive HCN limits are kept in Table 1 and included for various analyses.

The largest uncertainties are of the HCN observations, as described in detail in GSo4b, at a level of up to \( \sim 30\% \), whereas for several large nearby sources without sufficient mapping the uncertainties can be as large as \( \sim 50\% \) (\( \sim 20\% \) calibration error included). The uncertainties of CO luminosities are mainly dominated by the calibration errors and of level \( \sim 20\% \). FIR luminosities from IRAS and RC luminosities from NVSS are much more accurate; the uncertainties are of a few percent only.

For several large sources in the HCN survey sample, e.g., NGC 253, only the nuclear regions and the innermost disks are mapped in HCN, since they are limited by the sensitivity of the instruments, while a rough estimate of the NVSS image shows that \( \geq 70\% \) RC emission is from the same region. Obviously, tighter constraints in various correlations can be obtained once more sensitive and accurate HCN observations are conducted with more powerful telescopes, such as GBT4 and LMT,5 both of which are soon to be available.

3 NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.
4 The Robert C. Byrd Green Bank Telescope (GBT). http://www.gb.nrao.edu/gbt/
5 The Large Millimeter Telescope (LMT). http://www.lmtgtm.org/
**3. RESULTS AND ANALYSES**

### 3.1. RC–HCN Correlation

Similar to the FIR–HCN correlation (GS04a), the principal result from this research is the tight linear correlation between RC luminosity $L_{RC}$ and HCN line luminosity $L_{HCN}$(Figure 1(a)). The correlation extends over 3 orders of magnitude in luminosities and includes normal spiral galaxies, starbursts, and LIRGs/ULIRGs. Note that there appears to be no systematic difference between host galaxies with known AGN and the rest of the galaxies in the RC–HCN correlations. A linear regression yields a power-law slope of 0.99 ($\pm 0.05$). The corresponding correlation coefficient is $R = 0.92$ ($R^2 = 0.84$) for $L_{RC}$–$L_{HCN}$. The best-fit (logarithmic) relation between HCN and RC luminosities is

$$\log L_{RC} = 0.99(\pm 0.05) \log L_{HCN} - 2.0. \quad (1)$$

Compared with the FIR–HCN result (GS04a), $L_{RC}$–$L_{HCN}$ is an almost equally tight linear correlation as that of the $L_{IR}$–$L_{HCN}$.

When we use all galaxies excluding 6 HCN limits, the correlation remains almost the same with $\log L_{RC} = 0.98(\pm 0.07) \log L_{HCN} - 1.9$, and essentially the same correlation coefficient $R = 0.90$ ($R^2 = 0.81$).

The RC–CO correlation is also very strong ($R = 0.89$, $R^2 = 0.79$, shown in Figure 1(b)) and appears to be nearly as tight as the RC–HCN correlation. But similar to the FIR–CO correlation, the RC–CO correlation is nonlinear. It is also noticeable that the range of CO luminosity is smaller, covering only a bit over 2 orders of magnitude, whereas both HCN and RC luminosities spread over 3 orders of magnitude. The comparison of the luminosity ratios of $L_{RC}/L_{CO}$ and $L_{RC}/L_{HCN}$ with $L_{RC}$ shows a dramatic difference: the $L_{RC}/L_{CO}$ ratio increases substantially with increasing $L_{RC}$, whereas $L_{RC}/L_{HCN}$ appears to be nearly independent of $L_{RC}$ (Figures 2(a) and (b)). These are nearly the same plots with $L_{IR}$ instead of $L_{HCN}$ shown in GS04a, demonstrating the tight linearity of the correlation between $L_{RC}$ and $L_{HCN}$ in contrast to the nonlinearity of the correlation between $L_{RC}$ and $L_{CO}$ as we further illustrate below.
Figure 1. (a) Correlation between HCN and RC luminosities in 65 galaxies (the correlation coefficient is \( R = 0.92, R^2 = 0.84 \)). Galaxies with known embedded AGN are indicated with stars. Some limits in HCN luminosities are indicated with arrows. The representative error bar including 20% calibration uncertainty is shown for the source IRAS 17208–0014 which has the highest HCN luminosity in the sample (\( \sigma_L_{\text{HCN}} \sim 30\% \), \( \sigma_L_{\text{RC}} \sim 3.1\% \)). The fit line: \( \log L_{\text{RC}} = 0.99 (\pm 0.05) \log L_{\text{HCN}} - 2.0 \). (b) Correlation between CO and RC luminosities in 65 galaxies. The correlation coefficient is \( R = 0.89 (R^2 = 0.79) \). The representative error bar including 20% calibration uncertainty is also shown for the source IRAS 17208–0014 (\( \sigma_L_{\text{CO}} \sim 20\% \)). The fit line: \( \log L_{\text{RC}} = 1.31 (\pm 0.09) \log L_{\text{CO}} - 6.20 \).

