

MOLECULAR GAS IN INTERMEDIATE LUMINOSITY *IRAS* GALAXIES

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ABSTRACT

We report single dish CO ($J = 1-0$) measurements for 29 galaxies of intermediate infrared luminosity ($L_{\text{FIR}} = 10^{10}$ – $10^{11} L_{\odot}$) in the *IRAS* Bright Galaxy sample, at distances in the range 20–40 Mpc. Most of the galaxies were mapped at 3–7 points with a 55" beam. The total H_2 masses, assuming a standard Galactic CO-to- H_2 conversion ratio, lie in the range 5×10^8 – $2 \times 10^{10} M_{\odot}$. The mean ratio of $L_{\text{FIR}}/M_{\text{H}_2}$ for this intermediate luminosity sample is approximately three times that found for Virgo Spirals ($L_{\text{FIR}} = 10^9$ – $5 \times 10^{10} L_{\odot}$), and approximately one-third of that found for a sample of higher luminosity ($L_{\text{FIR}} = 10^{11}$ – $2.5 \times 10^{12} L_{\odot}$) *IRAS* Bright Galaxies.

Subject headings: galaxies: interstellar matter — galaxies: structure — infrared: sources — interstellar: molecules

I. *IRAS* BRIGHT GALAXIES

Analysis of the molecular gas content (Sanders, Scoville, and Soifer 1989, hereafter referred to as Paper I) of the most luminous galaxies in the *IRAS* Bright Galaxy sample (Soifer *et al.* 1987, 1989) has shown that the infrared luminosity-to-molecular mass ratio is typically factors of 5–20 greater than that seen for "normal" galaxies (for example, the Milky Way). Galaxies at the high-luminosity end of the sample systematically show optical morphology indicative of recent galactic mergers or close interactions. If it is supposed that an increased $L_{\text{FIR}}/M_{\text{H}_2}$ ratio is produced as a result of galactic mergers, it is expected that there will be a transition region from normal to extreme rates of energy generation per unit molecular mass (i.e., mass of star forming material) in which both merger and normal galaxies can be found. It is this intermediate luminosity range that was studied, in order to test that supposition.

The 313 galaxies in the *IRAS* Bright Galaxy sample are a flux limited sample obtained from the various *IRAS* catalogs (*IRAS Catalogs and Atlases—Explanatory Supplement* 1988) with $\delta \geq 30^\circ$, $|b| \geq 20^\circ$, and $F_{\nu}(60 \mu\text{m}) \geq 5.2 \text{ Jy}$ (Soifer *et al.* 1989). The complete intermediate luminosity sample ($L_{\text{FIR}} = 10^{10}$ – $10^{11} L_{\odot}$) contains 84 objects with Virgo-centric flow distances between 20 and 40 Mpc (a Hubble constant of $H_0 = 75 \text{ Mpc per km s}^{-1}$ is adopted throughout this paper). Twenty-nine of these galaxies were selected for the present study in order to sample the distribution of luminosity and optical morphology (i.e., both interacting and isolated galaxies). These 29 galaxies were mapped to determine their total CO content and the distribution of interstellar gas, and their molecular gas characteristics have been analyzed for correlation with both the optical morphology and the infrared luminosity.

As stated above, the complete intermediate luminosity sample contains 84 galaxies between $L_{\text{FIR}} = 10^{10} L_{\odot}$ – $L_{\text{FIR}} = 10^{11} L_{\odot}$. Constraints on the available observing time made the mapping of this complete sample infeasible. Further, as we wished to examine the molecular gas and infrared properties of these galaxies as a function of morphological type, it became necessary to bias our selection of galaxies for study toward interacting/merger systems. These systems are intrinsically less common, and it would have been impossible to draw any conclusions from the small number of such systems that would

have been observed if we selected galaxies for observation randomly. The observed sample is also biased toward higher luminosities with almost all of the intermediate luminosity galaxies above $L_{\text{FIR}} = 3.5 \times 10^{10} L_{\odot}$ being observed, while only one third of the galaxies below $L_{\text{FIR}} = 3.5 \times 10^{10} L_{\odot}$ were observed, as is shown in Figure 1. This luminosity bias results from the fact that the interacting systems tend to be more luminous in the far-infrared (Sanders *et al.* 1988).

In order to compare the results of this survey with higher luminosity galaxies, we also consider the sample studied in Paper I. This consists of 43 of the 69 galaxies present in the *IRAS* Bright Galaxy sample with $L_{\text{FIR}} \geq 10^{11} L_{\odot}$. The sample is almost complete (nine out of 10 galaxies observed) above $10^{12} L_{\odot}$ and the remaining 34 galaxies are drawn randomly from Bright Galaxy sample between $L_{\text{FIR}} = 10^{11}$ – $10^{12} L_{\odot}$ (Sanders *et al.* 1989).

II. OBSERVATIONS

The CO ($J = 1-0$) observations were obtained during three observing runs between 1981 June and October, using the 12 m NRAO telescope (HPBW = 55" at 115 GHz). The telescope is equipped with dual polarization SIS receivers ($T_{\text{RX}} = 110 \text{ K}$, SSB). Two $256 \times 2 \text{ MHz}$ channel filter banks, one for each polarization, provided a total velocity coverage of approximately 1360 km s^{-1} with a resolution of 5.6 km s^{-1} . Telescope pointing was monitored by observations of planets and quasars and was estimated to be accurate to $\pm 4''$ (rms). All of the observations were taken using the nutating subreflector which gave exceptionally flat baselines.

Each galaxy was observed at as many positions as were required to sample the optical disk. The number of positions observed, therefore, depends on the galaxy's apparent size and orientation. An optical image for each galaxy is shown with the observed positions superposed in Figure 2 (Plates 10–13), while a list of the observed positions is given in Table 1.

