# WARM-DENSE MOLECULAR GAS IN THE ISM OF STARBURSTS, LIRGS AND ULIRGS

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Draft version June 18, 2018

## ABSTRACT

The role of star formation in luminous and ultraluminous infrared galaxies (LIRGs,  $L_{\rm IR} \geq 10^{11} L_{\odot}$ ; ULIRGs  $L_{\rm IR} \geq 10^{12} L_{\odot}$ ) is a hotly debated issue: while it is clear that starbursts play a large role in powering the IR luminosity in these galaxies, the relative importance of possible enshrouded AGNs is unknown. It is therefore important to better understand the role of star forming gas in contributing to the infrared luminosity in IR-bright galaxies. The J=3 level of <sup>12</sup>CO lies 33K above ground and has a critical density of  $\sim 1.5 \times 10^4$  cm<sup>-3</sup>. The <sup>12</sup>CO(J=3-2) line serves as an effective tracer for warm-dense molecular gas heated by active star formation. Here we report on <sup>12</sup>CO (J=3-2) observations of 17 starburst spirals, LIRGs and ULIRGs which we obtained with the Heinrich Hertz Submillimeter Telescope on Mt. Graham, Arizona.

Our main results are the following: 1. We find a nearly linear relation between the infrared luminosity and warm-dense molecular gas such that the infrared luminosity increases as the warm-dense molecular gas to the power 0.92; We interpret this to be roughly consistent with the recent results of Gao & Solomon (2004a,b). 2. We find  $L_{\rm IR}/M_{\rm H_2}$  ratios ranging from ~10 to ~128 L<sub> $\odot$ </sub>/M<sub> $\odot$ </sub> using a standard CO-H<sub>2</sub> conversion factor of 3 × 10<sup>20</sup> cm<sup>-2</sup> (K km s<sup>-1</sup>)<sup>-1</sup>. If this conversion factor is ~an order of magnitude less, as suggested in a recent statistical survey (Yao et al. 2003), then 2-3 of our objects may have significant contributions to the  $L_{\rm IR}$  by dust-enshrouded AGNs.

Subject headings: ISM: molecules — galaxies: active — galaxies: ISM — galaxies: starburst — submillimeter

## 1. INTRODUCTION

An important result from the IRAS observatory was the discovery of large numbers of galaxies which emit prodigiously in the infrared. The IRAS Bright Galaxy Survey (BGS, flux limited,  $f_{60\mu m} \geq 5.4$  Jy; Soifer et al 1987, 1989) reported on infrared fluxes of 330 galaxies.

An interesting subset of these objects, coined Luminous Infrared Galaxies (LIRGs,  $L_{\rm IR} \geq 10^{11} L_{\odot}$ ), and Ultraluminous Infrared Galaxies (ULIRGs,  $L_{\rm IR} \geq 10^{12} L_{\odot}$ ), serve as a unique tool to better understand the temporal evolution of starburst phenomena (the field is reviewed by Sanders & Mirabel, 1996). As evidenced by morphological studies, ULIRGs are likely the product of galaxy mergers, or strongly interacting galaxies (Sanders et al. 1988, Lawrence et al. 1991, Leech et al. 1994). While many LIRGs are also merger remnants, they can also be gas and/or dust-rich spirals.

The source of infrared luminosity in ULIRGs and high luminosity LIRGs has been under contention for quite some time. The luminous activity from the central regions in LIRGs/ULIRGs suggests either a massive starburst, dust enshrouded AGN, or some combination of the two. High resolution (~1") millimeter observations have shown large amounts of molecular gas concentrated in the nuclear regions of these galaxies (e.g. Scoville et al., 1989, Bryant & Scoville 1999). Numerical simulations have shown that galaxy mergers can efficiently drive gas toward the nuclear regions of the remnants (Barnes & Hernquist 1992, Mihos

& Hernquist 1996). Nearly all bright IRAS galaxies have been found to be rich in molecular gas (Tinney et al. 1990, Sanders, Scoville & Soifer 1991, hereafter SSS91). This molecular gas is not only the nascent birthplace for massive star formation, but may also act as fuel for a hidden AGN. Additionally, the processes may be linked. Several authors have suggested that the large amounts of gas may lead to the buildup of large nuclear star clusters which may augment the formation for a central AGN (Scoville et al. 1989, Surace et al. 1998, Evans et al. 1999, Scoville et al. 2000).

Strong constraints must be placed on the interstellar medium (ISM) in LIRGs/ULIRGs in order to better understand the source of luminosity and their role in the evolutionary sequence of galaxies. Rotational transitions in carbon monoxide are often used as a tracer for molecular gas in the ISM. The first extensive studies of the molecular gas in LIRGs/ULIRGs via  $^{12}{\rm CO}$  (hereafter, CO) line emission were presented by Tinney et al. (1990), and SSS91. These authors analyzed CO (J=1-0) emission from a sample galaxies with  $L_{\rm IR} \gtrsim \! 10^{10}~{\rm L}_{\odot}$ .

