THE ASTROPHYSICAL JOURNAL, 490:166–172, 1997 November 20

NONLINEAR DEPENDENCE OF L_B ON $L_{\rm FIR}$ AND $M_{\rm H_2}$ AMONG SPIRAL GALAXIES AND THE EFFECTS OF TIDAL INTERACTION

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Received 1997 April 18; accepted 1997 July 2

ABSTRACT

Through the study of a carefully selected sample of isolated spiral galaxies, we have established that two important global physical quantities for tracing star-forming activities, $L_{\rm FIR}$ and $M_{\rm H_2}$, have a nonlinear dependence on another commonly cited global quantity, L_B. Furthermore, we show that simple power-law relations can effectively describe these nonlinear relations for spiral galaxies spanning 4 orders of magnitude in FIR and $M_{\rm H_2}$, and nearly 3 orders of magnitude in L_B. While the existence of a nonlinear dependence of $M_{\rm H_2}$ (assuming a constant CO-to-H_2 conversion) and $L_{\rm FIR}$ on optical luminosity (L_B) has been previously noted in the literature, an improper normalization consisting of simple scaling by L_B has been commonly used in many previous studies to claim enhanced molecular gas content and induced activity among tidally interacting and other types of galaxies. We remove these nonlinear effects using the template relations derived from an isolated galaxy sample and conclude that *strongly interacting galaxies do not have enhanced molecular gas content*, contrary to previous claims. With these nonlinear relations among L_B, $L_{\rm FIR}$, and $M_{\rm H_2}$ properly taken into account, we confirm again that FIR emission and star formation efficiency ($L_{\rm FIR}/M_{\rm H_2}$) are indeed enhanced by tidal interactions. Virgo galaxies show the same levels of $M_{\rm H_2}$ and $L_{\rm FIR}$ as isolated galaxies. We do not find any evidence for enhanced star-forming activity among barred galaxies.

Subject headings: galaxies: fundamental parameters — galaxies: interactions — galaxies: ISM — galaxies: photometry — infrared: galaxies — radio lines: galaxies

1. INTRODUCTION

Molecular gas (H_2) and far-infrared (FIR) quantities are important for analyzing the star formation activity in galaxies. They have been analyzed in the literature for different galaxy samples (Young & Scoville 1991 and references therein; Sofue et al. 1993; Braine & Combes 1993; Young et al. 1996; Solomon et al. 1997), although largely among IR-luminous galaxies. These two quantities correlate linearly, assuming a constant CO-to-H_2 conversion factor, and massive star formation within molecular clouds is sufficient to explain the observed trend in most cases. On the other hand, several authors have noted that these quantities do *not* correlate linearly with the total blue luminosity (L_B), in the sense that $M_{\rm H_2}/L_B$ and $L_{\rm FIR}/L_B$ increase with increasing L_B (Young 1987; Young et al. 1989; Sage & Solomon 1989). Nevertheless, a simple normalization using L_B has been commonly used to claim enhanced activities among different groups of galaxies (e.g., Braine & Combes 1993; Combes et al. 1994; Devereux & Hameed 1997), while what they have actually shown is this residual dependence on the luminosity. In this paper, we first examine the nature of nonlinearity involving L_B, and then reexamine the previous claims of enhanced molecular gas content and star-forming activity based on the normalization by L_B. We show here that the enhanced molecular gas content among bright interacting galaxies reported in the literature is entirely due to the nonlinear effect, but that the excess in the FIR emission is real and largely due to real enhancement induced by environmental effects.

We have compiled from the literature an extensive comparison sample of 207 galaxies of varying interaction classes and environments (isolated, weakly perturbed, strongly perturbed, Virgo cluster), representing a wide range of optical luminosity ($10^{8.6}\ L_\odot < L_B < 10^{11.4}\ L_\odot$), and for which FIR, CO, and optical luminosity (as measured by the blue luminosities L_B) are available. The FIR luminosity is obtained as $\log (L_{\rm FIR}/L_\odot) = \log {\rm FIR} + 2 \log D + 19.495$, where D is the distance in Mpc and ${\rm FIR} = 1.26 \times 10^{-14} \times (2.58 I_{60} + I_{100})$ W m^{-2} (Helou et al. 1988). The 60 μm and 100 μm fluxes are obtained from the NED database.[2] The molecular hydrogen mass is derived as $M_{\rm H_2} = 4.82 \alpha I_{\rm CO} d_B^2\ M_\odot$, assuming a constant CO-to-H_2 conversion factor of $\alpha = N_{\rm H_2}/I_{\rm CO} = 3 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$, where $I_{\rm CO}$ is the velocity-integrated CO intensity in K km s^{-1} and d_B is the half-power beam diameter in pc at the source distance (Sanders, Scoville, & Soifer 1991). The use of a constant conversion factor is discussed further in § 2. Because many nearby galaxies typically subtend several arcminutes in size and are much larger than the beam of the telescopes used, the comparison data consist mostly of the CO surveys using at least partial mapping. The optical luminosity is derived from the B_T^0 magnitude from the RC3 catalogue, corrected for Galactic absorption (using the extinction value given by Burstein & Heiles 1984, with the reddening law from Savage & Mathis 1979) and internal extinction (de Vaucouleurs et