3.2. Comparison of Correlations Between the Ratios

Figure 3(a) shows a correlation between luminosity ratios \( L_{\text{RC}}/L_{\text{CO}} \) and \( L_{\text{HCN}}/L_{\text{CO}} \) with a correlation coefficient \( R = 0.63 (R^2 = 0.40) \). This suggests that the new star formation efficiency (SFE = \( L_{\text{RC}}/L_{\text{CO}} \), i.e., SFR—derived by using the RC luminosity—per unit of molecular gas mass inferred by CO) depends on the fraction of molecular gas in a dense phase (indicated by \( L_{\text{HCN}}/L_{\text{CO}} \)). This correlation better demonstrates the connection between the RC and HCN luminosities (as shown in Figure 1). Both \( L_{\text{RC}} \) and \( L_{\text{HCN}} \) have been normalized by \( L_{\text{CO}} \) to better show the possible physical relationship between \( L_{\text{RC}} \) and \( L_{\text{HCN}} \) after removing the dependence upon the distance, galaxy size, and other possible selection effects.

Similarly, we can show the correlation between \( L_{\text{RC}} \) and \( L_{\text{HCN}} \) divided by \( L_{\text{CO}} \) for normalization (Figure 3(b)). Same as the correlation between \( L_{\text{IR}} \) and \( L_{\text{CO}} \) normalized by \( L_{\text{HCN}} \), the apparently strong correlation between \( L_{\text{RC}} \) and \( L_{\text{CO}} \) (Figure 1(b)) also disappeared once normalized by \( L_{\text{HCN}} \) (\( R = 0.20, R^2 = 0.04 \)). This reflects the tight linearity of the correlation between RC and HCN (Figure 1(a)), making the ratio RC/HCN nearly constant.

These are essentially the same arguments and procedures as in GS04a in comparing the FIR–HCN versus FIR–CO that shows a fundamental difference between HCN and CO (star-forming dense molecular gas and total molecular gas) in their relationship to FIR (SFR). Therefore, the difference between HCN and CO in their relationship to SFR is again clearly shown here using RC instead of FIR as a proxy of SFR. Meanwhile, the correlation between \( L_{\text{RC}} \) and \( L_{\text{IR}} \) after normalization by \( L_{\text{HCN}} \) (Figure 4(a)) remains rather tight (\( R = 0.74, R^2 = 0.55 \)) though there are very tight RC–HCN and FIR–HCN correlations, which suggests that the FIR–RC correlation is indeed the tightest among all correlations.

Nevertheless, the tight correlation between \( L_{\text{RC}} \) and \( L_{\text{HCN}} \) after normalization by \( L_{\text{IR}} \) (Figure 4(b)) has almost completely disappeared, too (e.g., Figure 3), whereas the correlation between \( L_{\text{IR}} \) and \( L_{\text{HCN}} \) divided by \( L_{\text{IR}} \) for normalization (Figure 4(c)) still remains as a meaningful correlation (\( R = 0.57, R^2 = 0.33 \)), and even a stronger correlation if they are normalized by CO instead of RC as shown in GS04a). This certainly shows some subtle differences in the tight correlations among FIR, RC, and HCN luminosities and surely implies that the FIR–HCN correlation is much better than the RC–HCN correlation. As further demonstrated with multi-parameter fits and discussed in Section 4, FIR and HCN might have a better direct physical relationship with SFR than other quantities involved in this paper. The RC–HCN correlation is likely a result of the combination of the two tightest FIR–RC and FIR–HCN correlations. This point can be further revealed and corroborated by comparing these correlations with the FIR/RC–CO/RC (FIR–CO normalized by RC) and FIR/CO–RC/CO (FIR–RC normalized by CO) correlations shown in Figure 5.

Using the RC luminosity as the normalization, the correlations between the FIR luminosity and HCN (Figure 4(c)) and CO (Figure 5(a)) luminosities still show weak, but mean-
Figure 3. (a) Correlation between RC/CO and HCN/CO shows that there is indeed a tight correlation between RC and HCN since both luminosities are normalized by $L_{\text{CO}}$. The correlation coefficient is $R = 0.63$ ($R^2 = 0.40$). (b) Normalized by $L_{\text{HCN}}$, the correlation between RC and CO (Figure 1(b)) has completely disappeared ($R = 0.20$, $R^2 = 0.04$). The uncertainties of the various ratios are $\sigma_{L_{\text{RC}}/L_{\text{CO}}} \sim 21\%$, $\sigma_{L_{\text{RC}}/L_{\text{HCN}}} \sim 30\%$, and $\sigma_{L_{\text{HCN}}/L_{\text{CO}}} \sim 37\%$.

Figure 4. (a) Correlation between RC and FIR is very prominent even after normalization by $L_{\text{HCN}}$ ($R = 0.74$, $R^2 = 0.55$), which implies that the correlation between RC and FIR luminosities is really tight. (b) Normalized by $L_{\text{IR}}$, the correlation between RC and HCN completely disappeared ($R = 0.14$, $R^2 = 0.02$). (c) Correlation between FIR and HCN is still prominent even after normalization by $L_{\text{RC}}$ ($R = 0.57$, $R^2 = 0.33$), which suggests that their correlation is really tight. The uncertainties for the various ratios are $\sigma_{L_{\text{IR}}/L_{\text{HCN}}} \sim 30\%$ and $\sigma_{L_{\text{RC}}/L_{\text{IR}}} \sim 4\%$ (duplicated uncertainties can be found in the captions of previous figures).

3.3. Multi-parameter Fits

Following the practices of the model parameter fits in GS04a, which have demonstrated that HCN is a much better active star formation tracer than CO, we here similarly discuss the three- and four-parameter fits, respectively, involving the RC, FIR, CO, and HCN luminosities.
This model fit basically shows that RC contributes little to HCN after fitting FIR for HCN, despite the strong correlation between RC and HCN.

