MOLECULAR GAS DEPLETION AND STARBURSTS IN LUMINOUS INFRARED GALAXY MERGERS

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ABSTRACT

Most luminous infrared galaxies (LIGs) are closely interacting/merging systems that are rich in molecular gas. Here we study the relationship between the stage of the galaxy-galaxy interactions, the molecular gas mass, and the star formation rate as deduced from the infrared luminosity $L_{\text{IR}}$ in LIGs. We find a correlation between the CO (1–0) luminosity [a measure of molecular mass $M(H_2)$] and the projected separation of merger nuclei (the indicator of merging stages) in a sample of 50 LIG mergers, which shows that the molecular gas content decreases as merging advances. The starburst is due to enhanced star formation in preexisting molecular clouds and not to the formation of more molecular clouds from atomic gas. Because of the starbursts, the molecular content is being rapidly depleted as merging progresses. This is further supported by an anticorrelation between $L_{\text{IR}}/M(H_2)$, the global measure of the star formation rate per unit gas mass, and the projected separation that implies an enhanced star formation “efficiency” in late-stage mergers compared with that of early mergers. This is the first evidence connecting the depletion of molecular gas with starbursts in interacting galaxies.

Subject headings: galaxies: evolution — galaxies: interactions — galaxies: ISM — galaxies: nuclei — galaxies: starburst — infrared: galaxies

1. INTRODUCTION

Luminous infrared galaxies (LIGs; $L_{\text{IR}} \gtrsim 2 \times 10^{11} L_\odot$, $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$) are the dominant population among objects with $L_{\text{bol}} \gtrsim 2 \times 10^{11} L_\odot$ in the local universe (for a comprehensive review, and also a definition of $L_{\text{IR}}$, see Sanders & Mirabel 1996). Most LIGs are merging/interacting (see, e.g., Sanders 1992; Leech et al. 1994; Murphy et al. 1996) and rich in molecular gas with a high star formation rate since most of the luminosity is radiated by dust in the far-IR. Sanders et al. (1988) suggested that the most extreme ultra-LIGs (ULIGs) with $L_{\text{IR}} \gtrsim 10^{12} L_\odot$, comparable to the bolometric luminosity of quasars (QSOs) are dust-enshrouded QSOs triggered by the interaction/merger of two gas-rich spirals. However, a starburst origin (see, e.g., Joseph & Wright 1985), even for ULIGs, has also been suggested. Evidence in favor of a starburst includes the molecular gas content, the radio continuum morphology, and the Infrared Space Observatory mid-IR spectroscopy (see, e.g., Solomon et al. 1997, hereafter S97; Downes & Solomon 1998, hereafter DS98; Condon et al. 1991; Genzel et al. 1998). The observed abundant supply of dense molecular gas traced by HCN emission, usually found only in star formation cores (Solomon, Downes, & Radford 1992; Gao 1996; Gao & Solomon 1999), shows that ULIGs are ideal stellar nurseries.

Although there have been extensive CO observations in LIGs/ULIGs, including CO imaging (see, e.g., Scoville et al. 1991; Scoville, Yun, & Bryant 1997; DS98), there has been no systematic attempt to trace the molecular gas properties during the galaxy-galaxy merger sequence starting with systems roughly separated by a galactic diameter. The purpose of this study is to investigate the connection between the progress of a merger and the molecular gas responsible for the star formation. There are many close mergers where the progenitors are not gas-rich galaxies; these may never become LIGs. All LIGs/ULIGs are molecular gas rich (Sanders, Scoville, & Soifer 1991; Gao 1996; S97).

The ideal sample for tracing a merger sequence should contain galaxies of various merging stages that initially started with roughly comparable molecular gas content. Since this is impossible, we select LIGs where we can identify the two progenitors from CCD images usually in the red or near-IR. By measuring the CO (1–0) luminosity as a function of the merger separation, the time dependence of the gas content can be traced statistically.

