THE RATIO OF MOLECULAR TO ATOMIC GAS IN INFRARED LUMINOUS GALAXIES

I. F. MIRABEL
California Institute of Technology; and Department of Physics, University of Puerto Rico

AND

D. B. SANDERS
Division of Physics, Mathematics, and Astronomy, California Institute of Technology

Received 1988 December 6; accepted 1989 February 22

ABSTRACT

In infrared luminous galaxies, the ratio of the CO(1 → 0) to H I integrated fluxes increases with the far-infrared excess, $f_{\text{far}}/f_{\text{ir}}$. All infrared active galaxies with $f_{\text{far}}/f_{\text{ir}} \geq 2$ have molecular to atomic gas mass fractions $\geq 0.5$. Among the galaxies with the higher infrared excesses there are systems with strikingly small atomic mass fractions, where less than 15% of the total mass of interstellar gas is in atomic form. The optical morphology of luminous infrared galaxies indicates that the majority, if not all, of these objects are interacting systems. Our observations suggest that the overall mass fraction of molecular to atomic gas, and the infrared luminosities per nucleon of interstellar gas are enhanced during galaxy-galaxy interactions.

Subject headings: galaxies: general — galaxies: interactions — interstellar: molecules

I. INTRODUCTION

It is commonly understood that tidal interactions alter the overall stellar distributions of galaxies (e.g., Toomre and Toomre 1972); however, it is still not well known what happens to the distribution and form (H$_2$, H I, H II) of the interstellar gas in interacting systems. The scarcity of high-sensitivity data to measure the gas content, and the lack of a quantitative method to measure the degree of interaction between galaxies, have both contributed to the limited progress in this field.

In this Letter we investigate the relations between the CO(1 → 0) and H I line fluxes as a function of the far-infrared (FIR) and blue luminosities, using a sample of galaxies that covers two orders of magnitude in intrinsic FIR luminosity ($2 \times 10^{11}$ $L_\odot$ to $2 \times 10^{12}$ $L_\odot$), namely, from galaxies with FIR luminosities comparable to that of the Milky Way on the lower end, up to galaxies with FIR luminosities comparable to the bolometric luminosities of quasars. The galaxies were selected from the IRAS bright galaxy sample of Soifer et al. (1987), and the atomic and molecular components were determined using two large and homogeneous surveys: one in H I conducted at Arecibo by Mirabel and Sanders (1988), the other in CO (1 → 0) carried out with the 12 m NRAO and 14 m FCRAO antennas by Sanders and Mirabel (1985) and Sanders et al. (1987, 1988b). In the present study we consider only the 26 galaxies included in both surveys. A full description and explanation of the data base can be found in the survey publications.

The data base used in this work has two virtues: (1) the 26 galaxies of this sample are unresolved by the telescope beams used for the observations at 21 cm and 2.6 mm, implying that our single-dish observations measure the total H I and CO flux, and (2) all the H I and CO data come from two homogeneous surveys, implying that systematic errors in the calibrations or flux-to-mass conversion factors can be easily corrected a posteriori.

II. THE MOLECULAR TO ATOMIC GAS RATIO

To study the relation between the atomic and molecular phases of the interstellar gas with the FIR excess we have plotted in Figure 1a the ratios of the integrated CO(1 → 0) and H I fluxes in units of Jy km s$^{-1}$ (assuming a sensitivity of 33 Jy K$^{-1}$ for the 2.6 mm observations at Kitt Peak). The masses of H I and H$_2$ were taken from Mirabel and Sanders (1988) and Sanders et al. (1988b), respectively. The FIR excess is defined as the ratio between the measured FIR flux, $f_{\text{fir}}$, and the blue flux, $f_{\text{b}}$, derived from the blue magnitudes, in units of W m$^{-2}$. As explained by Mirabel and Sanders (1988), $f_{\text{fir}}$ is an estimate of the total flux between 40 $\mu$m and 400 $\mu$m. The blue flux $f_{\text{b}} \equiv vF_v (0.43 \mu$m) in units of W m$^{-2}$ was computed from the relation $f_{\text{b}} \equiv vF_v = 3.106 \times 10^{-8} \times (2.51)^{-m} (W m^{-2})$, where $n$ is the $B_2$ magnitude corrected for galactic extinction (de Vaucouleurs, de Vaucouleurs, and Corwin 1976).