Of particular interest in the ISM is the properties of warm, dense gas, as it is this gas that directly traces star formation. Because CO (J=1-0) can be excited at relatively low temperatures ( $\sim$ 5 K above ground) and densities ( $\sim$ 10<sup>3</sup>cm<sup>-3</sup>), it serves as a good tracer for total molecular gas, but is relatively insensitive to the warmer, denser gas directly involved in the star formation process. In contrast, high lying rotational transitions of CO directly

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trace warm, dense gas. The J=3 level of CO lies 33K above ground and has a relatively high critical density of  $1.5 \times 10^4$  cm<sup>-3</sup>. The CO (J=3-2) transition can serve as a tracer of dense molecular gas heated by active star formation, and thus as a diagnostic for the starburst phenomena in these galaxies. Sensitivity to the presence of dense gas is important in determining the evolutionary state of LIRGs/ULIRGs. For example, in the well studied galaxy, Arp 220, Solomon, Downes & Radford (1992) presented single dish data taken in CO (J=1-0), HCO+(J=1-0), and HCN (J=1-0). The CO (J=1-0) spectra shows a single peak while the emission lines from the high-density tracers HCO+ and HCN each showed two peaks. Taniguchi & Shiova (1998) discussed the double-horned profile seen in the high-density tracers HCO+ and HCN as corresponding to the starburst regions associated with two separate nuclei in this galaxy. This model was further supported by high resolution observations by Sakamoto et al. (1999). It is therefore evident that high-density gas tracers are vital to the understanding of molecular gas in LIRGs and ULIRGs.

Several previous surveys of LIRGs and ULIRGs have relied on millimeter-wave studies of HCN (J=1-0) in order to probe the properties of the dense molecular component of these objects (e.g. Solomon, Downes & Radford, 1992, Gao & Solomon 2004b, and references therein). However, the low lying levels of HCN do not necessarily trace gas that is both warm and dense. For example, the J=1-0 emission of HCN traces densities of  $n(H_2) \gtrsim 3 \times 10^4 \text{cm}^{-3}$ ; however, it only lies at a temperature of  $\sim 4.25$ K above the ground state. Thus, while observations of this transition will reveal the physical conditions of dense molecular gas, both cool and warm, it does not necessarily probe the gas heated by active star formation. In order to study properties of the gas directly involved in star formation, one must look toward lines that have a high excitation temperature, as well as a high critical density.

While there have been numerous studies of CO (J=1-0) emission (Sanders & Mirabel, 1996 and references therein), there are relatively few studies of LIRGs and ULIRGs in higher lying CO transitions. Rigopoulou et al (1996) reported a CO (J=2-1) survey of 6 ULIRGs, and Yao et al. (2003) presented the first survey of CO(J=3-2) emission of LIRGs and ULIRGs from the Scuba Local Universe Galaxy Survey (SLUGS). Recent high-resolution studies of warm-dense molecular gas in individual LIRGs have been performed by Iono et al. (2004) and Wang et al. (2004).

In order to better understand the role of star formation in LIRGs and ULIRGs, and how it varies with infrared luminosity, we have conducted a survey of CO (J=3-2) emission as a tracer for warm-dense molecular gas in 17 normal starburst spirals, LIRGs and ULIRGs detected by the  $IRAS\ BGS$  survey. We made these observations at the 10m Heinrich Hertz Submillimeter Telescope (HHSMT) on Mt. Graham. A similar study has been recently performed by Gao & Solomon (2004a,b), using HCN (J=1-0) as a tracer for dense molecular gas. In §2 we present the observations and data; in §3 we discuss the excitation conditions via the CO (J=3-2)/CO(J=1-0) line ratio; in §4 we interpret the line profiles; in §5 we discuss the data with respect to

the dominant source of infrared luminosity (starburst vs. AGN), and in §6 we summarize.

#### 2. Sample selection and observations

The galaxies in this study were selected from the IRAS BGS sample which was flux limited at  $f_{60\mu m} \geq 5.4$  Jy. All but two of the objects observed here have previously shown strong CO (J=1-0) emission (Mirabel et al. 1990. Tinney et al. 1990, SSS91, Yao et al. 2004) and were therefore known to be rich in molecular gas. The galaxies were originally selected in their respective CO (J=1-0) surveys from the IRAS BGS surveys, and in the case of Yao et al. (2004), the SLUGS survey. The galaxies in these papers were chosen for position on the sky, and thus not biased for any particular galaxy properties. Our goal was to observe a number of galaxies over a wide IR luminosity range: we observed 17 galaxies ranging in IR luminosity from  $10.41 < \log(L_{\rm IR}) < 12.39$ , spanning from starburst spiral galaxies to ULIRGs. The infrared luminosities and  $60\mu$ m fluxes may be found in Table 1. All of the galaxies were chosen such that they were not redshifted out of the atmospheric transmission windows near 345 GHz. We additionally took care to observe objects whose CO emitting region would be unresolved within the 23" HHSMT beam (see also §3). We selected objects with a declination greater than  $\sim 1^{\circ}$ . The full list of objects observed can be found in Table 1.

We observed our sample of 17 galaxies on the HHSMT over three runs in November 2003, March 2004 and January 2005. We used the facility 345 GHz SIS receiver utilizing both polarizations. The acousto-optical spectrometer (AOS) was used as the backend, with a usable bandwith of 1GHz, and velocity resolution of 0.85 km s<sup>-1</sup>. For calibration sources, we observed Orion, W3OH and IRC10216. Telescope pointing was checked every hour with observations of planets. The observations were made in beam switching mode with a throw of 60", and a chopping frequency of 4 Hz. Typical integration time was  $\sim 4$ hours which yielded signal to noise ratios of about 10 in most sources. Note, that due to time constraints, we were not able to achieve this level of S/N for every object. Additionally, some of the higher luminosity objects fell at a redshift such that their observed frequencies were near atmospheric water lines, decreasing the S/N. The weather conditions were good with a typical  $\tau$  at 225 GHz of  $\sim 0.1$ . We detected CO (J=3-2) emission in 15 out of the 17 galaxies in our sample<sup>3</sup>.