2. THE SAMPLE

We focus exclusively on mergers that satisfy $S_{\text{sep}} \lesssim (D_1 + D_2)/2$, where $S_{\text{sep}}$ is the projected separation between the nuclei of the merging galaxies of the major diameters $D_1$ and $D_2$. In reality, we require that the pairs have touching/overlapping optical disks/tails. We exclude late mergers of $S_{\text{sep}} \lesssim 2^\circ$ ($\sim 1$ kpc at an angular distance of $\sim 100$ Mpc) so that $S_{\text{sep}}$ can be measured reliably. This also helps to distinguish genuine mergers from projection effects, exclude galaxies where there is confusion of the extranuclear starburst regions with galactic nuclei, and minimize other potential biases introduced by the seeing limit or severe dust obscuration. At larger distances, LIGs with $S_{\text{sep}} \sim 1$ kpc similar to the nearest ULIGs Arp 220 and Mrk 273 will simply be indistinguishable from the single-nucleus galaxies without subarcsecond imaging. Even at moderate distances ($\sim 200$ Mpc), some previously accepted close doubles, e.g., Mrk 231 (Armus et al. 1994) and IRAS 12112+0305 (Sanders 1992), turn out to be singles as seen by the Hubble Space Telescope (Surace et al. 1998; D. B. Sanders 1998, private communications).

Our sample selection is simple: all LIGs with $L_{\text{IR}} \gtrsim 2 \times 10^{11} L_\odot$, $2^\circ \lesssim S_{\text{sep}} \lesssim (D_1 + D_2)/2$ are selected if they have both CO data and CCD images. A heterogeneous sample of 50 LIGs has been used (Table 1); 19 of them are ULIGs. CO (1–0) observations have been conducted in $\sim 30$ LIGs of mostly mergers (Gao 1996). Most have been observed with...
the NRAO 12 m telescope, and a representation is shown in Figure 1 (details will be discussed in a future paper). This nearly completes the CO data for nearby LIG mergers in the bright galaxy sample (BGS; Soifer et al. 1989; Sanders et al. 1995). A volume-limited ($cz \leq 12,000$ km s$^{-1}$), nearly complete sample of 20 LIGs, mainly from the BGS, is highlighted in Table 1. Most LIGs, but not ULIGs, are in this subsample.

3. $L_{\text{CO}}$-$S_{\text{sep}}$ CORRELATION

We have separated the sample into 31 LIGs with $2 \times 10^{-12} < L_{\text{IR}} \leq 10^{-12}$ L$_\odot$ and 19 ULIGs with $L_{\text{IR}} > 10^{-12}$ L$_\odot$. The observed CO luminosities range over an order of magnitude $\log (L_{\text{CO}}/L_\odot) = 9.2-10.3$, $L_\odot = \text{K km s}^{-1} \text{pc}^2$ for the entire sample. This is at the high end of the distribution for normal molecular gas-rich galaxies. However, for ULIGs, the range is smaller with $\log (L_{\text{CO}}/L_\odot) = 9.92 \pm 0.12$ (S97).

The correlation between CO luminosity $L_{\text{CO}}$ and the nuclei separation $S_{\text{sep}}$ is evident in Figure 2a. We compute correlation coefficients of $\gamma = 0.80$ for 31 LIGs and $\gamma = 0.78$ for 20 volume-limited LIGs, with fits

$$L_{\text{CO}} = 10^{0.90 S_{\text{sep}} + 0.18} \text{ and } L_{\text{CO}} = 10^{0.82 \gamma S_{\text{sep}} + 0.20},$$

respectively. Clearly, this correlation indicates that $L_{\text{CO}}$ is decreasing as the merger progresses to advanced stages. The system with the highest $L_{\text{CO}}$ in the sample is Arp 302, which also has the largest separation. Even if Arp 302 is excluded, the correlation remains the same. While the correlation for the entire heterogeneous sample is still obvious ($\gamma = 0.6$), the correlation for ULIGs alone (the open circles in Figure 2) is not significant ($\gamma = 0.2$). In view of the near constancy of $L_{\text{CO}}$ for ULIGs (S97), this is not surprising.

There is no correlation between IR luminosity $L_{\text{IR}}$ and separation $S_{\text{sep}}$ (Fig. 2b), which indicates that the IR emission is not enhanced as the merger progresses, at least prior to reaching $S_{\text{sep}} \approx 2$ kpc. As discussed above, we have excluded close mergers/singles. Many of these are ULIGs. An anticorrelation of $L_{\text{IR}}$ with $S_{\text{sep}}$ appears to hold if small separation ULIGs are included, particularly the 10 ULIGs in the BGS (Sanders et al. 1988).