In addition to the program galaxies, Figure 1a also presents data for the Milky Way and the “Antennae” (NGC 4038/9) which is often considered to be the prototype of interacting galaxies. The arrows pointing downward correspond to galaxies with H I emission-absorption profiles. For those galaxies whose profiles are dominated by absorption, it is only possible to derive lower limits for the mass of atomic gas from the observed H I emission. However, for the galaxies NGC 7674, NGC 7469, and Mrk 331, which have profiles dominated by emission with relatively narrow absorption features, a reasonable upper limit for the H I emission flux can be obtained by extrapolating across the absorption feature, and therefore a range of I(CO)/I(H I) is indicated. The arrows pointing upward for the galaxies IC 4553 (= Arp 220) and IRAS 10173+0828 indicate that upper limits for the H I mass have been determined for these two galaxies. From VLA-C and VLA-A observations, Baan et al. (1987) found that the total mass of H I in IC 4553 must be lower than 4.5 x 10$^5$ $M_\odot$. An even more stringent upper limit of 10$^4$ $M_\odot$ of H I was obtained.
have $M(H_2)/M(H\ i) \leq 0.5$. Therefore, it seems that a relatively large molecular gas mass fraction is associated with a significant infrared excess, implying that the enhanced infrared activity in this sample of galaxies is more tightly associated with the molecular gas (e.g., Sanders and Mirabel 1985), rather than with the atomic gas (Mirabel and Sanders 1988). The trend in Figure 1a has a correlation coefficient of 0.83 and can be represented in analytical form by the equation

$$M(H_2)/M(H\ i) = 0.16 \left( f_{\text{IR}}/f_b \right)^{1.18}.$$  

(1)

III. THE INFRARED LUMINOSITY PER NUCLEON OF INTERSTELLAR GAS

In Figure 1b we plot the ratio of FIR flux to the sum of the spectral line fluxes [$f_{\text{CO}} + 10^4 f(H\ i)$], versus the FIR excess for 28 galaxies, including the Milky Way and the “Antennae.” Assuming a linear relation between CO luminosity and $M(H_2)$ (see § IV), the overall FIR flux per unit mass of interstellar gas has a wide range of values, from $3 L_\odot M_\odot^{-1}$ to $50 L_\odot M_\odot^{-1}$. The most luminous infrared galaxies have larger $L_{\text{FIR}}/[M(H_2) + M(H\ i)]$ ratios than isolated spirals ($1-3 L_\odot M_\odot^{-1}$) and starburst galaxies ($5-10 L_\odot M_\odot^{-1}$) (Sanders and Mirabel 1985; Young et al. 1986). For instance, IC 4553 (Arp 220) has a FIR flux per unit mass of interstellar gas at least 20 times the mean ratio for the Milky Way and about 5 times the ratio for a typical starburst like M82. The relation in Figure 1b has a correlation coefficient of 0.85 and can be expressed with the equation

$$L_{\text{FIR}}/[M(H\ i) + M(H_2)] = 3.02 \left( f_{\text{IR}}/f_b \right)^{0.56}.$$  

(2)

IV. GALAXY-GALAXY INTERACTIONS AND THE FAR-INFRARED ACTIVITY

In order to investigate the relation between the intensity of galaxy interactions and the FIR excess, we have made a systematic inspection of optical images of the galaxies in our sample taken with the 1.5 m and 5 m Palomar telescopes. The systems were classified using four categories, listed here in order of increasing degree of interaction: “Companion” (C) are the systems with a companion at an apparent distance in the range of 0.5–2 times the galaxy diameter; “Close contact pair” (P) are galaxies with a companion that is at a distance smaller than half the diameter; “Distorted” (D) are those galaxies with the appearance of a single disk that has obviously been tidally distorted; “Mergers” (M) are those where the two disks have lost their identity and appear as a single, coalesced system. Deep optical images of these merger systems with the 5 m Palomar telescope often reveal two close nuclei and/or two counterrotating tidal tails that are indicative of advanced mergers (Toomre and Toomre 1972). Clear examples of advanced mergers are the galaxies IC 4553 and Mrk 231.