The spectra were obtained with the spectrometer passband centered on the optical redshift, determined by emission line observations in the literature, or taken from a recent optical redshift survey (Soifer *et al.* 1987). The temperature scale was calibrated using an ambient chopper wheel and scaled by the telescope efficiency on a spatially extended source ($\eta_{\text{FSS}} = \eta_{\text{c}}$)

PLATE 10

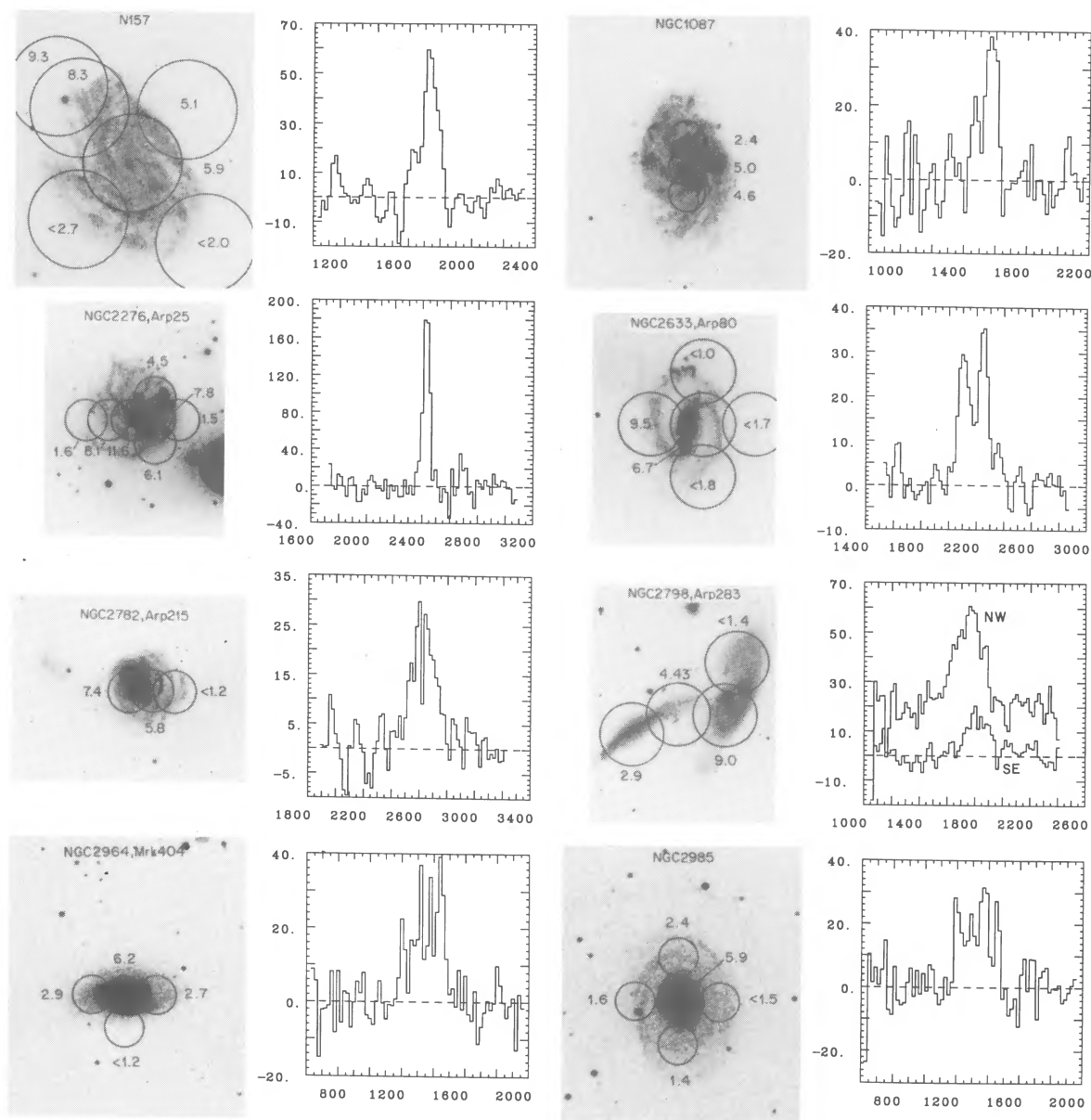


FIG. 2.—Optical images for the galaxies with 55" circles indicating the observed positions are shown along with the CO spectra obtained for the center position. In cases where two distinct galaxies were observed, profiles obtained on both nuclei are included. The integrated CO intensity (I_{CO}^*) observed at each position is noted inside the circles. The optical images used are taken from; NGC 7678, 2782, 2776, 2633, 2798, 7448, 5953/4, 6217, 3310, and 3395/6 (Arp 1966); NGC 4305, 5005, 5962, 157, 1087, 3147, 5383, 6181, and 6643 (Sandage 1961); NGC 5676 (Sandage and Tammann 1981); NGC 3079, 6907, and 7479 (Sandage and Bedke 1988); NGC 5678, 5713, 2964, 2985, 5775, and NGC 7541 were reprinted from Palomar Observatory Sky Survey I plates.

TINNEY, SCOVILLE, SANDERS, AND SOIFER (see 362, 473)