The data reduction was performed using the GILDAS CLASS package. We subtracted a linear baseline from the data, excluding points in the emission line from the fit. The data were then co-added, weighted by the rms noise of each spectrum. We smoothed the data to a resolution between 3.2 km s<sup>-1</sup> and 25.6 km s<sup>-1</sup>, depending on the noise levels. We converted from an antenna temperature,  $T_{\rm A}$ , to main beam temperature,  $T_{\rm MB}$ , by scaling by the main beam efficiency,  $\eta_{\rm mb}$ , using  $T_{\rm MB} = T_{\rm A}/\eta_{\rm mb}$ . Main beam efficiencies were measured to be ~0.50 at the CO (J=3-2) line frequency during the March 2004 observing run. Observing parameters may be found in Table 1.

While the galaxies were all resolved within our 23''

<sup>&</sup>lt;sup>3</sup> Please note that while we did not detect emission in NGC 3583, Yao et al. (2003) detected emission with peak temperature of  $\sim 0.1$  K. Baseline problems in our data prevented us from ascertaining if we saw a line or simply baseline ripple.

beam, the nuclear gas and dust emitting regions were not. In Figure 1, we show the HHSMT beamprint overlaid on the optical images taken from the *Digitized Sky Survey*<sup>4</sup> and the 2MASS images taken from the 2-Micron All Sky Survey. In the same Figure we show the CO (J=3-2) spectrum we obtained for each object in this study. The objects are arranged in order of increasing  $L_{\rm IR}$ .

3. CO 
$$(J=3-2)/(J=1-0)$$
 LINE RATIO

The ratio of intensities (K km s<sup>-1</sup>) of the CO (J=3-2) line to the CO (J=1-0) line,  $R_3$ , serves as a probe of the excitation temperature and optical depth of the emitting gas. A high ratio ( $\gtrsim$ 1) indicates the gas is warm, and optically thin.

Because the CO (J=3-2) and (J=1-0) observations were taken at different telescopes with different beam sizes, certain considerations must be taken into account when comparing the line intensities. Both the beam size, b, and angular extent of the sources on the sky, s, play a role in determining the ratio:

$$R_3 = \frac{I_{32}(s^2 + b_{32}^2)}{I_{10}(s^2 + b_{10}^2)} \tag{1}$$

Where I is the intensity (K km s<sup>-1</sup>):

$$I_{CO} = \int T_{\rm mb}({\rm CO}) dV \tag{2}$$

In recent high resolution (2"-3") millimeter-wave observations of 7 LIRGs, Bryant & Scoville (1999) find that nearly all of the detected CO (J=1-0) emission is concentrated within the central 1.6 kpc in 6 of the 7 objects. Because it is unlikely that there will be significant CO (J=3-2) emission where there is no CO (J=1-0), we assume that all of the emitting gas in our sample is confined within the same region, and, with the distances to each object, compute the angular extent of emitting gas for each object.

The CO (J=1-0) data were taken at the IRAM 30m, Kitt Peak 12m, the Nobeyama Radio Observatory, and the Swedish-European Submillimeter Telescope (SEST) (Mirabel et al. 1990, Tinney et al. 1990, SSS91, Yao et al. 2003). The beam size of the 10m HHSMT at 345 GHz is  $\sim 23''$ .

The  $R_3$  ratios are presented in Table 2. Our mean value of  $R_3$  is 0.50. In a survey of CO (J=3-2) emission in 28 nearby galaxies, Mauersberger et al. (1999) found a mean value of  $R_3$  of 0.63. Similarly, Yao et al. (2003) found a mean  $R_3$  of 0.66 in their survey of 60 LIRGs/ULIRGs. The average  $R_3$  for our objects is larger than the average value seen in Galactic molecular clouds of 0.4 (Sanders et al. 1993). The spread in the ratios in Table 2 suggest a variety of excitation conditions in the molecular gas in our sample of galaxies.

### 4. LINE PROFILES

The observed line profiles allow us to gain a better understanding of the kinematics of the emitting molecular gas. Krugel et al. (1990) examined simple models of galaxies in order to explain their line profiles. They assumed the gas was distributed in a disk, and constructed

isothermal models of galaxies gridded in radius and azimuth. They allowed the clouds to rotate around the center like a rigid body out to a distance,  $R_{\rm R}$ , set as a free parameter, and then forced the velocity to  $200 \text{ km s}^{-1}$ . We use the results of these models to illustrate possible kinematic signatures found in our observed line profiles. The line profiles of the objects in our sample tend to fall into three general categories: single Gaussian (e.g. NGC 2276), double-peaked (e.g. Arp220), and three component (e.g. NGC3079). These can all be explained by models in which the beam is larger than the emitting region, and a part of the flat rotation curve is included. While it is clear from Figure 1 that we have resolved the optical emitting region of all of the galaxies in this sample, as described in §3, the bulk of the CO-emitting gas likely remains unresolved within the  $23^{\prime\prime}$  beam. Here, we discuss the line profiles of the objects in this study, and how they relate to other observations from the literature.

Single-Gaussian Profiles: The single Gaussian line profile has a width which varies based on viewing angle: if the galaxy is face on, then the line width is dominated by the turbulent velocity among the emitting clouds. If, however, there is an inclination angle of  $i < 90^{\circ}$ , then the effects of the rotation of the galaxy are evident in the line width.