Figure 2 plots the type of interaction for all the galaxies of our sample. A striking result is that all of these objects show optical indications for galaxy-galaxy interactions. Although for a given range of FIR excess there is significant overlap between different types of interaction, mergers (M) and distorted disks (D) predominate among galaxies with $f_{\text{IR}}/f_b \geq 30$. On the contrary, galaxies easily identified as pairs (C and P) clearly predominate among galaxies with $f_{\text{IR}}/f_b \leq 10$. These results suggest that tidal interactions enhance the FIR activity of galaxies, and that the FIR excess is correlated with the strength of the interactions.
Fig. 2.—Morphology of the interactions in the plane of Fig. 1b. C = companion at apparent distance 0.5–2.0 times the galaxy diameter. P = companion at ≤0.5 galaxy diameter. D = single tidally distorted disk. M = advanced merger. All infrared active galaxies are interacting systems, and despite significant overlap, mergers (M) and strongly damaged disks (D) predominate among galaxies with the highest far-infrared excesses, whereas less intense interacting systems (C and P) predominate among galaxies with moderate far-infrared excesses.

V. DISCUSSION

In this Letter we have investigated in a sample of luminous infrared galaxies the relations of the CO(1 → 0) and H I fluxes with the FIR and blue fluxes. The most important results from this study are as follows: (1) the \( I(\text{CO})/I(\text{H} \, \text{I}) \) flux ratio increases with increasing infrared excess \( (f_{\text{IR}}/f_{\text{B}}) \); and (2) all galaxies with large infrared excess \( (f_{\text{IR}}/f_{\text{B}} \geq 2) \) have relatively large mass fraction of molecular gas \( (M(\text{H}_2)/M(\text{H} \, \text{I}) \geq 0.5) \). To compute the \( \text{H}_2 \) masses we have used the relation \( M(\text{H}_2) = 5.8 \, (\pi/4) d_{\text{beam}}^2 \, T(\text{CO}) \, dV \), where \( M(\text{H}_2) \) is in solar masses and \( d_{\text{beam}} \) is the size of the telescope beam in parsecs at the distance of the source. This equation was derived from CO surveys of the Milky Way by Sanders, Solomon, and Scoville (1984).

In deriving \( \text{H}_2 \) masses from \( I(\text{CO}) \), we realize that there may be a systematic bias of \( M(\text{H}_2) \) with mean molecular gas temperature that contaminates the trend shown in Figure 1. However, this effect should be relatively small as it is unlikely that the CO → \( \text{H}_2 \) conversion factor for the bulk of the molecular gas in the program galaxies varies by more than a factor of 2. The mean dust temperatures measured by IRAS for the galaxies in Figure 1a increase from ~30 K for galaxies with \( f_{\text{IR}}/f_{\text{B}} \sim 1 \), to ~50 K for galaxies with the highest \( f_{\text{IR}}/f_{\text{B}} \) ratios. Even with the extreme assumption that the gas temperature is equal to the dust temperature, there would be less than a factor of 2 increase in both the gas temperature and \( I(\text{CO}) \), since \( I(\text{CO}) \) is expected to vary linearly with the CO excitation temperature for \( T \gtrsim 30 \) K (cf. Maloney and Black 1988). Furthermore, even in very luminous infrared galaxies that typically have IRAS spectra indicative of warm (≥50 K) dust, recent determinations of the CO(2 → 1)/CO(1 → 0) luminosity ratio (Casoli et al. 1988; Sanders et al. 1989) show that this ratio is typically ≤1, suggesting that most of the CO(1 → 0) flux still comes from the molecular clouds with temperatures ~30 K, similar to the molecular clouds in the Milky Way.

Figures 1 and 2 clearly show an enhancement of the total mass fraction \( M(\text{H}_2)/M(\text{H} \, \text{I}) \) with increasing FIR excess for interacting, gas-rich spiral galaxies. Obviously, the large ratio of \( M(\text{H}_2)/M(\text{H} \, \text{I}) \) stems from an elevated value of \( M(\text{H}_2) \) or a lower value of \( M(\text{H} \, \text{I}) \). There are several mechanisms that could lead to the latter possibility, namely to a relative depletion of atomic hydrogen in the most luminous infrared galaxies. First, there is the possibility that a large fraction of the atomic hydrogen is being ionized. The \( \text{H} \, \text{I} \) in diffuse clouds with low dust content could be easily photoionized by the increasing density of UV photons associated with enhanced rates of massive star formation. However, the UV also photoionizes \( \text{H}_2 \) to produce \( \text{H} \, \text{II} \), and some theories (e.g., Shaya and Federman 1987) predict larger \( M(\text{H} \, \text{I})/M(\text{H}_2) \) ratios with more UV. An alternative cause for ionization of \( \text{H} \, \text{I} \) could be the supernovae-induced, large-scale winds found by Heckman, Armus, and Miley (1987) in starburst and luminous infrared galaxies. At their estimated mass fluxes of 10–100 \( M_\odot \) yr\(^{-1} \), such winds must ionize most of the atomic hydrogen in less than 10\(^8\) yr. However, at present it is not possible to directly measure \( M(\text{H} \, \text{II}) \) in these galaxies.