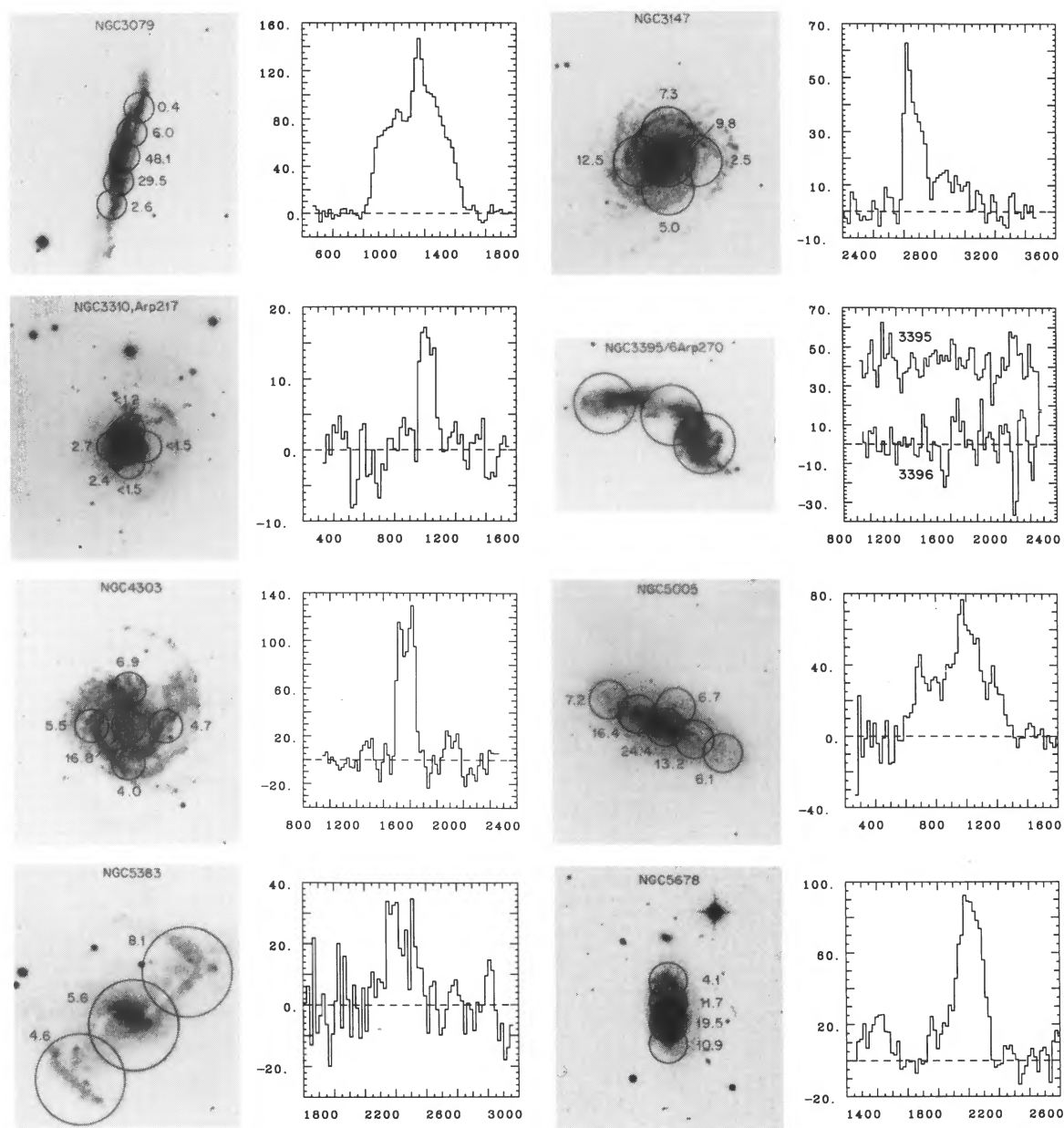


FIG. 2—Continued

TINNEY, SCOVILLE, SANDERS, AND SOIFER (see 362, 473)

PLATE 12

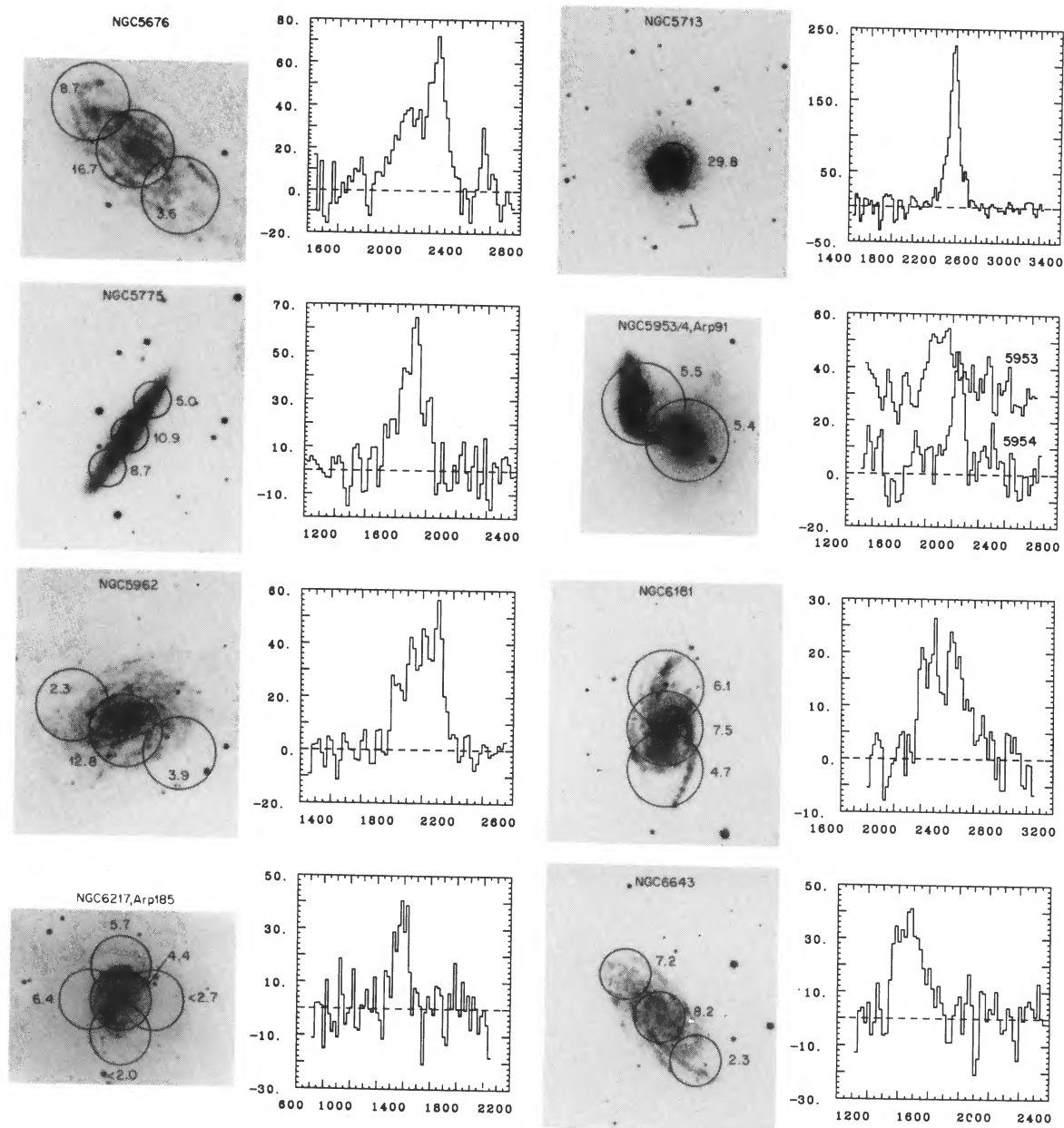


FIG. 2—Continued

TINNEY, SCOVILLE, SANDERS, AND SOIFER (see 362, 473)