The FIR luminosity from a model fit to the HCN and RC (the IR(L_{HCN}, L_{RC}) model), however, yields

\[
\log L_{IR}(L_{HCN}, L_{RC}) = (0.38 \pm 0.08) \log L_{HCN} + (0.61 \pm 0.07) \times \log L_{RC} + 4.30.
\]

Here, \(L_{HCN}\) and \(L_{RC}\) seem to be roughly comparably important in predicting FIR, though RC appears to have more weight than HCN. We caution here that the usually more than 10 times larger errors in HCN than those in RC could easily be a cause of this slight disfavor for HCN. This relation produces a much tighter fit than any of the simple two-parameter fits, including the tightest FIR–HCN and FIR–RC correlations.

3.3.2. The Four-parameter Fits

CO usually contributes the least whenever HCN is involved in the three-parameter (FIR, HCN, CO) fits (GS04a). Will this still be true if an additional parameter, RC, is added? We here discuss the four-parameter fits.

The RC luminosity from a model fit to the HCN, FIR, and CO (the RC(L_{HCN}, L_{IR}, L_{CO}) model) yields

\[
\log L_{RC}(L_{HCN}, L_{IR}, L_{CO}) = (-0.02 \pm 0.13) \log L_{HCN} + (0.87 \pm 0.10) \log L_{IR} + (0.22 \pm 0.13) \log L_{CO} - 5.55.
\]

The extremely weak dependence (almost independent) on \(L_{HCN}\) shows that the RC luminosity is determined principally from the FIR luminosity with only marginal contribution from the CO and essentially nothing from the HCN. An RC, CO, and FIR luminosity model for \(L_{HCN}\) (the HCN(L_{IR}, L_{RC}, L_{CO}) model) gives

\[
\log L_{HCN}(L_{IR}, L_{RC}, L_{CO}) = (-0.02 \pm 0.13) \log L_{RC} + (0.58 \pm 0.14) \log L_{IR} + (0.55 \pm 0.11) \log L_{CO} - 3.37.
\]

The \(L_{HCN}\) luminosity is independent (~0.02) of RC luminosity, and is almost equally determined by FIR and CO luminosity.

The FIR luminosity from a model fit to the HCN, RC, and CO (the IR(L_{HCN}, L_{RC}, L_{CO}) model), however, yields

\[
\log L_{IR}(L_{HCN}, L_{RC}, L_{CO}) = (0.40 \pm 0.09) \log L_{HCN} + (0.62 \pm 0.07) \log L_{RC} - (0.04 \pm 0.11) \log L_{CO} + 4.49.
\]

Here, \(L_{HCN}\) and \(L_{RC}\) seem to be roughly comparably important though RC appears to have more weight than HCN. This is much more extreme than the three-parameter fit (HCN+CO for FIR) given in Equation (3) of GS04a, and CO indeed contributes nothing to FIR when both HCN and RC are used in the fit. In other words, adding CO does not have any effect on predicting FIR once both HCN and RC are involved.
Finally, we show the CO luminosity from a model fit of the HCN, RC, and FIR (the CO(L_{HCN}, L_{RC}, L_{IR}) model), which yields

\[
\log L_{CO}(L_{HCN}, L_{RC}, L_{IR}) = (0.51 \pm 0.10) \log L_{HCN} + (0.21 \pm 0.12) \log L_{RC} - (0.06 \pm 0.14) \log L_{IR} + 4.54.
\]

(8)

The \(L_{CO}\) luminosity is independent \((-0.06)\) of FIR luminosity and is mainly determined by \(L_{HCN}(0.51)\) and marginally by \(L_{RC}(0.21)\). This is essentially very similar to Equation (5) in GS04a, i.e., CO is mainly determined by HCN with little contribution from FIR. Adding an additional parameter RC only affects the overall fit slightly and makes FIR useless in predicting CO from HCN. Although it is marginal, this might suggest that RC is slightly more important than FIR in predicting CO.

In summary, FIR–HCN and FIR–RC correlations are the strongest of all. Despite a tight RC–CO correlation, the RC–HCN correlation is much tighter in comparison. Nonetheless, it appears that the RC–HCN correlation might be a direct consequence of the combinational result from the two tightest RC–FIR and FIR–HCN correlations. The multi-parameter fit models further support these results and reveal the difference between HCN and CO in predicting FIR and RC. Being the tightest correlations for both FIR–RC and FIR–HCN, these results corroborate that it is practical to use RC instead of FIR to indicate the global SFR, and HCN is much more important than CO in relating to FIR.

4. DISCUSSION

4.1. The Most Fundamental Correlation: FIR–RC versus FIR–HCN

In the RC–HCN correlation shown in Figure 1(a), no significant differences can be seen between the AGN host galaxies and others (the galaxies with AGN embedded are represented by stars, a slight excess in RC appears to be present at high luminosity end). This indicates that these AGNs (except those in ULIRGs) do not show stronger excess in RC than the rest of the star-forming galaxies. Namely, AGN contribution to RC is, on average, presumably roughly less than half of the total RC emission, and not much systematic difference can be seen globally in this HCN sample of star-forming galaxies and LIRGs/ULIRGs (GS04a). Similarly, there is also no prominent difference between the AGN host galaxies and the rest of the star-forming galaxies in the FIR–HCN correlation (GS04a).