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[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

[2] The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

al. 1991; RC3) using the redshift given in NED. We adopt a value for the Hubble constant of $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. RELATIONSHIP AMONG L_B, $L_{\rm FIR}$, AND $M_{\rm H_2}$ FOR ISOLATED GALAXIES

In order to first understand the intrinsic nonlinear nature of L_B with respect to FIR luminosity and molecular gas content, we have assembled from the literature a reference sample of isolated galaxies representing a wide range of luminosities, extending from $L_B = 10^{8.6}$ to $10^{10.9}$ $L_\odot$. Our isolated galaxy sample consists of 68 objects from the distance-limited survey of the Nearby Galaxies Catalog (Tully 1988) of Sage (1993) and the class 0 objects of the *IRAS*-selected sample of Solomon & Sage (1988). For six galaxies, only upper limits on the CO luminosity are available. Morphological types range from Sa to Sd galaxies, each distributed along the entire luminosity range; types around Sc are the most abundant. This sample lacks completeness because the galaxies studied in the literature are frequently biased toward IR-luminous galaxies. However, our isolated galaxy sample is sufficient for this comparison study, since the range of optical luminosities present in other comparison samples are basically included.

In Figure 1*a*, we plot L_B against $M_{\rm H_2}$ for this sample. The data can be well described by a simple power law relation,

$$\log L_B = (0.57 \pm 0.03) \log M_{\rm H_2} + (4.9 \pm 0.6) . \qquad (1)$$

The coefficients are determined by a linear regression, taking the upper limits into account using the Astronomy Survival Analysis package (ASURV).[3] We do not find any dependence on morphological type. Sage & Solomon (1989) report a slope of 0.53 ± 0.07 for a sample of isolated and weakly perturbed galaxies, and Young et al. (1989) find a slope of 0.72 ± 0.03 for a sample of 124 galaxies with CO data. Removing the five nearby dwarf galaxies with lowest luminosities ($L_B < 7 \times 10^7$ $L_\odot$), which clearly separate from the overall tendency, we find a slope of 0.54 for the Young et al. (1989) sample, consistent with our result.

In Figure 1*b* we plot $L_{\rm FIR}$ against $M_{\rm H_2}$, which ratio is a measure of the star formation efficiency (SFE) (see Young & Scoville 1991). This correlation has been widely considered in the literature and found to be nearly linear when a large range of luminosities are considered, i.e.,

$$\log L_{\rm FIR} = (0.90 \pm 0.05) \log M_{\rm H_2} + (1.5 \pm 0.4) , \qquad (2)$$

with a dispersion similar to that of the L_B-$M_{\rm H_2}$ relation.

These plots demonstrate that L_B increases more slowly than the molecular gas content (for a constant CO-to-H_2 conversion factor) and FIR luminosity, and more importantly, that these nonlinear dependencies are present even among carefully selected isolated spirals. While the physical cause for the observed nonlinear relations is uncertain, it is possible that the physical mechanisms responsible for the FIR and CO ($M_{\rm H_2}$) emissions may be closely related, but distinct in nature from optical emission. For ease of the subsequent discussion, we have parameterized these empirical nonlinear relations in terms of $M_{\rm H_2}$, but we do not claim that $M_{\rm H_2}$ (or any of the three physical quantities compared here) is the fundamental driver.

If one postulates that the root of the nonlinear relations shown in equations (1) and (2) lies in the FIR and CO emissions, then an obvious possible cause is the metallicity dependence on the luminosity. In fact, a positive correlation between metallicity and absolute magnitude has been obtained by Roberts & Haynes (1994) for a large sample of spiral galaxies, and Arimoto, Sofue, & Tsujimoto. (1996) have proposed an empirical dependence between CO-to-H_2 conversion and absolute magnitude based on their observational data and the CO emission model of Sakamoto (1996). Indeed, there are clear indications that the CO intensity may not be a good tracer of the molecular content