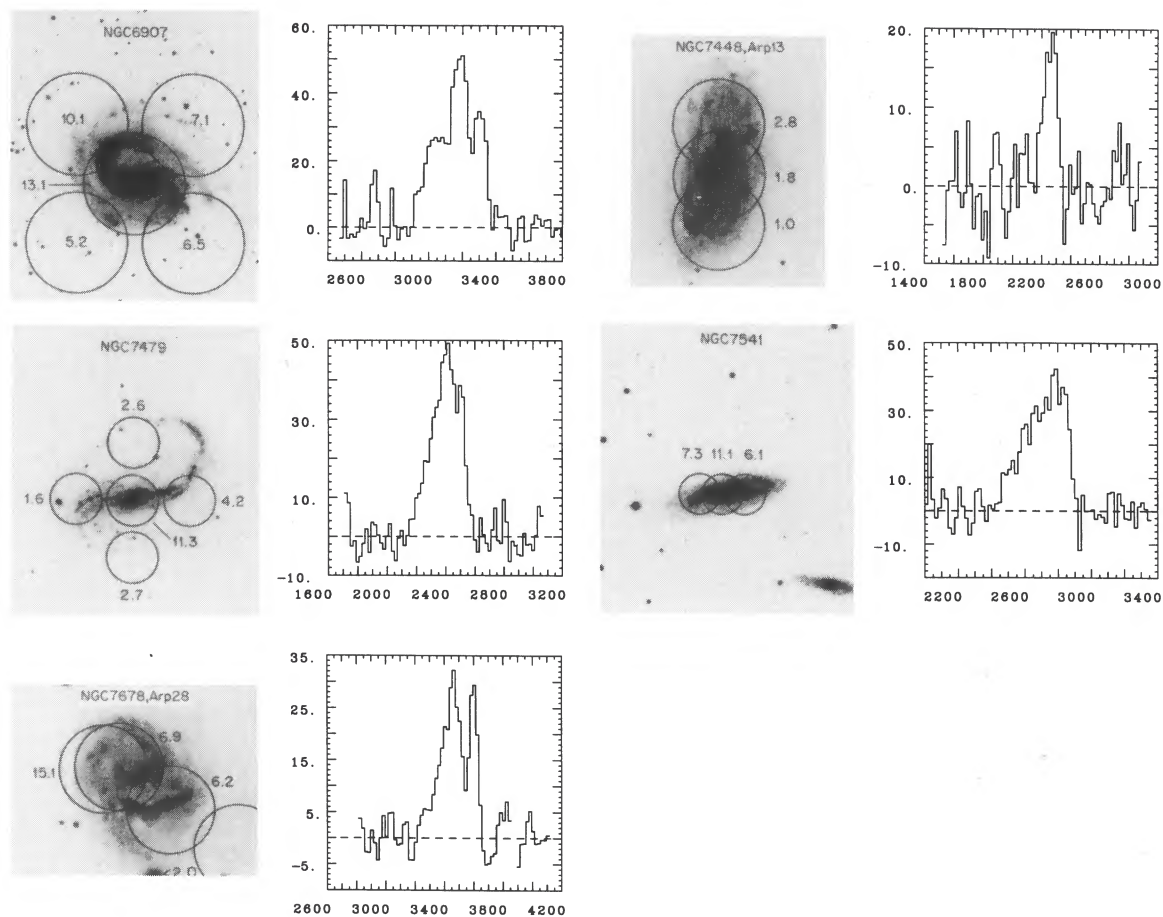


FIG. 2—Continued

TINNEY, SCOVILLE, SANDERS, AND SOIFER (see 362, 473)

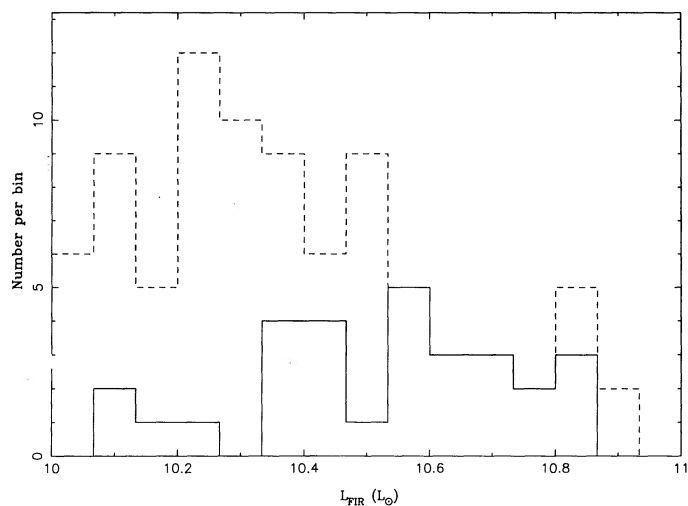


FIG. 1.—Histogram of the 84 galaxies in the complete intermediate luminosity sample (dotted line) as a function of far-infrared luminosity—the selection of these galaxies is described in § I. Also shown overlain (solid line) is the observed sample of 29 galaxies.

to give line temperatures on the T_R^* scale. These temperature units (T_R^*) correspond to the brightness temperature of a source of size equivalent to that of the Moon. After adding both polarizations, the CO spectra were Gaussian-smoothed to a resolution of 20 km s^{-1} giving a typical rms noise of 3–5 mK for 1–2 hr of integration per position.

The total intensity ($I_{\text{CO}}^* = \int T_R^* dv$) for each position was obtained by integrating the spectrum between velocity limits encompassing the observed lines. The peak T_R^* , mean velocity (V_{mean}), linewidth at half the peak T_R^* (ΔV) and integrated intensity (I_{CO}^*) were computed at each position (Table 1). The uncertainty quoted in I_{CO}^* is determined by the rms noise in each spectral line, as well as the linewidth and baseline subtraction uncertainty (Wilson and Scoville 1989). Also shown in Figure 2 is a sample spectrum (usually centered on the optical nucleus) for each galaxy.

III. ANALYSIS

Computation of the total CO luminosity from the I_{CO}^* measurements for these galaxies is problematic, largely because each observed I_{CO}^* is actually a convolution of the galaxy's intrinsic I_{CO} distribution with the telescope beam pattern. The preferred technique would be to measure I_{CO}^* at enough positions on each galaxy that the total luminosity can be simply found by integrating the observed I_{CO}^* profile, since the convolution performed by the telescope beam leaves the galaxy's total flux unchanged. Unfortunately, due to limited observing time, few of the galaxies were observed at enough positions to make this possible.