The correlation between global FIR and RC luminosities is found to be tight and linearly valid over 5 orders of magnitude in thousands of galaxies (e.g., Yun et al. 2001). This is also reinforced here by the HCN survey sample even though the ranges in luminosities are over only 3 orders of magnitude due to very limited sample size. Moreover, radio AGNs usually show distinct excess in RC over FIR as compared to the general populations of normal galaxies in the FIR–RC correlation. But, AGNs in the HCN sample do not particularly show any significant radio emission excess. As detailed above, it turns out that the FIR–RC is the tightest correlation among all. But the FIR–HCN correlation is essentially as tight as the FIR–RC correlation, and these two correlations are the tightest. It might even be possible that the FIR–HCN correlation could be tighter than the FIR–RC correlation, especially in view of the significantly larger uncertainties in the estimate of HCN than other parameters. This is also intuitively implied since both FIR and HCN are directly and physically related to active massive star formation.

Several models were previously posed to interpret this correlation (e.g., Voelk 1989; Helou & Bicay 1993; Niklas & Beck 1997; Murgia et al. 2005). Most recently, Lacki et al. (2010) suggested that the FIR–RC correlation is a combinational result of the efficient cooling of cosmic-ray (CR) electrons in starbursts and a conspiracy of several factors: the decrease in the radio emission due to bremsstrahlung, ionization, and inverse Compton cooling in starbursts is countered by secondary electrons/positrons and the decreasing critical synchrotron frequency, which both increase the radio emission; low effective UV dust opacity leads to the decreasing FIR emission, which balances the decrease in radio emission caused by CR escape for lower surface density galaxies. In fact, this kind of calorimetry theory that galaxies act in a reasonable approximation as calorimeters for the stellar UV radiation and for the energy flux of the CR electrons was proposed 20 years ago (Voelk 1989).

Although the molecular gas connection to the FIR–RC correlation in galaxies is proposed by Murgia et al. (2005), we demonstrated here that the addition of the total dense molecular gas traced by HCN appears to be globally insignificant in providing the dense star-forming gas connection between the FIR (SFR) and RC (the RC(L_{HCN}, L_{IR}, L_{CO}) model, Equations (2), (5), and B(3)). Yet, the contribution of CO is non-negligible and appears to be more important than HCN. Nevertheless, the star formation materials, particularly the dense gas HCN, definitely play an important role in the obvious connection of SFR to both the FIR and RC emission. Both HCN and RC contribute nearly equally to FIR, and there is no additional contribution to FIR by adding CO (the IR(L_{HCN}, L_{IR}, L_{CO}) model, Equations (4), (7), and B(3)). Thus, CO seems to be the least important of the four parameters RC, FIR, CO, and HCN in relating to SFR even though they all show quite good correlations with each other.

4.1.1. The Origin of the Tightest Correlation: FIR–RC and FIR–HCN

In conventional models, the RC emission produced from synchrotron radiation is related with massive star formation via several steps: star formation → supernovae and SNRs → relativistic electrons accelerated by SNRs. So, too, is the FIR emission related: star formation → UV radiation → absorption and re-emission by dust enshrouding newborn stars. These should all be expected to be the dominant FIR and RC emission in active star-forming galaxies. Nevertheless, CR electrons involve other radiation processes, generating mostly the background RC emission that is not related to massive star formation (the general interstellar radiation field). Additionally, the old stars also heat up the dust and additionally contribute to the general interstellar radiation field. The contribution of the general interstellar radiation field to the total FIR emission in galaxies might be significant at the low-L_{IR} end, where the general infrared interstellar radiation field is comparable to or even more dominant than the FIR radiation from the active star formation.

The temporal and spatial inconsistencies between these processes could be obstacles to understanding fully the physical origin of the FIR and RC correlation. Given the obvious star formation connection of both FIR and RC and the important role of the star formation materials, i.e., the molecular gas, especially the dense molecular gas, in actually giving birth to massive stars, it can surely help us figure out which of these correlations are more fundamental, and which are possibly
indirectly less fundamental correlations. Globally, we have seen the bigger role of HCN than CO in the FIR–RC correlation. Locally, the spatially resolved studies perhaps help us much better to make the whole picture clearer, by taking the molecular gas and dense molecular gas into account in the analysis of various comparisons of the correlations.

Temporally, massive stars live $\sim 10^7$ yr and the relativistic electrons probably have lifetimes of $\sim 10^8$ yr in star-forming galaxies; the RC luminosity therefore probes star formation activity not much earlier than $10^9$ yr ago. Taking the molecular gas in the dense phase as the initial stage in initiating the massive star formation procedure, and the total molecular gas as the potential star formation gas reservoir as a necessity in eventually forming the dense cores of GMCs, we can sort the three probes of SFR into a time line: CO (GMCs, assembly of star formation material—–a necessity for later core collapse and star formation in GMCs) $\to$ HCN (probes dense GMC cores, massive star formation sites) $\to$ FIR (probes newborn young massive stars) $\to$ RC (probes the end products of the short-lived massive stars). If the dense cores of GMCs are forming massive stars on a timescale smaller than the depletion time of dense gas in galaxies ($\lesssim 10^7$ yr; GS04a), followed by the life span of massive stars, then this is phenomenologically consistent with our result that only HCN–FIR and FIR–RC correlations are the tightest and have the least scatter from linearity, while HCN and RC luminosity appears to be the result of a combination of the former two correlations, not an immediate relation in time. The obvious contrast between Figure 3(a) (or FIR–HCN normalized by CO (Figure 5(a) in GS04a)) and Figure 5(b) might be reflected in the differences in these timescales that it is much more dynamic and scattered in luminosity ratios involving HCN rather than CO.