NGC 7817: The optical and 2MASS images (Figure 1) indicate our observations of the circumnuclear star-forming region are unresolved in this spiral galaxy. The CO (J=1-0) line profile appears to have a possible double-peak which would be consistent with the fact that we are viewing this galaxy slightly edge-on (SSS91).

NGC 2276, NGC6701: The narrow single-Gaussian line profiles for these galaxies are likely due to viewing these spirals  $\sim$ face on.

NGC 834: The CO (J=1-0) profile in this spiral (Chini, Krugel & Lemke 1996, Hattori et al. 2004) is difficult to interpret due to noise (SSS91, Young et al. 1995). It appears to be double-horned in CO (J=1-0). A large ring of star forming gas is seen in H $\alpha$  maps by Hattori et al. (2004): this ring may be the origin of the 1-0 double peak. This double peak may emerge in a CO (J=3-2) spectrum with a higher signal to noise ratio.

 $IRAS\ 23436+5257,\ IRAS\ 07251-0248$ : The emission lines presented here for these galaxies are the first to be published. The objects appear to be disturbed and/or interacting galaxies (Figure 1).

UGC~5101: The CO (J=3-2) spectrum presented here has an asymmetric profile with a high-velocity bulge. The HCN (J=1-0) line appears to be a more symmetric Gaussian (Gao & Solomon, 2004b). The CO (J=1-0) spectrum, in contrast has a clear double-horned profile (Solomon et al. 1997). Armus et al. (2004), discuss the presence of a buried AGN in this galaxy through the detection of [Ne V] 14.3  $\mu \rm m$  line. Farrah et al. (2003) describe this object as having an enshrouded AGN which plays a large role in contributing to the near-IR flux, but becoming more negligible at longer wavelengths. Many other authors have discussed the possibility of an enshrouded AGN in this object (e.g. Imanishi, Dudley & Maloney, 2001, Imanishi

<sup>&</sup>lt;sup>4</sup> The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.

et al. 2003, and references therein). Sanders et al. (1988) interpret the morphology as a late-stage merger. NICMOS images show only a single nucleus (Scoville et al. 2000), making it unlikely that the possible double-peak is due to individual nuclei from progenitor galaxies in a merger. High resolution mapping will help to interpret this line profile better.

IRAS 17208-0014: Gao & Solomon (2004a) present HCN (J=1-0) observations of this object, and Rigopoulou et al.(1996) present CO (J=2-1) observations of this object. Our profile appears consistent with both sets of data. The object has the optical spectrum of an HII region (Veilleux, Sanders & Kim. 1999). Scoville et al. (2000) and Farrah et al. (2003) classify IRAS 17208-0014 as being powered by a pure starburst, with little to no AGN component. NICMOS images show this galaxy to have a disturbed outer disk (Scoville et al. 2000).

Double Horned Profiles: The double-horned profile was evident in many of our objects as well. There are two distinct sub-categories: those with symmetric peaks (e.g. NGC 3094 and Arp 220), and those where one peak is higher than the other (e.g. NGC 992). Krugel et al. model the symmetrical double-peaked objects as galaxies that are unresolved, with the bulk of the emitting gas confined to a circumnuclear ring. However, as was discussed in \{1, and below, there may be alternative explanations for NGC 828 and Arp 220. The asymmetric double peak profile is more enigmatic. Krugel et al. suggest that if the gas is distributed symmetrically in the galaxy's disk, such profiles might arise if the observation is centered off the center of the disk. Alternatively, this profile may arise if the LIRG/ULIRG has two distinct nuclei from a merger, and the emitting molecular gas from one has a larger velocity dispersion than the other.

NGC 3094: While our data for this object are sufficiently noisy that a double peak is not clear, higher resolution data from Yao et al. (2003) show the double peak to be evident. Imanishi (2000) classifies this object has having a highly obscured AGN.

NGC 992: While the CO (J=3-2) spectrum shows an asymmetric double-horned profile, the CO (J=1-0) profile is inconclusive. The general shape is similar, but noise dominates the features enough to make it difficult to ascertain whether or not there are two individual peaks in the 1-0 profile (SSS91). The galaxy appears to be a spiral (Chini, Krugel & Lemke 1996) undergoing a starburst (Ashby, Houck & Matthews, 1995). It is likely, following the modeling of Krugel et al., that the asymmetric line profile arises from a telescope pointing offset from the center of the CO disk.

NGC 828: Hattori et al. (2004) observed H $\alpha$  in this object, and describe it as a disturbed spiral galaxy. Kinematic evidence from high-resolution CO (J=1-0) mapping suggest that this galaxy is an ongoing merger (Wang, Scoville & Sanders, 1991). CO (J=1-0) spectra (SSS91, Young et al. 1995) appear to display two peaks, although the double-horn is significantly more asymmetric than is seen in the two major peaks in the 3-2 spectra presented in this study.

NGC 7771: The observation may be slightly off from the optical center (DSS images, Figure 1), although the entire gas emitting region appears to remain unresolved within

the beam (2MASS images, Figure 1). The CO (J=1-0) profile looks single-Gaussian. The double peak is likely due to the rotational structure of the galaxy.