An alternative technique, used here, is to assume a characteristic form for the CO distribution in these galaxies and, using a telescope beam model, let the observations constrain a model fit. From the resulting model, a total luminosity can be simply found. A thorough description of the details of this process is contained in Kenney and Young (1988), who used this technique to determine luminosities for Virgo cluster spiral galaxies. We adopt a beam model with a $55''$ HPBW Gaussian for the primary beam, and an extended error beam of 0.05% of the Gaussian peak (Jewell 1988).

For 18 of the 29 galaxies, we were able to obtain good fits with a model consisting of 4 kpc exponential disks and, where

necessary (for NGC 5962), an unresolved nuclear source. The exponential disk distribution was chosen as it fits well the observed radial profiles of nearby spiral galaxies mapped at resolutions less than 2 kpc (Scoville and Sanders 1987). In evaluating the total flux, each model was truncated at a radius of one beamwidth larger than the largest observed radius. This was done so that the galaxy's luminosity is not overestimated by counting more flux than the observations constrain. However, the placement of this cutoff is not a major source of systematic uncertainty—varying the cutoff by one-half beamwidth produces only a $\sim 10\%$ change in the galaxy's integrated flux. Fitting a 3 kpc disk was found to produce equally good fits, on average, and reduced the overall flux from each galaxy by only $\sim 15\%$.

The formal uncertainties in the final flux for these models are typically $\sim 10\%$ – 40% ; however, given the possibly oversimplifying assumption of an exponential CO distribution, the resulting total CO fluxes are probably not more accurate than $\sim \pm 50\%$ —and in a few cases are uncertain by a factor of 2. For NGC 2276, 2985, 3147, 4303, and 7479, the coverage of observations was sufficient to allow a direct integration of observed I_{CO}^* values to obtain the luminosity. A comparison of these results with the models fitted showed the two techniques to agree to within $\lesssim 50\%$, with the model fits tending to produce systematically higher values. This discrepancy highlights the fact that the CO luminosities are uncertain by $\sim \pm 50\%$ due to our lack of detailed knowledge of the CO distribution—especially nonaxisymmetries due to galactic interactions and spiral structure.

Of the 12 remaining galaxies, four are interacting pairs whose optical disks are almost completely covered by the telescope beam. Seven of the others have CO distributions sufficiently nonaxisymmetric that an interpretation in terms of a gas disk is questionable. For these galaxies, total fluxes have been determined by adding together the observed I_{CO}^* values, taking double sampling by overlapping beams into account where necessary. The remaining galaxy (NGC 5713) was sampled at only one point (see Fig. 2), and its luminosity, based on this measurement, is given as a lower limit. A fitting of an exponential disk, as done for the other galaxies would increase its luminosity by a factor of 2. The only galaxy not detected in the survey was NGC 3395/Arp 270, and its quoted luminosity is a 3σ upper limit.

In Table 2, the derived L_{CO} values are given (as well as L_{FIR}) for each galaxy. Far-infrared luminosities were calculated using the 60 and $100 \mu\text{m}$ fluxes of Soifer *et al.* (1989), to which a single temperature component has been fitted assuming a λ^{-1} emissivity law, as described by Persson, Helou, and Rice (1985). Distances were derived from the Virgocentric flow model of Aaronson *et al.* (1982), assuming a Hubble constant of $H_0 = 75 \text{ Mpc per km s}^{-1}$.

The total mass of molecular gas is obtained from the CO luminosities assuming a constant conversion factor between the CO luminosity and the molecular hydrogen mass. The mass of molecular gas (H_2) in solar masses is given by $M_{\text{H}_2} = 4.82 \times L_{\text{CO}}$ where L_{CO} is in $\text{K km s}^{-1} \text{ pc}^2$. The constant 4.82 is equivalent to the conversion factor of $3 \times 10^{20} \text{ H}_2 \text{ cm}^{-2} [\text{K km s}^{-1}]^{-1}$ (see Scoville and Sanders 1987). The factor of 3×10^{20} has been determined from galactic measurements of GMCs for which the mass is estimated from application of the virial theorem and from correlations of galactic CO emission with the γ -ray emissivity (Scoville *et al.* 1987; Solomon *et al.* 1987; Bloeman *et al.* 1986).