Spatially, CO traces large-scale molecular gas distribution (entire GMCs plus diffuse molecular clouds), where most of the molecular gas is not forming stars, whereas the high-density regions (dense GMC cores traced by high-dipole moment molecules such as HCN) of much smaller spatial scales are indeed the locations of active star formation in galaxies. Murgia et al. (2005) showed that the spatially resolved tight CO–RC correlation holds down to $\sim 100$ pc size scale in galaxies which is close to the GMC size scale. Paladino et al. (2006) further probed the RC–FIR–CO correlations down to linear scales of a few hundred pc using new Spitzer IR images of six BIMA CO Survey of Nearby Galaxies (BIMA SONG; Helfer et al. 2003) and observed local deviations from the correlations in regions with a high SFR where a low RC/FIR ratio is found. We showed here, however, that the global HCN–RC correlation is actually much tighter than the CO–RC correlation, but we need a similarly detailed, spatially resolved local comparison between RC and HCN and FIR and HCN in galaxies in order to examine how the FIR–RC–HCN correlations extend to much smaller size scale.

Murphy et al. (2006, 2008) have taken an initial look at the FIR–RC correlation within the disks of 4, later increased to 29, nearby face-on galaxies in the Spitzer SINGS legacy program (Kennicutt et al. 2003), and found the trend that the ratio of FIR to RC decreases with increasing radius, which is consistent with what Marsh & Helou (1995) found at intermediate spatial resolution. They also studied how the star formation activity affects the FIR–RC correlation within galaxies by testing a phenomenological model which smears the FIR images to match the radio images. They found that the mean distance traveled by the CR electrons is most sensitive to the dominant age of the CR electron population, rather than the interstellar medium (ISM) parameters, which may inhibit their propagation, such as the ISM density, radiation-field energy density, and magnetic field strength. Comparison of such detailed spatially resolved correlations in line with our findings in the global quantities could help us reach our final goal, i.e., understanding the FIR–RC correlation. Globally, HCN seems better than CO, the validity of correlations of RC–CO and FIR–RC on small scale has already been proven; we need high-fidelity HCN imaging and/or resolved HCN observations to truly compare all.

Both FIR and RC emission involves physical processes of both small and large spatial scales even though most of the FIR emission is dominated by active star-forming regions of small scales. Mooney & Solomon (1988) showed that the FIR–CO correlation for GMCs improves, once the diffuse FIR emission that originated from the general interstellar radiation field of large spatial scale was subtracted. RC might be dominated by large-scale shocks/bubbles associated with SNRs as well as even larger scale of magnetic fields, where CR electrons pass along the field lines and experience efficient cooling, whereas HCN traces a smaller size scale than that of FIR and RC. Yet, they are associated with three different periods in the time sequence connected with the entire star formation processes. FIR emission originates from the dust that enshrouds the newborn stars while HCN emission outlines regions of dense molecular gas that eventually nurse newborn stars, whereas RC emission is produced from the significantly diffused CR electrons and large-scale shocks, which have traveled a long distance from the previous star-forming sites. The difference between these three emissions in time sequence is in de facto agreement with that of the corresponding locations in spatial scales: dense molecular cores further collapse to form massive stars that then quickly evolve and go through supernovae to become SNRs.

In short, CO and FIR emission are almost entirely associated with the GMCs, but most FIR emission is probably associated with star-forming sites inside the dense cores of the much smaller scales traced by the HCN emission. On the other hand, RC is probably dominated by large-scale diffuse emission though some FIR emission is also associated with the large-scale general interstellar radiation field. These differences are possibly suggested by the multi-parameter fits that RC correlates much tighter with FIR than with HCN though CO seems more important than HCN in predicting RC (Equations (2) and (5)), and HCN correlates much tighter with FIR than with RC, though CO seems to be equally important as FIR in predicting HCN (Equations (3) and (6)). Both FIR and HCN trace smaller scale star-forming regions, whereas RC traces the overall large-scale environment, which is affected by the feedback of massive star formation and previously hosted massive stars.