Arp 220: This object is well studied in the literature, and we will only briefly discuss the line profile. As discussed in §1, the CO (J=1-0) spectrum of Arp 220 shows a single Gaussian peak, while the spectrum from high-density tracers (e.g. HCN J=1-0, CO J=3-2) reveal a double peak. The double peaks are interpreted to belong to each nuclei of the progenitor galaxies (Taniguchi & Shioya, 1998).

**Triple-Peaked Profiles:** Of our sample, NGC 3079 and NGC 6286 were best fit by three Gaussians; When fit to a single Gaussian, the FWHM's of these objects are  $\sim 450~\rm km~s^{-1}$ . Krugel et al. observed a similar feature in the starburst galaxy, Mrk 1034, and modeled this as the spectral signature of a resolved galaxy where the inclination was such that both the central core, and extended gas with a flat rotation curve were being observed. This type of model produces the symmetric spectra seen in some of our observations, with the height of the central peak rising with respect to the two outer peaks as the inclination angle of the galaxy drops.

NGC 3079: This galaxy appears to fit the Krugel et al. model. Indeed the 2MASS image shows that the beam extends significantly beyond the nuclear dust and gas emitting region. Tinney et al. (1990) presented a CO (J=1-0) spectrum of NGC 3079 compiled from a map; the profile appears to be an asymmetric double-horn.

NGC 6286: The optical and 2MASS images reveal this observation to be of an edge on spiral. The asymmetric line profile was best fit by three Gaussians, although it is likely to simply be a double-horned spectrum that was observed off of the CO emission center. Indeed, the CO (J=1-0) line profile appears more symmetric, although the presence of more than one peak is difficult to determine given the noise (SSS91).

## 5. SOURCE OF IR LUMINOSITY

The search for the driving source of high luminosity LIRGs and ULIRGs has been the subject of numerous observational and theoretical studies. While it is clear that there is active star formation in these objects, there remains evidence that dust-enshrouded active nuclei may play an important role as well (e.g. Yun & Scoville, 1998). In this section, we investigate the source of IR luminosity in the high-luminosity LIRGs and ULIRGs in our sample.

# 5.1. $L_{\rm IR}$ versus $L_{\rm CO~J=3-2}$

Correlations between infrared luminosity, and the luminosity due to high density tracers such as HCN have been discussed extensively (Solomon et al. 1992, Gao & Solomon 2004a,b). In a recent survey of normal (spiral) galaxies, LIRGs and ULIRGs, Gao & Solomon (2004b) found a linear relationship between  $L_{\rm IR}$  and  $L_{\rm HCN}$  over three orders of magnitude in infrared luminosity; this suggests that over the IR luminosity range spanned ( $\log(L_{\rm IR}) \lesssim 12.36$ ) the dense molecular gas (and thus, high mass star formation) is the dominant form of IR emission in both the LIRGs and ULIRGs. Additionally, Carilli et al. (2004) have shown for high redshift ULIRGs that the correlation between IR luminosity and HCN luminosity is nearly lin-

ear as well. These correlations suggest that at some level, the dense interstellar medium and infrared luminosity in these objects are intertwined. Since CO (J=3-2) is an indicator of warm-dense gas, we use our dataset combined with those of other works to further test this hypothesis. Similar to the Gao & Solomon study, we probe infrared luminosities up to  $\log(L_{\rm IR})$ =12.39.

We obtained values for  $L_{\rm IR}$  from SSS91 and the *IRAS Revised Bright Galaxy Survey* (Sanders et al. 2003). We calculated  $L_{\rm CO}$  using

$$L_{CO} \approx \pi/(4 \ln 2) \theta_{\rm mb}^2 I_{32} \ d_{\rm L}^2 (1+z)^{-3}$$
 (3) is the FWHM of the telescope Gaussian beam,

where  $\theta_{\rm mb}$  is the FWHM of the telescope Gaussian beam, and  $d_{\rm L}$  is the luminosity distance. The data for  $L_{\rm CO}$  are presented in Table 2. So that we may increase the number of objects in our analysis, we included 14 objects which we detected (please see caption of Figure 2 concerning exclusions), as well as 40 objects<sup>5</sup> studied by Yao et al. (2003). In order to account for calibration differences in the data sets, we used Arp 220 as a common calibrator, and scaled our  $L_{\rm CO}$  values such that the Arp 220 CO luminosities matched. This scaling factor was 0.26.

We present  $L_{\rm IR}$  vs.  $L_{\rm CO~J=3-2}$  in Figure 2. We fit the data using a linear  $\chi^2$  minimization routine, and recovered for the fit:

$$\log(L_{\rm IR}) = 0.92(\pm 0.07) \times \log(L_{\rm CO~J=3-2}) + 3.28(\pm 0.60)$$
(4)

This result is roughly consistent with the linear slope found by Gao & Solomon (2004a,b).