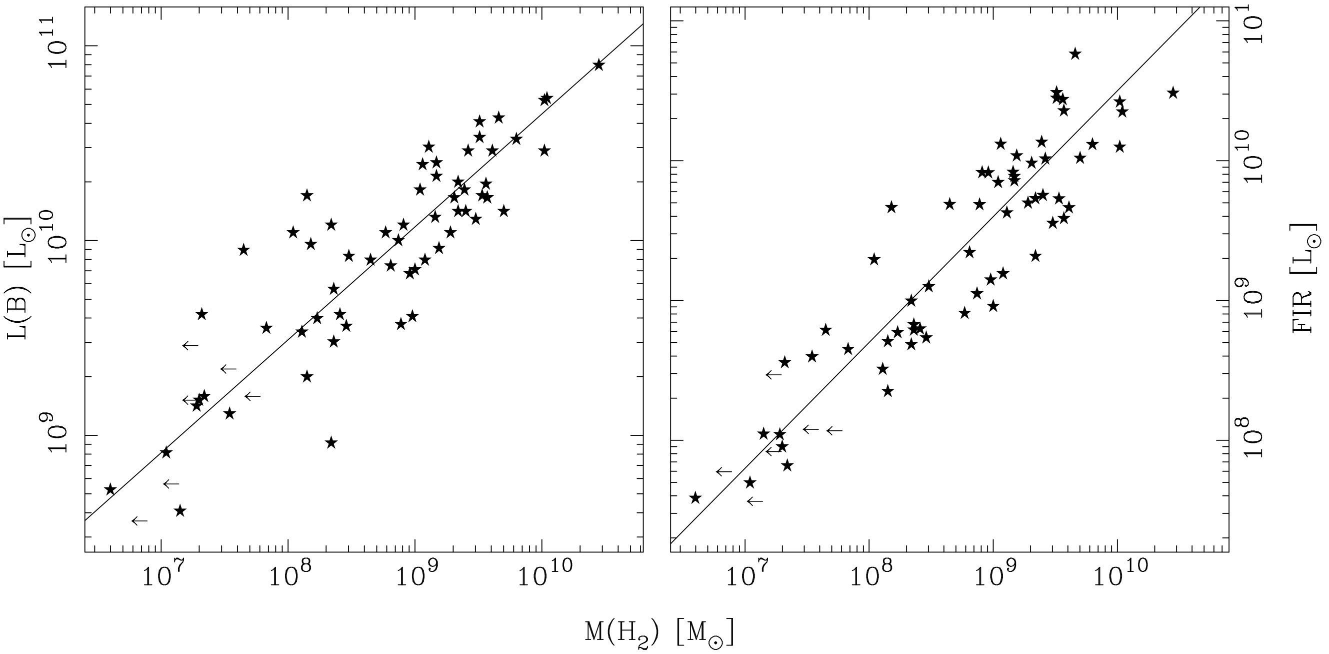

FIG. 1.—Dependence of L_B and $L_{\rm FIR}$ on $M_{\rm H_2}$ for the isolated galaxy sample. The solid lines correspond to the fitted power law given in eq. (1).

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[3] Astronomy Survival Analysis (ASURV) Rev 1.2 package is a generalized statistical analysis package that implements the methods presented by Feigelson & Nelson (1985) and Isobe, Feigelson, & Nelson (1986), and described in detail in Isobe & Feigelson (1990) and La Valley, Isobe, & Feigelson (1992).

among metal-poor galaxies (Cohen et al. 1988; Rubio et al. 1991). Also, the nonlinear dependence in equation (1) is nearly reproduced by the metallicity dependence derived by Roberts & Haynes if the CO emission is assumed to depend linearly on the metallicity. However, there are observational and theoretical reasons to believe that such a metallicity dependence cannot work. For example, the observational evidence for metallicity dependence offered by Arimoto et al. becomes marginal if the low spatial resolution data on M51 and LMC are removed. Also, full chemical and radiative transfer modeling of CO emission by Wolfire, Hollenbach, & Tielens (1993) and Maloney & Wolfire (1997) suggests that CO emission is a robust tracer of M_{H_2} against metallicity variation; no metallicity dependence is expected until the metal abundance becomes low enough to make the CO transition optically thin.

Alternatively, if the nonlinear relations derived above are rooted in L_B, then optical extinction and scattering models may offer an explanation. A naive expectation is that larger extinction in more massive galaxies with larger dust column densities would result in a slower increase in L_B with size (e.g., Young et al. 1989). Buat & Xu (1996) also find a good correlation between the optical depth in B and the ratio of FIR to blue luminosity. Therefore, it is natural to suspect that the root of the observed nonlinearity may lie with L_B rather than with L_{FIR} or M_{H_2}.