4.2. Radio Continuum (RC, and FIR and HCN) as Star Formation Rate (SFR) Indicator

Gao & Solomon (GS04a) have extensively discussed the dense molecular gas in relationship to the total molecular gas and SFR indicated by the FIR emission. The HCN emission is associated with the high-density molecular gas which is the direct active star formation material. Compared with CO, the HCN luminosity is much better at predicting the FIR luminosity for all galaxies including ULIRGs (GS04a). This is represented by a much better $L_{IR} - L_{CO}$ correlation than the $L_{IR} - L_{HCN}$ correlation (GS04a). A similar result is obtained
here by the comparison between the $L_{\text{RC}}$--$L_{\text{HCN}}$ correlation and the $L_{\text{RC}}$--$L_{\text{CO}}$ correlation. Although the extreme claim that globally, the RC–CO correlation is as good as the FIR–RC correlation is made by Murgia et al. (2005), perhaps due to a small range of parameters and limited sample size, we find here that RC luminosity correlates with $L_{\text{HCN}}$ much more tightly than with $L_{\text{CO}}$, and that FIR–RC and FIR–HCN are the tightest correlations of all. The physical explanation for the tight correlation between the HCN and FIR is obviously that stars are formed in dense molecular gas, whereas the tight correlation between HCN and RC would further strongly support this interpretation and at least globally indicate that the RC could be used as a tracer of star formation. For a detailed discussion on SFR, dense molecular gas, total molecular gas, and their various ratios, readers are referred to Section 4 in Gao & Solomon (GS04a).

According to the tight FIR–RC correlation, which is also valid down to kpc/sub-kpc size scale within galaxies (e.g., Marsh & Helou 1995; Lu et al. 1996; Murphy et al. 2006, 2008), detailed SFE maps can be deduced by using local RC luminosity as a local SFR tracer and comparing them to the CO images. This application was first used in studies of individual interacting galaxies, like Arp 244—pioneered by Gao et al. (2001)—and Taffy galaxy (Gao et al. 2003; Zhu et al. 2007). These SFE maps allow us to identify the most active star-forming sites, and characterize and investigate the star formation properties in local regions of kpc/sub-kpc size scales.

Nonetheless, the mean SFE, which measures the SFR (deduced from RC) per unit mass of molecular gas available to form stars, is found to vary weakly with Hubble morphological type (among galaxies) and distances from galaxy centers (within individual galaxy disks; Murgia et al. 2002). Murgia et al. (2005), however, do not measure any systematic trend in the CO/RC ratio as a function of radius in the nine BIMA SONG galaxies studied. A hydrostatic pressure regulation model was used to interpret the excellent correlation between the CO, RC, and FIR emissions in galaxies on both large and small scales to avoid invoking any explicit dependence on the star formation scenario (Murgia et al. 2005). Given the assumption that CO surface brightness is proportional to molecular gas surface density, the model predicts $I_{\text{RC}} \propto I_{\text{CO}}^{1.4}$, which is consistent with our global result and also, probably results from the linear correlation between FIR–RC, consistent with the 1.4 power in global FIR versus CO (GS04a) and FIR versus $(H_\alpha+H\beta)$ (Kennicutt 1998b) as well as recent local resolved studies (Calzetti et al. 2007; Kennicutt et al. 2007). We note that if the observational result that $L_{\text{HCN}} = 1.38 \log L_{\text{CO}} - 4.79$ (GS04a) is used, the prediction of this model will become $I_{\text{RC}} \propto I_{\text{HCN}}$, also perfectly consistent with the result of our global correlation fits.

However, Paladino et al. (2006) observed local deviations from the RC–IR–CO correlations in regions with a high SFR, such as the spiral arms, in six galaxies for which high-resolution Spitzer 24 $\mu$m mid-IR data are available. Further studies in a variety of star-forming galaxies are necessary to enlarge the dynamical range of parameter spaces and to achieve better agreements in the local RC–FIR–CO and even RC–FIR–CO–HCN correlations. Nevertheless, Paladino et al. (2006) concluded that, down to $\sim 100$ pc scale, they have not yet probed the physical scales at which the correlations break down.

Based on Spitzer mid-IR observations, Wu et al. (2005) find that the 8 $\mu$m and 24 $\mu$m luminosities of star-forming galaxies are both strongly correlated with their RC (1.4 GHz) and H$\alpha$ luminosities over a range in luminosities of nearly 3 orders of magnitude. This suggests that, alternatively, mid-IR emission of much better spatial resolution than FIR can be approximately used as local tracers of SFR as well. Yet, it is still unclear, on local sub-kpc scales, how the various correlations between each SFR indicator—from mid-IR to FIR, RC, and molecular gas tracers CO and HCN—would be quantitatively different.

With the help of the high-resolution capability of Spitzer, and now Herschel, as well as high-resolution and high-sensitivity HCN and CO imaging (with the upcoming ALMA), we can further analyze these correlations down to sub-kpc scales in galaxies and extremely smaller scale (sub-pc) inside the dense GMC cores in the Milky Way. Whether these relations hold or break down will help make our understanding of star formation in both external galaxies approaching microscopic scales and the active star-forming regions in our Galaxy more comprehensive.

5. SUMMARY

We summarize our main results and present our concluding remarks in the following.

1. For the HCN survey sample of 65 galaxies, including normal galaxies and LIRGs/ULIRGs, the most luminous galaxies in the local universe, a tight linear correlation between the global RC and HCN luminosities is established. This correlation is comparably tight as that between FIR and HCN and is valid over 3 orders of magnitude including ULIRGs. Normalized by $L_{\text{CO}}$, the correlation between RC and HCN is still prominent, which suggests that the SFE ($L_{\text{RC}}/L_{\text{CO}}$) is clearly proportional to the dense molecular gas fraction ($L_{\text{HCN}}/L_{\text{CO}}$). Compared with the same trend found between the FIR-derived SFE and dense molecular gas fraction, this consistency supports these suggestions from another point of view.