If the observed FIR emission is produced primarily by heating from massive stars, the star formation rate (SFR) can be given as a function of  $L_{\rm IR}$  (Kennicutt, 1998):

$$SFR(M_{\odot} \text{ yr}^{-1}) \approx 2 \times 10^{-10} (L_{IR}/L_{\odot})$$
 (5)

Previous studies of the relationship between  $L_{\rm IR}$  and  $L_{CO\ J=1-0}$  have found a nonlinear relationship such that the infrared luminosity increases as the CO (J=1-0) luminosity to the  $\sim 1.25$ . Because  $L_{\text{CO J}=1-0}$  is proportional to the total molecular gas mass (Appendix A of SSS91), this has been interpreted as an increase in star formation efficiency (SFE), defined as the SFR over the total molecular gas mass, as a function of SFR (e.g. Solomon et al. 1992).  $L_{\rm IR}/{\rm CO}({\rm J}=1-0)$  serves as a tracer for star formation efficiency as a function of all available molecular gas.  $L_{\rm IR}/{\rm HCN}({\rm J=1-0})$  serves as a tracer for SFE as a function of all available dense, star-forming gas (e.g. Gao & Solomon, 2004b). In contrast, CO(J=3-2) traces warm, dense gas heated by embedded stars (§1) and thus  $L_{\rm IR}/{\rm CO}({\rm J}{=}3{\text -}2)$  probes the infrared luminosity as a function of recent star formation. It follows then, that the linear relationship seen between  $L_{\rm IR}$  and  $L_{\rm HCN}$ implies that the SFR per unit dense molecular gas mass remains constant through  $\log(L_{\rm IR})\lesssim 12.3;$  this result is confirmed by our observed relationship between  $L_{\rm IR}$  and  $L_{\rm CO~J=3-2}$  which shows a nearly constant SFR as a function of warm-dense molecular gas heated by active star formation. These observations strengthen the conclusion of Gao & Solomon (2004b) that the IR luminosity in LIRGs and ULIRGs up to an IR luminosity of at least  $\log(L_{\rm IR})$  $\sim 12.3$  is primarily driven by heating from O and B stars.

The observed linear relationships suggest that star formation does play an important role in powering the infrared luminosity in LIRGs and ULIRGs. However, it may be that this relationship breaks down at higher IR luminosities as possible AGN contribution becomes more important. As an example, we extrapolate our fit to observations of Hyperluminous Infrared Galaxies (HLIRGs). Extrapolating from our fit, a galaxy with  $\log(L_{\rm IR}){\sim}13$  would require  ${\sim}4\times10^{11}{\rm M}_{\odot}$  of warm-dense molecular gas in the nuclear regions. For comparison, the HLIRG FSC 10214+4274 has  $L_{\rm FIR}{=}1.8\times10^{14}{\rm L}_{\odot}$  and CO (J=3-2)-traced warm-dense gas mass of  $M_{\rm H2}{=}2.2\times10^{11}~{\rm M}_{\odot}$  (an upper limit as the luminosity may have been enhanced by gravitational lensing, Close et al. (1995)); similarly, HLIRG FSC 15307+3252 has  $L_{\rm FIR}{=}1.3\times10^{13}{\rm L}_{\odot}$  and has an upper limit of warm-dense gas mass (as measured from CO J=4-3 observations) of  $M_{\rm H2}\lesssim10^{10}~{\rm M}_{\odot}$ . Both are believed to have central AGN as their main source for infrared luminosity (Yun & Scoville 1998).

The disparity in the measured versus predicted amount of warm-dense gas in these HLIRGs suggests that at higher infrared luminosities, there may exist a strong deviation from the fit described by Equation 4 which may be evident from the higher luminosity points in Figure 2. This implies that the infrared emission may grow non-linearly with increasing emission from warm-dense molecular gas.

It may be that there is an interplay between an AGN and star formation contribution to  $L_{\rm IR}$ . The case has been mounting for an evolutionary sequence between hierarchical mergers and AGN formation (e.g. Scoville, 2003). It has recently become clear that most galaxies contain supermassive black holes (Kormendy & Richstone, 1995, and references therein). There is also evidence that there is a connection between black hole growth and central ISM physics in the remnants of galaxy mergers. Recent SPH simulations have shown that AGN feedback in galaxy merger remnants can rapidly quench star formation after the initial merger-induced starburst (Springel, Di Matteo & Hernquist 2004a,b). Starbursts may be the dominant source of IR luminosity in less IR-luminous galaxies, while the AGN contribution becomes more important in higher luminosity objects. Quenching of star formation owing to AGN feedback may be responsible for a steepening of the slope in the  $L_{\rm IR}$  versus  $L_{\rm CO}$  plot for the galaxies with  $\log(L_{\rm IR}) \gtrsim 12.3~{\rm L}_{\odot}$ . Indeed, some 35%-50% of ULIRGs with  $L_{\rm IR} \ge 10^{12.3} L_{\odot}$  show AGN activity from optical and NIR spectra (Tran et al. 2001; Veilleux, Kim & Sanders, 2002). This luminosity is approximately where our sample of LIRGs and ULIRGs ends, and a location for a possible deviation from the fit in Figure 2. Additionally, Farrah et al. (2002) discuss coeval starburst and AGN activity in a sample of SCUBA HLIRG sources.

More CO (J=3-2) observations of ULIRGs with  $L_{\rm IR}\gtrsim 10^{12.3} {\rm L}_{\odot}$  are needed to test these hypotheses. Theoretical models testing these concepts will be presented in an upcoming paper.

# 5.2. L<sub>IR</sub> versus Mass of Star-Forming Molecular Gas

One of the main arguments for the existence of a dust enshrouded AGN as the main power source in luminous infrared galaxies is a SFE  $(L_{\rm IR}/{\rm M_{H_2}})$  larger than that seen in normal spiral galaxies. If the sole source of energy is a

<sup>&</sup>lt;sup>5</sup> All the objects for which Sanders et al. 2003 reported an infrared luminosity

nuclear starburst, then, assuming a reasonable initial mass function, there should be an Eddington-like limit on the star formation efficiency given by SFE  $\sim 500~L_{\odot}/M_{\odot}$ : objects with ratios significantly higher than this are likely to require an additional source of energy (Scoville, Yun & Bryant 1997; Scoville, 2003).