In a simple geometrical extinction model in which optically thick tracers such as blue light represent surface area and optically thin tracers such as FIR and integrated CO intensity represent volume elements, a nonlinear dependence is naturally expected between these two classes of tracers; i.e., $L_B \propto (M_{\mathrm{H}_2})^{2/3}$ for a spherical uniform cloud. In reality, the structure of the ISM is more complex and clumpy or filamented, and the effective optical depth is significantly reduced by extinction geometry and efficient scattering compared to a uniform screen model (Witt, Thronson, & Capuano 1992; Witt & Gordon 1996). Nevertheless, it is remarkable that the nonlinear relation between L_B and M_{H_2} is observed with nearly the same power-law dependence as predicted by this simple model, and one may infer that the basic assumptions of the model stated above must hold at clump–interclump size scales. We note that the predicted exponent of 2/3 is independent of the cloud shape as long as the cloud structure remains self-similar at different size scales.

The extinction model also correctly predicts other optical depth–dependent trends. For example, the exponent of the correlation between L_B and L_{FIR} is expected to be *steeper* than that of L_B-M_{H_2} because the additional surface element provided by H I among the low-luminosity galaxies is partly compensated in FIR by the dust emission associated with the H I gas. A formal fit for the L_B-L_{FIR} relation in our isolated galaxy sample gives

$$\log L_B = (0.65 \pm 0.09) \log L_{\mathrm{FIR}} + (3.9 \pm 0.9) , \qquad (3)$$

and the slope of the correlation is indeed larger than that of L_B-M_{H_2} (0.57 ± 0.03). We predict that the optical luminosity at longer wavelengths (L_H or L_K) would produce a more linear relationship with M_{H_2} than L_B.

3. REEVALUATION OF THE TIDAL AND ENVIRONMENTAL EFFECTS

Regardless of their physical causes, two global physical quantities, L_{FIR} and M_{H_2}, clearly show nonlinear dependence with respect to L_B among a large sample of isolated galaxies. The relations are well described by a simple power law spanning 4 orders of magnitude in L_{FIR} and M_{H_2} and nearly 3 orders of magnitude in L_B (see § 2). Therefore, any comparison of L_{FIR} and M_{H_2} normalized simply by L_B produces a misleading result. This is particularly true for the studies of bright interacting galaxies found in the literature in which the samples are selected based on their high luminosities. Here we reevaluate the impact of tidal and environmental effects on individual galaxies by examining their global properties using the empirical relations derived from our isolated galaxy sample as templates in order to discriminate size-dependent effects from environmentally induced effects. Deviations from the template power laws (eqs. [1] and [2]) are evaluated below for galaxies suffering different degrees of interaction. We also examine whether the presence of a bar correlates with any enhancement in the star formation efficiency. While each subsample analyzed here represents a different range of luminosities with a different mean luminosity, almost the entire range of optical luminosities considered is represented in our isolated galaxy sample, and the use of these template relations is justified.

The FIR and CO data available in the literature are severely sensitivity limited, and special care has to be taken to incorporate the upper limits properly in the analysis. Standard statistical tests such as Kolmogorov-Smirnov (KS) or Mann-Whitney cannot be rigorously applied to these heavily censored data, and we instead use equivalent tests provided by ASURV. In particular, to quantify the statistical probability of the compared samples representing the same distribution function, we use the log rank and Peto-Prentice generalized Wilcoxon tests, which are known to be the most robust against the censoring pattern.

3.1. *Interacting and Cluster Galaxies*

The entire sample studied here consists of 139 galaxies, divided into three subclasses: weakly perturbed (WP), strongly perturbed (SP), and Virgo Cluster (VC) galaxies. The WP sample has 43 galaxies, including classes 1, 2, and 3 of Solomon & Sage (1988) and class 2 objects from the luminous *IRAS* sample of Sanders et al. (1991). The SP sample has 38 galaxies, including interaction class 4 of Solomon & Sage (1988), interaction classes 3 and 4 of Sanders et al. (1991), and closely interacting pairs from Combes et al. (1994). The definitions of "weakly perturbed" and "strongly perturbed" are given in the references listed above, SP galaxies being identified as those in the final stages of mergers. In addition, we have constructed a sample composed of 58 member galaxies in the Virgo cluster, including both bright (Kenney & Young 1988a, 1988b) and faint spirals (Boselli, Casoli, & Lequeux 1995). In the SP and VC samples, 3 and 18 galaxies, respectively, have only upper limits in CO.