Since the infrared luminous galaxies are interacting systems, it is also possible that after a strong gravitational impact only the molecular gas, which is predominantly in massive clouds concentrated in the inner regions of the galaxies, will be retained, whereas the more diffuse, loosely bound \( \text{H} \, \text{I} \) component usually found in the outer regions, will be ejected onto intergalactic space. Although galaxy-galaxy interactions may result in large masses of atomic gas being drawn out to large distances during the formation of long tidal tails (e.g., the “Antennae”), our observations suggest that it is unlikely that this is a dominant effect in the most FIR luminous galaxies of our sample. The striking relative low mass of \( \text{H} \, \text{I} \) in IC 4553 and IRAS 10173+0828 holds for volumes of space with radius of 200 kpc from the center of these galaxies (Mirabel and Sanders 1988).

Finally, it is possible that the relative depletion of \( \text{H} \, \text{I} \) in galaxies with large infrared excess may be primarily due to an enhancement of molecular cloud formation. In merger-induced shocks, as a consequence of the large amounts of interstellar gas driven toward the central regions, there may be an increase of the rate of conversion of \( \text{H} \, \text{I} \) into \( \text{H}_2 \). Although the \( \text{H}_2 \) that was present before cloud-cloud collisions will be initially dissociated by shocks of velocity ~100 km s\(^{-1} \), the large amounts of centrally concentrated molecular gas found by Scoville et al. (1986) and Sanders et al. (1988a) in advanced merger systems are an indication of very efficient mechanisms for the formation of \( \text{H}_2 \).

VI. CONCLUSIONS

From the study of a sample of 26 galaxies covering far-infrared luminosities in the range of \( 2 \times 10^{10} \sim 2 \times 10^{12} \, L_\odot \) we conclude the following:

1. The ratio of \( \text{CO}(1 → 0) \) flux to \( \text{H} \, \text{I} \) flux increases with increasing far-infrared excess.

2. Assuming \( M(\text{H}_2) = 5.8 \, L_\odot \), all galaxies with \( f_{\text{IR}}/f_{\text{B}} \geq 2 \) have \( M(\text{H}_2)/M(\text{H} \, \text{I}) \geq 0.5 \), and ratios of \( M(\text{H}_2)/M(\text{H} \, \text{I}) \) as large as 4–20 are found in galaxies with the highest far-infrared excess.

3. The \( L_{\nu}(\text{M}(\text{H}_2))/L_{\nu}(\text{M}(\text{H} \, \text{I})) \) ratio increases with increasing far-infrared excess. Galaxies with the highest infrared excess may have infrared luminosities per nucleon as high as ~20 times that found in the Milky Way.

4. All galaxies in the infrared luminous sample are interacting systems. The optical morphology of these objects
suggestion that galaxy-galaxy collisions enhance the infrared activity, the overall mass fraction of molecular to atomic gas, and the far-infrared luminosity per nucleon of interstellar gas.

We thank Ilya Kazés for confirming the 21 cm Arecibo observations of IRAS 10173 + 0828 with the Nançay radiotelescope. We thank Tom Soifer, Jeff Kenney, and Nick Scoville for their comments on the original manuscript. I. F. M. thanks Nick Scoville, Tom Soifer, and Sri Kulkarni for their kind hospitality at Caltech. I. F. M. was partially supported by a grant from the National Science Foundation. D. B. S. was supported by the IRAS extended mission program.

REFERENCES


I. F. MIRABEL: Department of Physics, University of Puerto Rico, Box AT, University Station, San Juan, PR 00931
D. B. SANDERS: Downs Laboratory, 320-47, California Institute of Technology, Pasadena, CA 91125

© American Astronomical Society • Provided by the NASA Astrophysics Data System