The gas mass is obtained using a linear relation between the CO luminosity and  $M_{\rm H2}$  (Young & Scoville, 1982; Tinney et al., 1990; SSS91).

$$M_{H2} = 4.82L_{CO}(M_{\odot}) \tag{6}$$

where  $L_{\rm CO}$  is in K km s<sup>-1</sup>. This relation is derived assuming a CO-H<sub>2</sub> conversion factor of 3 x  $10^{20}$  cm<sup>-2</sup> (K km s<sup>-1</sup>)<sup>-1</sup>, and was derived for Galactic GMCs (Scoville & Sanders 1987). However, evidence exists that implies this conversion factor may not hold for external galaxies (Maloney 1989). Through a Large Velocity Gradient (LVG) analysis, Yao et al. (2003) suggested that for LIRGs/ULIRGs, the CO-H<sub>2</sub> conversion factor lies between 1.3 x  $10^{19}$  and 6.7 x  $10^{19}$  cm<sup>-2</sup> (K km s<sup>-1</sup>)<sup>-1</sup>, or a factor of 0.04 to 0.22 times the conventional conversion factor. Nevertheless, we adopt the Galactic value in order to facilitate comparisons with published analyses of CO (J=1-0) observations.

While the ratio of infrared luminosity to total gas mass may be a strong indicator as to the source of infrared luminosity, it is the *dense* gas mass that is expected to more directly trace star formation. Thus, a prudent test is to examine the ratio of  $L_{\rm IR}$  to  $M_{\rm H2,dense}$ . Gao & Solomon (2004a,b), found that this ratio remains between ~20 and ~200, independent of total IR luminosity for normal spirals, LIRGs and ULIRGs. They additionally reported that the average  $L_{\rm IR}$  to  $M_{\rm H2,dense}$  in their sample was ~90L $_{\odot}/M_{\odot}$ , comparable to molecular cloud cores (Mooney & Solomon 1988). These ratios were found through analysis of HCN (J=1-0).

We present the ratio  $L_{\rm IR}/M_{\rm H2,warm-dense}$  for our sample of LIRGs in Table 2. As is evident, none of the objects have a ratio  $L_{\rm IR}/M_{\rm H2} > 500 L_{\odot}/M_{\odot}$ . There are a few important caveats to note. This number could be significantly skewed if our mass estimates are off. Certainly (following the derivation presented in Appendix A of SSS91) if the CO-to-H<sub>2</sub> conversion factor is, as derived by Yao et al. (2003), an order of magnitude lower than the conventional values, the  $L_{\rm IR}/{\rm M}_{\rm H2}$  values would increase accordingly. Using the CO-H<sub>2</sub> conversion factors calculated by Yao et al., we find 2-3 of our objects have ratios higher than 500, indicating the possibility of an AGN component to the observed far infrared luminosity. It should also be noted that the ratios presented here are of star formation rate per unit warm, dense gas mass - this hints at the possibility that the actual star forming gas available is not enough to produce the infrared luminosities seen in some objects. Additionally, it is not clear that the CO-to-H<sub>2</sub> conversion factor is the same in all galaxies. Better constraints on variations in the CO-to-H<sub>2</sub> conversion factor are necessary in order to use this method to make a robust statement concerning the source of IR luminosity.

## 6. SUMMARY

We have presented single-dish CO (J=3-2) observations of a sample of starbursts, LIRGs and ULIRGs in order to study properties of the warm-dense, star forming gas.

We detected emission in 15 out of 17 galaxies within our noise limits. We have found a nearly-linear relationship between the infrared luminosity and amount of warm-dense gas, confirming the recent results by Gao & Solomon for galaxies with  $\log(L_{\rm IR}) \lesssim 12.3$ . Depending on the value of the adopted CO-H<sub>2</sub> conversion factor, our analysis suggests that star formation alone may not be sufficient to generate the IR emission observed in the more luminous galaxies.

We would like to thank the entire HHSMT staff for continual support. We additionally acknowledge R.S. Bussmann, Abigail Hedden, and Elaina Hyde for their assistance during observations. We thank the referee for helpful comments that have greatly improved the quality of this manuscript, and for a prompt review. D.N. would like to thank Craig Kulesa, and Bob Stupak for helpful conversations, and acknowledges the NSF Graduate Research Fellowship Program for funding during part of this study.

The HHSMT is operated by the Arizona Radio Observatory (ARO), Steward Observatory, University of Arizona, with partial funding from the Research Corporation. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration

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 $\begin{array}{c} \text{Table 1} \\ \text{Observation Information}^1 \end{array}$ 