In Figure 2, we plot M_{H_2} against L_B for the VC, WP, and SP samples, along with a solid line representing the power law derived from our isolated galaxies sample (eq. [1]). We have analyzed the residuals of each subsample with respect to the isolated galaxies template, and none of the three subsamples can be distinguished from the isolated galaxy template. In Table 1, we summarize the median values of the residuals and the semi-interquartile distances that measure the dispersion of the distribution. The deviation of the residuals from zero value are statistically negligible, and

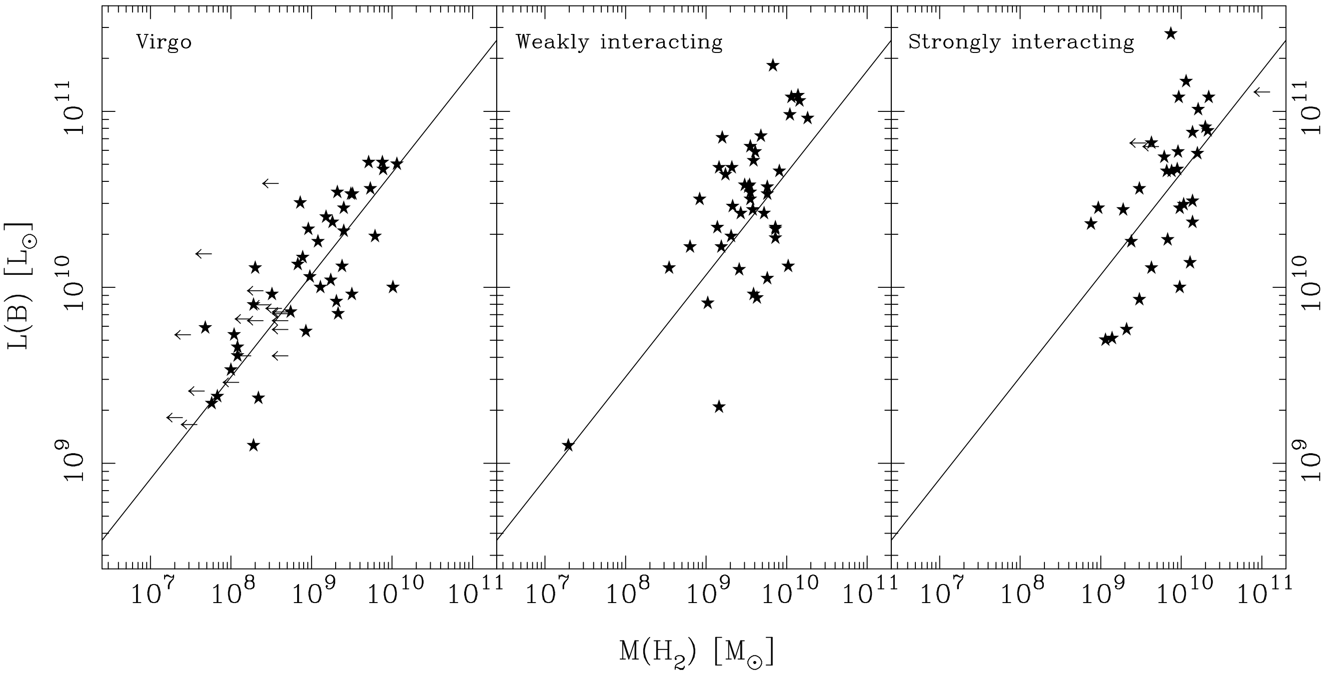

FIG. 2.—Dependence of L_B on M_{H_2} for the three samples of interacting galaxies. The plotted line corresponds to the template power law derived from the isolated galaxies.

this fact indicates that neither the optical luminosity *nor the molecular gas content* as measured in CO are significantly affected by tidal interactions. This contradicts the previous reports of enhanced molecular gas content among strongly interacting pairs (Braine & Combes 1993; Combes et al. 1994). Virgo spirals show a gas content similar to isolated galaxies, as has been previously suggested (see Boselli 1994 and references therein).

The relation between L_{FIR} and M_{H_2} is plotted in Figure 3 for the three subsamples, along with the power-law relation obtained from the isolated galaxy sample. While the Virgo spirals and WP sample galaxies follow the same L_{FIR}-M_{H_2} relation as the isolated galaxy sample, the SP sample galaxies show a clear deviation: enhanced FIR emission for given molecular gas content, already known in the literature as the increased star formation efficiency ratio (L_{FIR}/M_{H_2}; e.g., Sanders et al. 1991). The FIR luminosity of the SP sample galaxies lies mostly within the range covered by the isolated galaxy sample, but the SP sample extends to a higher FIR luminosity and has a higher mean FIR luminosity than the isolated sample, requiring some extrapolation of equations (1) and (2). We note, however, that the ranges of M_{H_2} and L_B covered by the SP and isolated comparison samples are the same, clearly indicating that the FIR emission is enhanced among the SP sample galaxies. We have improved our understanding of the L_{FIR}/M_{H_2} ratio by properly accounting for the strong nonlinear luminosity dependence, whereas previous studies of the L_{FIR}/M_{H_2} ratio were performed with an assumption of no luminosity dependence, despite claims of enhanced molecular gas content in some cases.