2. We also observe the tight correlation between RC and total FIR luminosities, which is well established in previous studies of much larger samples. This FIR–RC correlation is the tightest one (with a correlation coefficient $R = 0.96$) among the various correlations between RC, FIR, CO, and HCN luminosities discussed in this paper. Moreover, there is also a significant correlation between the normalized luminosities $L_{\text{RC}}/L_{\text{HCN}}$ and $L_{\text{IR}}/L_{\text{HCN}}$ even though FIR is almost equally tightly correlated with HCN. This confirms the well-established FIR–RC correlation independently with our HCN sample though the detailed physical processes that relate them are still not fully understood.

3. The three- and four-parameter fits show that RC correlates much tighter with FIR than with HCN and that HCN correlates much tighter with FIR than with RC. Therefore, the combination of the well-known strongest FIR–RC correlation and perhaps the tightest linear correlation between FIR and HCN luminosities accounts for the RC–HCN correlation. With the support of other various FIR–RC–HCN–CO correlations discussed in this paper, we corroborate that at least on a global scale it is practical to use RC luminosity instead of FIR luminosity as an indicator of SFR, and HCN is much more important than CO in predicting FIR.

4. The various correlations are discussed under the current understanding of the star formation process, from raw material for star formation to star birth and death. Our global correlation results show that HCN relates tighter with SFR tracers FIR and RC as compared with CO, and that FIR seems to be the bridge that connects HCN with RC. These correlations are roughly consistent with the physical
picture of massive star formation processes spatially and temporally.

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**APPENDIX A**

**IR AND RC CORRELATION**

We conclude that among all various correlations, only the FIR–RC and FIR–HCN correlations stand out distinguishably better than the rest. Here, we plot the well-known FIR–RC correlation in Figure 6 for our HCN sample. Similar to Figure 1(a), AGNs are labeled in order to see whether there is any obvious trend in the difference between AGNs and other galaxies. In particular, we plot other directly related correlations such as FIR/RC versus HCN and FIR/RC versus HCN/CO (Figure 7) in order to examine any systematic contribution to the possible scatters in the tightest FIR–RC correlation.

The obvious trend in Figure 7(a), in which FIR/RC versus HCN emission is plotted, is that smaller scatter in the FIR/RC ratio (thus a bit tighter correlation) can be expected at the lower HCN luminosity end, i.e., the normal galaxies and less luminous LIRGs since all ULIRGs have large HCN luminosity. However, for ULIRGs and starburst galaxies (i.e., galaxies with HCN/CO > 0.06, as claimed by GS04a), there is an obvious trend of larger scatters in the FIR/RC ratio for higher HCN/CO ratio (Figure 7(b)) or high luminosities in HCN or even CO. The situation is quite similar if we show the IR and RC luminosities in the x-axis.

In fact, the FIR/RC ratio is not entirely constant and seems to weakly correlate with the HCN/RC (Figure 4(b)), yet is only marginally dependent on the CO/RC ratio (Figure 5(a)). Again, this appears to suggest that the extremely large scatter in the FIR/RC ratio only exists in galaxies with either the highest or smallest HCN/RC ratios.

**APPENDIX B**

**OTHER THREE-PARAMETER FITS**

In Section 3.3.1, we only listed the three-parameter (FIR, HCN, RC) fits. The details of the three-parameter (FIR, HCN, CO) fits can be found in GS04a, which manifest a much tighter linear FIR–HCN correlation versus the nonlinear less tight FIR–CO correlation. For the sake of completeness, we list here two other combinations of three-parameter fits involving RC, HCN, and CO: FIR, RC, and CO. First, RC, HCN and CO:

\[
\log L_{RC}(L_{HCN}, L_{CO}) = (0.72 \pm 0.13) \log L_{HCN} + (0.40 \pm 0.18) \log L_{CO} - 3.53.
\]

(B1)

The contributing factor from HCN (0.72) to RC is nearly twice that from CO (0.40). This is much less than the factor of > 5 difference between HCN and CO in the fit to FIR (GS04a):

\[
\log L_{HCN}(L_{RC}, L_{CO}) = (0.44 \pm 0.08) \log L_{RC} + (0.69 \pm 0.12) \log L_{CO} - 1.00, \quad \text{and} \\
\log L_{CO}(L_{RC}, L_{HCN}) = (0.18 \pm 0.08) \log L_{RC} + (0.49 \pm 0.09) \log L_{HCN} + 4.28.
\]

(B2)
These two fits show that HCN and CO contribute to each other much more than RC does. Yet RC’s contribution to HCN is quite close to that of CO, whereas RC’s contribution to CO is significantly less than that of HCN.

And now FIR, RC, and CO:

\[
\log L_{RC}(L_{IR}, L_{CO}) = (0.86 \pm 0.07) \log L_{IR} + (0.21 \pm 0.11) \log L_{CO} + 5.50, \text{ and}
\]

\[
\log L_{IR}(L_{RC}, L_{CO}) = (0.79 \pm 0.07) \log L_{RC} + (0.23 \pm 0.10) \log L_{CO} + 4.09. \quad (B3)
\]

These results are very similar to the results of Equations (2) and (4), demonstrating the tight RC–IR correlation with much less contribution from CO. The difference is that the HCN contribution is nearly comparable to that of RC, much more than that of CO, in the fit to FIR:

\[
\log L_{CO}(L_{IR}, L_{RC}) = (0.33 \pm 0.15) \log L_{IR} + (0.29 \pm 0.14) \log L_{RC} + 3.92. \quad (B4)
\]

Here, both FIR and RC contribute to CO equally. This is totally unlike Equation (3) where FIR contributes most to HCN with much less contribution from RC. Similarly, in Equation (5) of GS04a, HCN also contributes much more to CO than FIR.