Object	RA (J2000)	Dec (J2000)	cz	Distance 5	<sup>2</sup> Date Observed	Reference <sup>3</sup>	$\log L_{\rm IR}$	$^{4}$ $f_{60\mu m}$	4 Detection?
			${\rm km~s^{-1}}$	Mpc			$L_{\odot}$	Jy	
NGC 7817	0:04:10.1	20:46:30.6	2315	31.9	11/03	1	10.41	*	Yes
NGC 3583	11:14:28.0	48:17:38.5	2168	35.09	11/03	3	10.54	7.43	No
NGC 3079	10:02:16.3	55:39:46.9	1142	18.19	03/04	3	10.73	50.67	Yes
NGC 3094	10:01:38.3	15:45:10.3	2404	37.04	11/03	3	10.73	10.88	Yes
NGC 2276	7:28:27.8	85:45:09.8	2380	35.83	03/04	2	10.81	14.29	Yes
NGC 834	2:11:14.4	37:41:11.2	4687	61.48	03/04	1	10.94	6.65	Yes
NGC 992	02:37:25.4	21:05:47	4136	53.83	03/04	1	11.02	11.40	Yes
NGC 6701	18:43:14.9	60:38:58.1	3933	56.64	03/04	1	11.05	10.05	Yes
NGC 6621	18:12:54.9	68:21:27.0	6234	86.42	03/04	1	11.23	6.78	No
NGC 828	02:10:09.42	39:11:26.29	5371	70.37	11/03	1	11.31	11.46	Yes
NGC 6286	16:58:36.6	58:55:25.7	5637	79.78	11/03	1	11.32	9.24	Yes
NGC 7771	23:51:36.2	20:08:00.4	4336	57.11	11/03	1	11.34	19.67	Yes
IR23436 + 5257	23:46:05.8	53:14:00	10233	134.78	01/05	*	11.51	5.66	Yes
UGC 5101	09:32:10.5	61:21:22	11785	158.61	01/05	5	11.95	11.68	Yes
Arp 220	15:35:05.2	23:29:22.7	5450	79.90	11/03	3	12.21	104.09	Yes
IR07251-0248	07:27:37.5	-02:54:55	26257	343.74	01/05	*	12.32	6.49	Yes
IR17208-0014	17:23:21.4	-00:17:00	12852	175.68	01/05	4	12.39	32.13	Yes

 $<sup>^1\</sup>mathrm{All}$  objects are in order of increasing  $L_{\mathrm{IR}}.$ 

 $<sup>^2</sup>$ Distances given are proper distances, and are taken from Sanders et al. 2003 except for NGC 7817 which is from SSS91. Values for cz taken from the same references.

<sup>&</sup>lt;sup>3</sup>References are for J=1-0 data: 1: Sanders et al. 1991, 2: Tinney et al. 1990, 3: Yao et al. 2003, 4: Mirabel et al. 1990, 5: Gao & Solomon, 2004b. An asterisk denotes no CO (J=1-0) observations that we could find.

 $<sup>^4</sup>L_{\rm IR}$  and  $60\mu{\rm m}$  flux from Sanders et al. 2003, except for NGC 7817 which was not given.

Table 2
Physical Properties

Object	Intensity	±	$R_3$ 1	$^{\mathrm{L}}CO$	±	$\rm M_{\rm H2}~CO(3\text{-}2)$	±	$L_{ m IR}/{ m M}_{ m H2~warm,dense}$
	$_{ m K~km~s}^{-1}$	$_{ m K~km~s}^{-1}$		$10^9 {\rm K~km~s^{-1}~pc^2}$	$10^9 {\rm K~km~s^{-1}~pc^2}$	10 <sup>9</sup> M <sub>☉</sub>	$10^9 {\rm M}_{\odot}$	$L_{\odot}/M_{\odot}$
NGC 7817	2.94	0.07	0.03	0.04	0.001	0.20	0.005	128.52
NGC 3079	183.46	3.18	0.51	0.852	0.01	4.11	0.07	13.07
NGC 3094	15.10	0.41	0.60	0.290	0.008	1.40	0.04	38.69
NGC 2276	12.23	0.20	0.12	0.219	0.004	1.06	0.02	60.91
NGC 834	11.15	0.37	0.28	0.585	0.02	2.82	0.09	30.89
NGC 992	21.16	1.25	0.34	0.852	0.05	4.11	0.24	25.48
NGC 6701	28.80	0.42	0.45	1.28	0.02	6.19	0.09	18.13
NGC 828	59.21	1.77	0.50	4.06	0.121	19.56	0.58	10.44
NGC 6286	42.61	0.13	0.65	3.75	0.01	18.08	0.06	11.56
NGC 7771	19.28	0.22	0.32	0.873	0.01	4.2	0.05	52.07
IR23436+5257	20.05	1.19	*	4.96	0.29	23.9	1.4	13.54
UGC 5101	7.17	1.1	0.50	2.45	0.38	11.8	1.8	75.53
Arp 220	89.96	1.91	1.60	7.95	0.17	38.30	0.81	42.34
IR07251-0248	7.70	0.31	*	11.79	0.47	56.8	2.3	36.78
IR17208-0014	10.49	1.11	0.42	4.37	0.46	21.1	2.2	116.33

 $<sup>^1\</sup>mathrm{Asterisk}$  denotes no CO (J=1-0) data available.

- Fig. 1.— Each 3-panel row contains the following information from left to right: The DSS image with the 23'' HHSMT beam overlaid; The 2MASS image with the 23'' HHSMT beam overlaid; The CO (J=3-2) emission line obtained at the HHSMT in this study.
- FIG. 2.—  $L_{\rm IR}$  vs.  $L_{\rm CO~3-2}$ . The slope of the fit is 0.92. Crosses are data points from Yao et al. (2003) while filled in squares are data taken in this study. Errors for objects from our sample derived from errors in intensity calculations. We estimate an error of 10% for the objects taken from the Yao et al. (2003) sample. No error bars are given for the  $L_{\rm IR}$  data points. We have excluded NGC7817 from the fit (but left its point on the plot) as it has an extremely small  $L_{\rm CO}$  with respect to the locus of objects we observed. When including this object, the slope changes to  $0.85\pm0.07$