Since we have shown that H_2 content is independent of tidal disruption and environment, any deviations from the template will indicate changes in the FIR emission. In Table 2 we summarize the statistics and probability of association in the L_{FIR}/M_{H_2} distribution for the VC, WP, and SP samples with respect to the isolated galaxy sample. A zero value for the probability indicates that the compared distributions are statistically different from the isolated galaxy sample. Also included in Table 2 are the median and semi-interquartile distance of log (L_{FIR}/M_{H_2}) for all the samples as obtained from the cumulative distribution functions. All of the statistical tests performed indicate large differences in

TABLE 1

STATISTICAL PARAMETERS OF THE RESIDUALS RELATIVE TO THE M_{H_2}-L_B TEMPLATE OBTAINED FROM ISOLATED GALAXIES

Sample	Median	Q[a]
Isolated	0.043	0.17
Weakly perturbed.......	0.204	0.21
Strongly perturbed......	0.101	0.27
Virgo cluster............	0.197	0.14

[a] Semi-interquartile distance. For a normal distribution, $\sigma = 3/2$ Q.

TABLE 2

STATISTICAL PARAMETERS OF log (L_{FIR} /M_{H_2}) DISTRIBUTION

Parameter	Isolated	Virgo	Weakly Perturbed	Strongly Perturbed
log rank statistic	...	1.103	2.193	5.769
Probability...........	...	0.270	0.028	0.000
Peto-Prentice..........	...	0.191	1.889	6.457
Probability...........	...	0.848	0.059	0.000
Median	0.633	0.583	0.737	1.171
Semi-interquartile......	0.287	0.404	0.279	0.184

NOTE.—Distribution for the studied samples as compared with the isolated galaxies template (from the Astronomy Survival Analysis package).

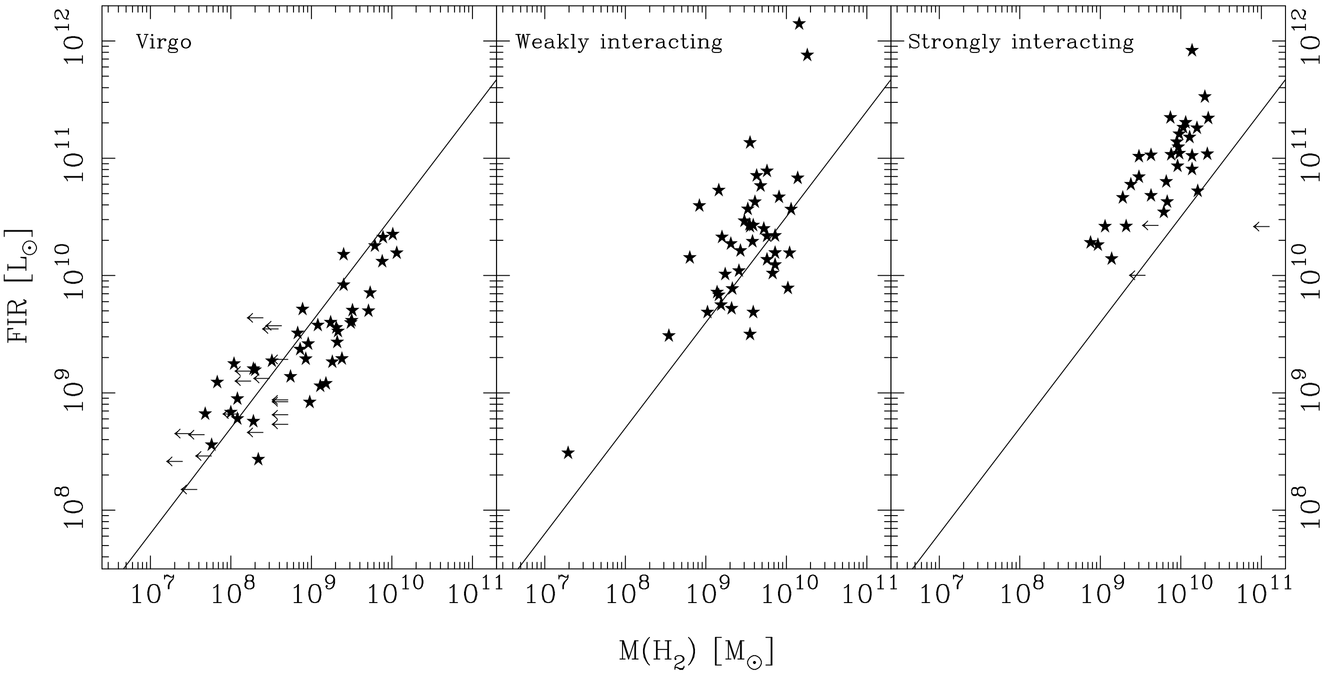

FIG. 3.—Dependence of $L_{\rm FIR}$ on $M_{\rm H_2}$ for the interacting galaxy sample

the distribution of the SP galaxies with respect to the isolated galaxies, as is clearly shown in Figure 3. The VC galaxies show a $L_{\rm FIR}$-$M_{\rm H_2}$ distribution very similar to that of the isolated galaxies, as indicated by the similarity of their median values and by high statistical likelihood.