TABLE 1
COMPLETE LIST OF CO OBSERVATIONS

Galaxy	α^a	δ^a	$\Delta\alpha^b$ (")	$\Delta\delta^b$ (")	Peak T_R^{*c} (K)	V_{mean}^d (km s $^{-1}$)	ΔV^e (km s $^{-1}$)	I_{CO}^{*f} (K km s $^{-1}$)
NGC 157	0 ^h 32 ^m 13 ^s .8	−8°40′23″.2	0	0	0.060	1750	90	5.87 ± 0.99
			42	42	0.046	1580	200	9.26 ± 0.72
			−42	−42	≤0.017	—	—	≤1.98
			30	30	0.042	1620	200	8.3 ± 1.5
			−30	30	0.050	1670	100	5.1 ± 1.1
NGC 1087	2 43 51.8	−00 42 25.2	30	−30	≤0.060	—	—	≤2.67
			0	0	0.039	1530	120	4.95 ± 0.71
			0	42	0.034	1560	70	2.37 ± 0.74
			0	−42	0.037	1440	120	4.58 ± 0.91
NGC 2276, Arp 25	7 10 11.6	85 50 52.6	0	0	0.130	2430	60	7.83 ± 0.81
			30	0	0.215	2420	50	11.6 ± 1.0
			60	0	0.113	2440	70	8.12 ± 0.99
			90	0	0.042	2410	30	1.60 ± 0.83
			−30	0	0.016	2440	90	1.48 ± 0.68
NGC 2633, Arp 80	8 42 32.9	74 16 58.6	0	30	0.068	2450	60	4.47 ± 0.74
			0	−30	0.098	2440	60	6.05 ± 0.52
			0	0	0.036	2190	180	6.68 ± 0.46
			0	45	≤0.010	—	—	≤1.00
			0	−45	≤0.020	—	—	≤1.80
NGC 2782, Arp 215	9 10 52.5	40 19 11.7	45	0	0.062	2210	150	9.50 ± 0.84
			−45	0	≤0.018	—	—	≤1.70
			0	0	0.036	2630	150	5.75 ± 0.61
			30	0	0.033	2600	22	7.37 ± 0.76
NGC 2798, Arp 283	9 14 10.0	42 12 28.5	−30	0	0.020	2580	140	2.8 ± 1.0
			0	0	0.041	1740	210	8.96 ± 0.57
			80	−18	0.020	1800	130	2.85 ± 0.43
			40	0	0.025	1750	170	4.43 ± 0.364
NGC 2964, Mrk 404	9 39 56.5	32 4 35.6	−10	45	≤0.015	—	—	≤1.35
			0	0	0.047	1360	130	6.22 ± 0.69
			0	−45	≤0.013	—	—	≤1.23
			45	0	0.028	1220	100	2.86 ± 0.60
			−45	0	0.021	1190	120	2.69 ± 0.75
NGC 2985	9 45 54.1	72 30 42.6	0	0	0.033	1330	170	5.92 ± 0.69
			0	60	0.035	1360	60	2.37 ± 0.59
			0	−60	0.025	1200	50	1.38 ± 0.52
			60	0	0.021	1360	70	1.60 ± 0.53
			−60	0	≤0.017	—	—	≤1.50
NGC 3079	9 58 35.0	55 55 16.6	0	0	0.147	1150	320	48.1 ± 3.6
			12	−43	0.094	1190	310	29.5 ± 1.4
			24	−86	0.029	1300	80	2.58 ± 0.88
			−12	43	0.062	1030	90	6.0 ± 1.1
			−24	86	≤0.018	—	—	≤2.04
NGC 3147	10 12 38.4	73 39 0.4	0	0	0.063	2740	150	9.80 ± 0.54
			0	30	0.077	2680	90	7.29 ± 0.54
			0	−30	0.025	2860	190	4.97 ± 0.49
			30	0	0.044	2820	280	12.5 ± 0.7
			−30	0	0.022	2690	110	2.50 ± 0.68
NGC 3310, Arp 217	10 35 39.6	53 45 48.5	0	0	0.017	1060	100	2.43 ± 0.40
			0	30	≤0.012	—	—	≤1.20
			0	−30	≤0.016	—	—	≤1.50
			30	0	0.019	890	260	2.72 ± 0.59
			−30	0	≤0.016	—	—	≤1.50
NGC 3395/6, Arp 270	10 47 5.1	33 14 58.6	0	0	≤0.024	—	—	—
			−30	−25	≤0.025	—	—	—
			60	10	≤0.033	—	—	—
			0	0	0.129	1570	120	16.8 ± 1.0
NGC 4303	12 19 21.4	4 44 57.7	0	60	0.151	1620	40	6.93 ± 0.86
			0	−60	0.053	1550	70	3.98 ± 0.86
			−60	0	0.120	1600	40	5.52 ± 1.07
			60	0	0.083	1510	50	4.67 ± 0.90
			0	0	0.077	950	310	24.4 ± 1.1
NGC 5005	13 8 37.8	37 19 27.6	41	19	0.096	1090	170	16.4 ± 0.9
			82	38	0.056	1110	120	7.2 ± 1.1
			−41	−19	0.087	760	150	13.2 ± 1.4
			−82	−38	0.062	720	90	6.1 ± 1.5
			−13	27	0.054	950	120	6.7 ± 1.4
NGC 5383	13 55 0.2	42 5 19.6	0	0	0.036	2230	150	5.62 ± 0.96
			−32	32	0.041	2320	190	8.08 ± 0.90
			32	−32	0.040	2330	110	4.60 ± 0.74

TABLE 1—Continued

Galaxy	α^a	δ^a	$\Delta\alpha^b$ (")	$\Delta\delta^b$ (")	Peak $T_R^*{}^c$ (K)	V_{mean}^d (km s $^{-1}$)	ΔV^e (km s $^{-1}$)	$I_{\text{CO}}^*{}^f$ (K km s $^{-1}$)
NGC 5678	14 30 37.4	58 8 24.6	0	0	0.093	1980	210	19.5 $\pm$ 1.5
			0	−30	0.081	2020	120	10.2 $\pm$ 1.0
			0	30	0.045	1890	260	11.7 $\pm$ 0.9
			0	60	0.048	1760	80	4.13 $\pm$ 0.96
NGC 5676	14 31 1.2	49 40 37.5	0	0	0.072	2150	230	16.7 $\pm$ 1.5
			32	32	0.044	2000	190	8.66 $\pm$ 0.96
			−32	32	0.042	2250	80	3.6 $\pm$ 1.1
NGC 5713	14 37 37.7	−0 4 34.1	0	0	0.227	2180	130	29.8 $\pm$ 0.5
NGC 5775	14 51 26.8	3 44 52.7	0	0	0.065	1690	160	10.9 $\pm$ 0.9
			−33	50	0.038	1640	130	4.95 $\pm$ 0.76
			33	−50	0.104	1800	80	8.7 $\pm$ 1.0
NGC 5953/4, Arp 91	15 32 13.3	15 21 41.6	0	0	0.046	2030	110	5.43 $\pm$ 0.78
			30	24	0.025	1940	220	5.48 $\pm$ 0.75
			0	0	0.056	1990	220	12.8 $\pm$ 0.5
NGC 5962	15 34 13.8	16 46 15.5	−41	−17	0.032	1850	120	3.9 $\pm$ 1.0
			41	17	0.038	2080	60	2.30 $\pm$ 0.60
			0	0	0.027	2380	280	7.53 $\pm$ 0.60
NGC 6181	16 30 9.6	19 55 48.5	0	30	0.031	2410	190	6.05 $\pm$ 0.52
			0	−30	0.022	2330	210	4.71 $\pm$ 0.73
			0	0	0.041	1370	100	4.36 $\pm$ 0.96
			0	30	0.063	1420	90	5.7 $\pm$ 1.1
			0	−30	≤ 0.023	—	—	≤ 2.04
NGC 6643	18 21 13.4	74 32 47.5	30	0	0.045	1360	140	6.4 $\pm$ 1.1
			−30	0	≤ 0.030	—	—	≤ 2.73
			0	0	0.041	1490	190	8.24 $\pm$ 0.78
			38	46	0.061	1540	110	7.18 $\pm$ 0.66
			−38	46	0.025	1400	90	2.25 $\pm$ 0.82
NGC 6907	20 22 7.9	−24 58 20.2	0	0	0.051	3160	250	13.1 $\pm$ 0.7
			32	32	0.039	3160	260	10.1 $\pm$ 0.9
			−32	−32	0.058	3250	110	6.45 $\pm$ 0.86
			−32	32	0.036	3160	190	7.06 $\pm$ 0.86
			32	−32	0.027	3180	190	5.16 $\pm$ 0.82
NGC 7448, Arp 13	22 57 34.7	15 42 47.2	0	0	0.024	2200	70	1.77 $\pm$ 0.58
			0	30	0.030	2240	90	2.82 $\pm$ 0.55
			0	−30	0.024	2210	70	0.96 $\pm$ 0.75
			0	0	0.049	2400	220	11.3 $\pm$ 0.4
NGC 7479	23 2 26.5	12 3 8.1	0	60	0.020	2300	120	2.60 $\pm$ 0.56
			0	−60	0.037	2490	70	2.70 $\pm$ 0.70
			60	0	0.015	2270	100	1.63 $\pm$ 0.71
			−60	0	0.025	2380	170	4.21 $\pm$ 0.74
			0	0	0.044	2700	250	11.1 $\pm$ 0.6
NGC 7541	23 12 11.4	4 15 39.2	30	0	0.046	2770	150	7.27 $\pm$ 0.53
			−30	0	0.030	2660	200	6.10 $\pm$ 0.44
			0	0	0.037	3470	160	6.23 $\pm$ 0.54
NGC 7678, Arp 28	23 25 56.6	22 8 30.6	32	25	0.034	3490	200	6.91 $\pm$ 0.44
			42	24	0.083	3560	180	15.2 $\pm$ 0.4
			−42	−24	≤ 0.018	—	—	≤ 2.01