There is a significant anticorrelation between $L_{\text{IR}}/M(H_2)$ (or $L_{\text{IR}}/L_{\text{CO}}$) and separation $S_{\text{sep}}$ (Fig. 2c), $\gamma = -0.61$ for 31 LIGs). Here we have used a standard conversion factor of $4.7 M_\odot/L_\odot$ applicable to giant molecular clouds (GMCs), in order to obtain the molecular gas mass from $L_{\text{CO}}$. It clearly suggests that the star formation rate, normalized to the available molecular mass or star formation efficiency, increases at small separations. This indicates an increased rate for the conversion of gas to stars, which is the primary criterion for a starburst.

We checked for possible selection effects by examining the dependence of the parameters on the distance to the source. There is no strong dependence of the projected separation on the distance even in the large heterogeneous sample; the correlation between $L_{\text{CO}}$ and the distance is weak and is nonexistent for the nearby BGS LIGs.

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**Table 1**

| Source/Name (IRAS) | $cz$ (km s$^{-1}$) | $L_{\text{IR}}$ (10$^{12}$ L$_\odot$) | $L_{\text{CO}}$ (10$^{10}$ L$_\odot$) | Separation (arcsec, kpc) |
|-------------------|------------------|-------------------------------|----------------------------------|-------------------------|
| NGC 7592, Mrk 928 | 3516.4           | 4.3                           | 3.8                              | 2.5, 2.1                |
| NGC 6670          | 10540.0          | 4.2                           | 8.4                              | 35, 22.5                |
| Mrk 1027          | 8215.4           | 4.2                           | 2.1                              | 8.2, 4.1                |
| UGC 4881          | 11519.3          | 6.3                           | 8.4                              | 11.0, 9.9                |
| Arp 236, VV 114,  | 6016.4           | 4.7                           | 10.7                             | 16.0, 6.1                |
| UC 1 IC 1623      | 10177.3          | 4.7                           | 12.0                             | 15.0, 10.7               |
| 20551             | 10177.3          | 4.7                           | 12.0                             | 15.0, 10.7               |
| 00267              | 10177.3          | 4.7                           | 12.0                             | 15.0, 10.7               |
| IC 336            | 10177.3          | 4.7                           | 12.0                             | 15.0, 10.7               |
| Mrk 1027          | 10177.3          | 4.7                           | 12.0                             | 15.0, 10.7               |

**Note.**—Sources in the nearby complete sample have been highlighted in boldface.

1. The CO luminosity is recalculated using the consistent formula in S97, $L_\odot = \text{K km s}^{-1} \text{pc}^2$.
2. S97.
3. Armus, Heckman, & Miley 1987.
4. Murphy et al. 1996.
5. Our data.
6. Mazzarella & Boroson 1993.
7. Sanders 1992.
8. Sanders et al. 1991.
9. Kollatschny et al. 1991.
10. Fig. 1, S97, and D-C. Kim & D. B. Sanders (1993, 1996, 1998, private communications).
11. Klaas & Elsässer 1993.
12. Mirabel et al. 1990.
13. Melnick & Mirabel 1990.
14. Surace et al. 1998.
15. Kazés et al. 1990.
16. van den Broek et al. 1991.
17. Mirabel, Sanders, & Kazés 1989.
18. Sanders et al. 1989.
19. Goldader et al. 1997.
4. IMPLICATIONS AND DISCUSSION

We conclude that there is a strong correlation between \( L_{\text{CO}} \) and \( S_{\text{sep}} \) for ULIGs, although almost no correlation for LI
gs. CO observations of widely separated interacting galaxies \( S_{\text{sep}} \approx (D_1 + D_2)/2 \), nonmergers show no corre
lation between \( L_{\text{CO}} \) and \( S_{\text{sep}} \) (Combes et al. 1994). After merging begins, \( S_{\text{sep}} < (D_1 + D_2)/2 \sim 20 \) kpc, the molecular gas content is decreasing as the merging advances. Since we may over-
estimate the molecular gas mass in ULIGs and late mergers (S97; D98) by using a constant conversion factor, the depen
dence of molecular gas mass on separation may be even steeper than that in equation (1).