REFERENCES

Adler, D. S., Allen, R. J., & Lo, K. Y. 1991, ApJ, 382, 475
Appleton, P. N., et al. 2004, ApJS, 154, 147
Baan, W., et al. 2008, A&A, 477, 747
Calzetti, D., et al. 2007, ApJ, 666, 870
Condon, J. J. 1987, ApJS, 65, 485
Condon, J. J. 1992, ARA&A, 30, 575
Condon, J. J., Anderson, M. L., & Helou, J. 1991, ApJ, 376, 95
Condon, J. J., & Broderic, J. J. 1988, AJ, 96, 30
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderic, J. J. 1998, AJ, 115, 1693
Condon, J. J., Helou, G., Sanders, D. B., & Soifer, B. T. 1990, ApJS, 73, 359
Condon, J. J., Helou, G., Sanders, D. B., & Soifer, B. T. 1996, ApJS, 103, 81
Devereux, N. A., & Young, J. S. 1990, ApJ, 350, L25
Evans, N. J., II. 1999, ARA&A, 37, 311
Gao, Y., Lo, K. Y., Lee, S.-W., & Lee, T.-H. 2001, ApJ, 548, 172
Gao, Y., & Solomon, P. M. 2004a, ApJ, 606, 271 (GS04a)
Gao, Y., & Solomon, P. M. 2004b, ApJS, 152, 63 (GS04b)
Gao, Y., Zhu, M., & Seaquist, E. R. 2003, AJ, 126, 2171
Gracia-Carpio, J., et al. 2008, A&A, 479, 703
Helfer, T., et al. 2003, ApJS, 145, 259
Helou, G., & Bicay, M. D. 1993, ApJ, 415, 93
Henkel, C., Whiteoak, J. B., & Mauersberger, R. 1994, A&A, 284, 17
Israel, F., & Rowan-Robinson, M. 1984, ApJ, 283, 81
Kennicutt, R. C. 1998a, A&A&A, 36, 189
Kennicutt, R. C. 1998b, ApJ, 498, 541
Kennicutt, R. C., et al. 2003, PASP, 115, 928
Kennicutt, R. C., et al. 2007, ApJ, 671, 333
Krumholz, M. R., & Thompson, T. A. 2007, ApJ, 669, 289
Lacki, B. C., Thompson, T. A., & Quataert, E. 2010, ApJ, in press (arXiv: 0907.4161)
Lu, N. Y., et al. 1996, A&A, 315, L153
Marsh, K. A., & Helou, G. 1995, ApJ, 445, 599
Mooney, T. J., & Solomon, P. M. 1988, ApJ, 334, 515
Murgia, M., Crapsi, A., Moscadelli, L., & Gregorini, L. 2002, A&A, 385, 412
Murgia, M., Helfer, T. T., Ekers, R., Blitz, L., Moscadelli, L., Wong, T., & Paladinino, R. 2005, A&A, 437, 389
Murphy, E. J., Helou, G., Kenney, J. D. P., Armus, L., & Braun, R. 2008, ApJ, 678, 828
Murphy, E. J., et al. 2006, ApJ, 638, 157
Nguyen-Q-Rieu, Jackson, J. M., Henkel, C., Truong, B., & Mauersberger, R. 1992, ApJ, 399, 521
Niklas, S., & Beck, R. 1997, A&A, 320, 54
Paladino, R., Murgia, M., Helfer, T. T., Ekers, R., Blitz, L., Gregorini, L., & Moscadelli, L. 2006, A&A, 456, 847
Rickard, L. J., Turner, B. E., & Palmer, P. 1977, ApJ, 218, L51
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Schinnerer, E., et al. 2007, ApJS, 172, 46
Schmidt, M. 1959, ApJ, 129, 243
Segalovitz, A. 1977, A&A, 54, 703
Shibatsuka, T., Matsushita, S., Kohno, K., & Kawabe, R. 2003, PASJ, 55, 87
Solomon, P. M., Downes, D., & Radford, S. J. E. 1992, ApJ, 387, L55
Sorai, K., Nakai, N., Kuno, N., & Nishiyama, K. 2002, PASJ, 54, 179
Voelk, H. J. 1989, A&A, 218, 67
Wright, A., & Otrupcek, R. 1990, Parkes Catalog (PKS Catalog; Epping: Australia Telescope National Facility)
Wu, H., Cao, C., Hao, C. N., Liu, F. S., Wang, J. L., Xia, X. Y., Deng, Z. G., & Young, C. K. S. 2005, ApJ, 632L, 79
Young, J. S., & Scoville, N. Z. 1991, ARA&A, 29, 581
Yun, M. S., Reddy, N. A., & Condon, J. J. 2001, ApJ, 554, 803
Zhu, M., Gao, Y., Seaquist, E. R., & Dunne, L. 2007, AJ, 134, 118