^a Positions quoted are those used as the zero offset reference when observing on the NRAO 12 m telescope, and are based on the centroid of *IRAS* emission (1950.0 epoch).

^b $\Delta\alpha$ and $\Delta\delta$ are the offsets from the reference position given (positive $\Delta\alpha$ is east).

^c T_{peak} for each position is given in units of K on the T_R^* scale.

^d Velocities quoted are the centroid velocity for each line.

^e ΔV is the line width at half-maximum.

^f I_{CO}^* is the integrated line emission at each position—calculation of uncertainties in I_{CO}^* is described in the text.

Some uncertainty exists about the application of this Galactic conversion from L_{CO} to M_{H_2} for galaxies which are infrared luminous or, as in some of our cases, interacting. A number of effects have been proposed which would increase the $L_{\text{CO}}/M_{\text{H}_2}$ ratio for such galaxies (Maloney 1989). However, in the absence of a measurement of this ratio for these galaxies, we continue to use the galactic conversion, although it should be noted that the $L_{\text{CO}}/M_{\text{H}_2}$ ratio may be significantly increased in infrared luminous or interacting galaxies. If this is the case, the ratio of $L_{\text{FIR}}/M_{\text{H}_2}$ is increased, thus strengthening the correlation found below between $L_{\text{FIR}}/M_{\text{H}_2}$ and the presence of a

galactic interaction. In any case the results of this work may be interpreted in terms of L_{CO} rather than M_{H_2} , since a constant conversion factor is used throughout.

IV. CORRELATION OF FAR-INFRARED LUMINOSITIES WITH MOLECULAR MASS

CO masses determined for the intermediate luminosity galaxies range from 5×10^8 to $2 \times 10^{10} M_{\odot}$, i.e., 0.25–20 times the molecular mass of the Milky Way (see Scoville and Sanders 1987). Shown in Figure 3 are the derived CO and far-infrared luminosities for galaxies in both the intermediate luminosity

TABLE 2
CO AND INFRARED LUMINOSITIES OF THE INTERMEDIATE LUMINOSITY SAMPLE

Galaxy	D (Mpc)	L_{CO} ($10^9 \text{ K km s}^{-1} \text{ pc}^2$)	M_{H_2} ($10^9 M_\odot$)	L_{FIR} ($10^9 L_\odot$)	$L_{\text{FIR}}/L_{\text{CO}}$ ($L_\odot \text{ per } [\text{K km s}^{-1} \text{ pc}^2]$)	Morph	Notes
NGC 157	21.2	0.72	3.5	27.5	38	1	a
NGC 1087	19.1	0.50	2.4	13.5	27	1	b
NGC 2276, Arp 25	37.0	3.4	16	49.0	14	2	b
NGC 2633, Arp 80	34.2	1.4	6.7	44.7	13	2	a
NGC 2782, Arp 215	38.4	1.9	9.4	28.8	15	4	a
NGC 2798, Arp 283	28.4	0.81	3.9	38.9	48	3	a
NGC 2964, Mrk 404	22.7	0.52	2.5	15.8	30	1	c
NGC 2985	23.1	0.72	3.5	13.2	18	1	c
NGC 3079	21.1	2.9	14	44.7	15	2	a
NGC 3147	43.2	3.4	16	57.5	17	1	d
NGC 3310, Arp 217	18.9	0.11	0.53	24.5	220	4	a
NGC 3395/6, Arp 270	28.5	<0.18	<0.87	23.4	>130	3	e
NGC 4303	29.1	3.5	17	100.0	29	2	c
NGC 5005	21.2	2.9	14	35.5	12	1	c
NGC 5383	37.6	2.0	9.6	22.4	11	1	a
NGC 5678	32.8	3.3	16	34.7	11	1	c
NGC 5676	35.3	3.3	16	51.3	16	1	c
NGC 5713	31.3	>2.0	>9.4	49.0	<25	3	f
NGC 5775	28.7	2.0	9.6	60.3	20	1	c
NGC 5953/4, Arp 91	32.9	0.7	3.5	30.2	43	3	a
NGC 5962	32.7	1.6	7.7	28.8	18	1	b, g
NGC 6181	37.6	1.7	8.2	37.2	22	2	c
NGC 6217, Arp 185	24.6	0.43	2.1	16.6	39	1	a
NGC 6643	26.1	1.6	7.5	28.8	18	1	c
NGC 6907	42.6	2.5	12	67.6	12	2	c
NGC 7448, Arp 13	30.7	0.37	1.8	22.9	61	1	b
NGC 7479	32.8	2.4	12	38.9	16	2	c
NGC 7541	35.8	1.9	9.2	72.4	38	1	c
NGC 7678, Arp 28	47.7	3.1	15	44.7	14	2	a

NOTE.—Distances were calculated using the Virgocentric flow model of Aaronson *et al.* (1982) with $H_0 = 75 \text{ Mpc km s}^{-1}$. Typical uncertainties for L_{CO} and $M(\text{H}_2)$ are $\pm 50\%$, except for the few cases noted below.