Mergers separated by a few kiloparsecs produce the same \( L_{\text{IR}} \) as mergers with \( S_{\text{sep}} \approx 15 \) kpc with less molecular gas (Fig. 2 and eq. [1]). It is not the increase in molecular gas that leads to the high \( L_{\text{IR}} \) but the increase in average gas surface density that produces a higher star formation efficiency. In more than a dozen early/intermediate-stage mergers in this sample, CO imaging reveals that most of the gas is in the inner merging disks, except for the widely separated pairs that are not yet closely interacting, which have extended CO (Gao et al. 1997; 1999a; Lo, Gao, & Gruendl 1997). Arp 302 (Lo et al. 1997), the widest pair (\( S_{\text{sep}} = 25 \) kpc), has two extended CO disks (\( \geq 10 \) kpc), and one of them shows roughly an exponential disk with a scale length of \( \sim 7 \) kpc extending out to \( 20 \) kpc in diameter. NGC 6670 (\( S_{\text{sep}} = 15 \) kpc) shows central sources with \( \geq 1 \) kpc radii and strong CO disks out to \( \sim 5 \) kpc with weaker emission out to \( 15 \) kpc in both galaxies. Arp 238 (\( S_{\text{sep}} = 12 \) kpc) and Arp 55 (\( S_{\text{sep}} = 10 \) kpc), the intermediate-stage mergers, show central \( \sim 1 \)–2 kpc sources and extensions out to \( \sim 5 \)–10 kpc in both pairs of disks. Late mergers like Arp 299 (Aalto et al. 1997) and NGC 6090 (\( S_{\text{sep}} < 5 \) kpc) show gas concentrations between the merging disks.

For a pair of gas-rich spirals initially separated at \( S_{\text{sep}} \approx 20 \) kpc, merging at (orbital decay speed) \( V \sim 40 \) km s\(^{-1}\), the time to reach \( S_{\text{sep}}^n \approx 2 \) kpc is \( 500[(S_{\text{sep}}^n - S_{\text{sep}}^0)/20 \) kpc\]/(40 km s\(^{-1}\)/\( V \) Myr. If the LI
gs with different separations are interpreted as a sequence, then, using a standard conversion factor and equation (1), the implied average star formation (gas depletion) rate is

\[
100A \left( \frac{V}{40 \text{ km s}^{-1}} \right) \left( \frac{20 \text{ kpc}}{S_{\text{sep}}^n} \right)^{0.2} M_{\odot} \text{ yr}^{-1}, \tag{2}
\]

where \( A = [1 - (S_{\text{sep}}^n/S_{\text{sep}}^0)^{0.8}]/(1 - S_{\text{sep}}^n/S_{\text{sep}}^0) \approx 1 \). Of course, the trend evident in Figure 2a may not be a true time sequence since it is a snapshot of many LI
gs at various separations. Nevertheless, this star formation rate, deduced from the observed depletion of molecular gas, is similar to that inferred from \( L_{\text{IR}} \) (under the assumption that the IR luminosity is from embedded high-mass stars): about \( 100 \) \( M_{\odot} \) yr\(^{-1}\) for \( L_{\text{IR}} \approx 5 \times 10^{10} L_{\odot} \) (see, e.g., Sanders & Mirabel 1996).

At the extreme end of the merger sequence are ULIGs with small separations or no evidence of two remaining nuclei, which have very compact gas concentrations and about 5 times more \( L_{\text{IR}} \) than LI
gs. Most of the molecular gas in ULIGs is concentrated in the central 1 kpc and is not in normal GMCs; the translation of \( L_{\text{CO}} \) to molecular gas mass is fundamentally different (S97; D98), and the molecular gas mass is lower than expected from use of a standard conversion factor. Never
evertheless, ULIGs still have close to \( 10^9 M_{\odot} \) molecular gas. Even allowing for this, ULIGs do not follow the correlations we find for LI
gs (Fig. 2). The difference may be due to the different physical parameters of the starbursts. The starbursts in ULIGs appear to take place predominantly in extreme starburst regions of \( \sim 200 \) pc size and \( L_{\text{IR}} \sim 3 \times 10^{11} L_{\odot} \) (D98),