An evident result is that the star formation efficiency in the SP sample is enhanced on average by a factor of 3.5 over the isolated galaxy sample, consistent with the results in the literature (Sanders et al. 1986; Solomon & Sage 1988; Young & Scoville 1991), even when various nonlinear dependencies are properly accounted for (the probability of the SP sample having the same distribution as the isolated sample being zero). Our new analysis also removes any uncertainty regarding variations in $M_{\rm H_2}$ as a function of interaction strength (thus affecting the $L_{\rm FIR}/M_{\rm H_2}$ ratio), since no such variation is found. The weakly interacting systems

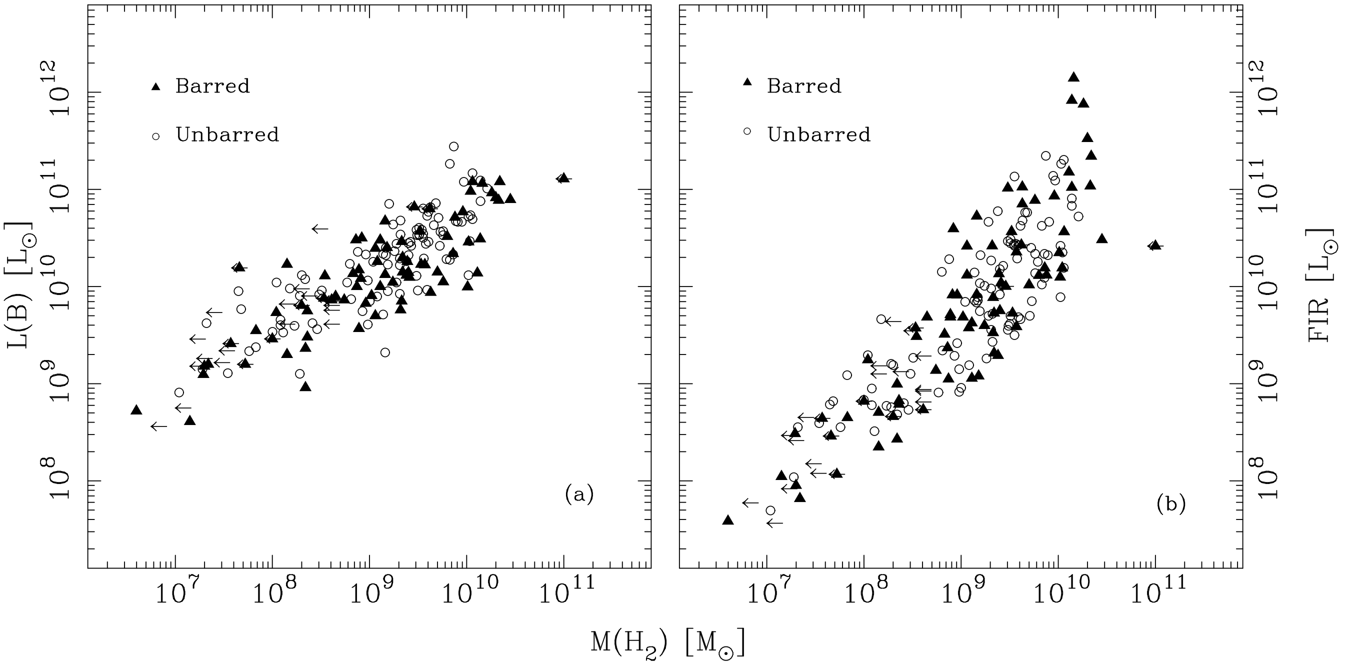

FIG. 4.—Dependence of L_B and $L_{\rm FIR}$ on $M_{\rm H_2}$ for all galaxies in our sample, separated by barred and unbarred morphology