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\text{Fig. 1.---A representation of the CO observations made with the NRAO 12 m telescope (the 55" FWHM beam is indicated). The vertical scale of the CO spectra is the antenna temperature } T_A \text{ in millikelvins, and the horizontal axis is the redshift in units of km s}^{-1}. \text{The total CO luminosity in NGC 6670 is } \sim 70\% \text{ of the sum of the two beam measurements.}
\]
Fig. 2.—(a) CO luminosity vs. $S_{\text{sep}}$ for 50 LIG mergers. A strong correlation holds for the less luminous LIGs ($L_{\text{CO}} \leq 10^{12} L_{\odot}$, filled circles with line fit), which resemble the volume-limited complete sample, whereas no correlation holds for the ultraluminous ones (ULIGs, open circles). (b) No correlation holds between $L_{\text{IR}}$ and $S_{\text{sep}}$ for either ULIGs or LIGs. (c) The anticorrelation between $L_{\text{IR}}/M(\text{H}_2)$, the measure of star formation efficiency, and $S_{\text{sep}}$ suggests the enhanced star formation efficiency of late-stage mergers. We use the same conversion factor from $L_{\text{CO}}$ to molecular gas mass even though there is evidence that ULIGs require a smaller conversion factor ($S97$; $D98$). The fit is for LIGs.

with substantial velocity structure characterized by rotation or barlike motion. They are the primary sources of the millimeter continuum, with more than 1000 mag of visual extinction. For example, Arp 220 has two extreme starburst regions. These may be the remnants of nuclei or condensations in the gas, but they now are composed almost entirely of gas and young stars. Active galactic nuclei might also contribute to $L_{\text{IR}}$ in some ULIGs (see, e.g., Veilleux, Sanders, & Kim 1997).

Mihos & Hernquist (1996) have predicted the star formation rate and the gas depletion during a merger sequence in two extreme cases: galaxies with bulges and those without (see their Fig. 5). The decrease in molecular gas mass in our sample (Fig. 2a) is consistent with their model prediction (especially when ULIGs are excluded) for a diverse group of initial conditions and bulge/disk ratios. In the models, only mergers with bulges have enough gas left for a final extreme burst, as in ULIGs.

The models failed to predict the gas concentration in the overlap region, either atomic gas in early mergers, e.g., NGC 6670 (Wang et al. 1998), or molecular gas in intermediate mergers, e.g., Arp 244 and Arp 299 (Gao et al. 1998, 1999b; Aalto et al. 1997). Although gas inflow into the center in late mergers is predicted (Mihos & Hernquist 1996; Barnes & Hernquist 1996), this is near the final merging ($S_{\text{sep}} \leq 3$ kpc). Successful models should distinguish between diffuse atomic gas and molecular gas in GMCs and should produce this feature when galaxies are still 5–15 kpc apart. Star formation in the overlap region is predicted in a model by the compression of preexisting GMCs, which is due to the heating of the atomic interstellar medium by shocks (Jog & Solomon 1992). Preexisting GMCs are clearly the source of star formation even before the true merging of the disks, as is evident in Arp 302.

5. CONCLUDING REMARKS

We show here that there is a strong correlation between CO luminosity, a measure of $M(\text{H}_2)$, and the projected separation for LIGs. Although there is no correlation between the star formation rate ($L_{\text{IR}}$) and separation, LIGs with smaller separation have a higher star formation rate per solar mass of molecular gas. This increase in star formation efficiency is due to the increased molecular gas surface density. Advanced mergers have less molecular gas mass (not more) than when the mergers started. This implies that the starburst is not fueled by a large inflow of a huge mass of diffuse atomic gas from large galactic radii converting to molecular gas but rather that existing GMCs form stars throughout the merging process over a few hundred million years.

Although the correlations are robust for LIGs, they do not exist for ULIGs. The difference may be due to the different physical parameters and timescales of the starbursts. The starbursts in ULIGs appear to take place predominantly in extreme starburst regions with radii $\sim 100$ pc, $\sim 10^6 M_{\odot}$ molecular gas, $L_{\text{IR}} \sim 3 \times 10^{11} L_{\odot}$, and a very high star formation efficiency ($D98$). The dynamical timescales in extreme starbursts are characterized by only about a million years ($V \sim 250$ km s$^{-1}$ and a size of $\sim 200$ pc).

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