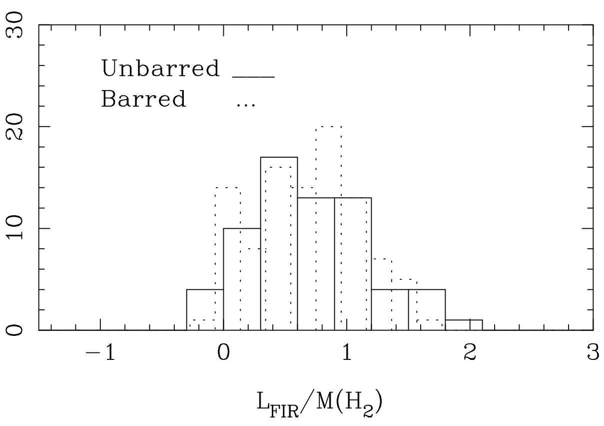

FIG. 5.—Histogram of the star formation efficiency measured by L_{FIR}/M_{H_2} for our full sample, divided into barred and unbarred galaxies.

show some marginal excess in SFE (30%, well within 1 σ). This is understandable, since observational separation between weak and strong interactions is not always straightforward, and some contamination exists between the two samples.

3.2. *Barred and Unbarred Galaxies*

Out of 196 galaxies in our sample with morphological classification listed in NED, 117 are classified as barred (38 isolated, 28 WP, 13 SP, and 38 VC) and 79 as unbarred (30 isolated, 15 WP, 14 SP, and 20 VC). The same analysis is now performed for the barred versus unbarred galaxies in order to test the previous claims that enhanced star-forming activity is associated with barred spirals (e.g., Young 1992).

In Figure 4*a* we plot L_B against M_{H_2} for the barred and unbarred galaxies; no clear difference is seen between them, indicating that the total molecular mass is independent of their barred morphology. In fact, L_B distributions of barred and unbarred galaxies are found to be indistinguishable by the various statistical tests applied. The same conclusion is drawn for their M_{H_2} distributions ($\langle \log L_B \rangle_{\rm bar} = 10.231$, $\langle \log L_B \rangle_{\rm unbar} = 10.110$; $\langle \log M_{H_2} \rangle_{\rm bar} = 9.195$, $\langle \log M_{H_2} \rangle_{\rm unbar} = 9.110$).

We have also looked for any differences in the L_{FIR}-M_{H_2} distribution as shown in Figure 4*b*. Again, the data overlap, and the FIR emission of barred and unbarred galaxies is found to be indistinguishable by the statistical tests performed ($\langle \log L_{FIR} \rangle_{\rm bar} = 9.691$, $\langle \log L_{FIR} \rangle_{\rm unbar} = 9.687$). Thus, the star formation efficiency seems independent of the barred morphology, as shown in the histogram of the ratio L_{FIR}/M_{H_2} in Figure 5. The median values are $(L_{FIR}/M_{H_2})_{\rm unbar} = 0.69$ ($\sigma = 1.59$) and $(L_{FIR}/M_{H_2})_{\rm bar} = 0.76$ ($\sigma = 1.58$), respectively. Since bar morphology and starburst activity are sometimes associated with tidal interactions, this result may indicate that the lifetime of a stellar bar, if transient, is much longer than the timescale for a starburst.

4. CONCLUSIONS

Through the study of a carefully selected sample of isolated spiral galaxies, we have clearly established that the two important global physical quantities for tracing star-forming activities, L_{FIR} and M_{H_2}, have a nonlinear dependence on another commonly cited global quantity, L_B. Furthermore, we show that simple power-law relations can effectively describe these nonlinear relations for spiral galaxies spanning 4 orders of magnitude in FIR and M_{H_2} and nearly 3 orders of magnitude in L_B. These nonlinear relations are critically important in comparing different samples of galaxies, since a simple normalization and the resulting residual dependence would imply that samples consisting of the more luminous galaxies would show intrinsically larger ratios. Using the nonlinear template relations obtained from the isolated galaxy sample, we have reanalyzed previous claims of enhanced molecular gas content and star formation through tidal interactions. We have also examined the effect of the cluster environment and the presence of stellar bars on the H_2 content and on any enhancement of star formation activity.

In the frame defined by the optical luminosity, molecular gas content, and FIR luminosity, we found that gravitational interaction affects only the FIR emission. We found no evidence for enhanced molecular gas content among the interacting galaxies, and we conclude that the previous claims for this phenomenon are a result of using a size normalization based on L_B without properly accounting for the nonlinear dependence. We do confirm that enhanced FIR emission (star formation) by tidal interaction is real. We found no evidence for enhanced star formation among barred galaxies in comparison with the unbarred galaxies.

The authors thank N. Scoville, P. Solomon, and J. Sulentic for useful discussions. J. P., A. O., and L. V.-M. are partially supported by DGICYT (Spain) Grant PB 93-0159 and Junta de Andalucía (Spain). M. S. Y. is supported by the NRAO Jansky Research Fellowship.

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