^a The galaxy (or pair of galaxies) has been sampled in an irregular fashion, although all or most of the optical image has been covered, or had emission displaying a pronounced nonaxisymmetry making a model fit impossible.

^b The total flux of the galaxy has been determined by a model fit as described in the text, but due to poor detections or nonaxisymmetry in the observed CO distribution, the L_{CO} and $M(\text{H}_2)$ values are good only to a factor of 2.

^c The total flux of the galaxy has been determined by a model fit as described in the text.

^d The optical morphology of NGC 3147 is that of a normal face on Sb spiral, however its CO emission is peculiar. At the (30°E, 0°N) position over one-half the flux observed comes from a broad ($\sim 200 \text{ km s}^{-1}$) component which is 400 km s^{-1} redward of the emission seen from the galaxy at every other position observed. This double emission has also been observed by Young *et al.* 1986a. Although no optical object is apparent here, the emission would seem to be most likely due to a background galaxy screened by NGC 3147—the velocity separation makes it unlikely the emission is part of the face-on spiral. However, as the infrared emission is an average of the emission from the two components, we have also simply integrated the observed CO emission into one luminosity.

^e No line was detected at any position in NGC 3395/6 (Arp 270), and the quoted limits represent 3σ estimates for an integration over 1000 km s^{-1} around the de Vaucouleurs *et al.* velocity.

^f Only one position was sampled in NGC 5713, so the L_{CO} quoted is a lower limit; an exponential model fit (though poorly constrained) gives a total luminosity of $5.0 \times 10^9 \text{ K km s}^{-1} \text{ pc}^2$.

^g A good model fit to NGC 5962 could only be made by introducing a centrally peaked source centered on the optical nucleus.

sample and the higher luminosity galaxies of Paper I. The latter are generally at greater distances since a larger volume must be included to sample the relatively rare, high-luminosity galaxies. It should be noted, however, that we find no evidence for significant variation in the infrared luminosity of the Paper I galaxies when we bin them as a function of distance (see Table 3) and therefore the results presented here are not due to sample biases produced by galaxies at different distances.

On the basis of the optical images, we have separated the galaxies into four broad classes characterizing the possibility of a galactic interaction: (1) isolated objects with no extended tails and no companion within three optical diameters; (2) galaxies with an asymmetric or distorted appearance, but no evidence of a close-by companion; (3) galaxies with an ongoing interaction as judged from the presence of two overlapping or nearby galaxies; and (4) advanced merger systems as indicated by the presence of tidal tails or shells around a single stellar

system. In Figure 3 the galaxies are plotted with squares (1), triangles (2), circles (3), and stars (4) depending upon their classification.

a) Variation of $L_{\text{FIR}}/L_{\text{CO}}$ with L_{FIR}

It can be seen from Figure 3, that there is a significant difference in the $L_{\text{FIR}}/L_{\text{CO}}$ ratio between the intermediate and high-luminosity galaxies. However, these results must be interpreted carefully, as the Paper I survey measured the CO emission from each galaxy with only one 55'' beam. For distance galaxies ($d > 100 \text{ Mpc}$) a single 55'' beam will detect all of the galaxy's flux (assuming a 4 kpc exponential disk for the CO distribution). However, for closer galaxies, undersampling must be corrected for. At 30–70 Mpc, a single beam will detect only 50%–75% (respectively) of the galaxy's flux.

In Table 4 the mean $L_{\text{FIR}}/L_{\text{CO}}$ ratios for the observed intermediate luminosity sample are shown, while in Table 3 these

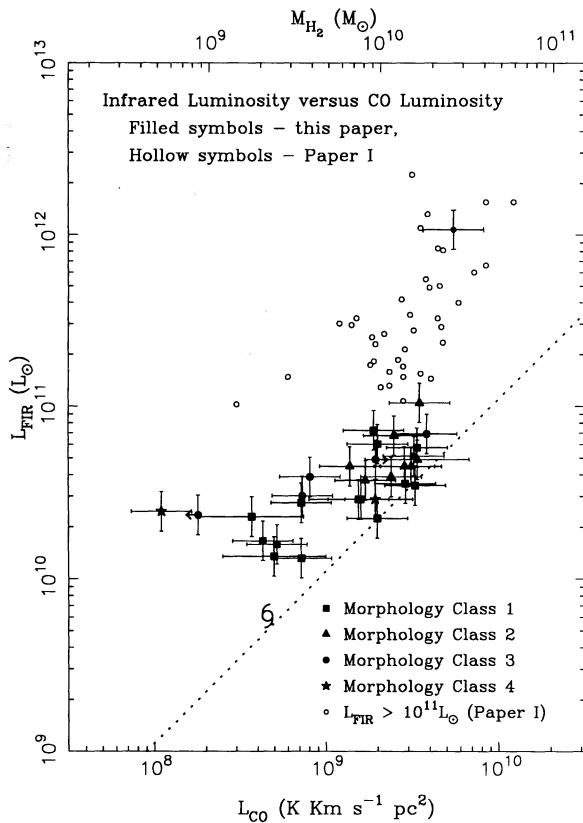


FIG. 3.—The far-infrared luminosity is shown as a function of CO luminosity for the intermediate luminosity galaxies in the present sample (filled symbols), together with measurements obtained in Paper I for more distant *IRAS* bright galaxies with $L_{\text{FIR}} \geq 10^{11} L_{\odot}$ (hollow symbols). The interaction class (see text for definition) is shown for all galaxies in the intermediate luminosity sample. The dotted line indicates the mean far infrared-to-CO luminosity ratio obtained for normal gas-rich spirals by the study of Virgo spirals due to Kenney and Young (1988). The Galactic far-infrared and CO luminosity is also shown (spiral symbol—Scoville and Good 1989). Uncertainties for the intermediate luminosity sample are discussed in the text. A typical uncertainty of $\pm 50\%$ is shown for the Paper I sample, and $\pm 30\%$ for the far-infrared luminosities in both samples (Soifer *et al.* 1989). (Nearby galaxies not well sampled in the Paper I study have been omitted. These galaxies are NGC 23, 877, 3221, 3583, 4793, 5430, 7817.)

figures are calculated for the Paper I sample as a function of distance and luminosity. For the Paper I galaxies with $d > 100$ Mpc (where the luminosities are not significantly undersampled) the mean $L_{\text{FIR}}/L_{\text{CO}}$ ratio in the range $L_{\text{FIR}} = 10^{11}$ – $10^{12} L_{\odot}$ is a factor of 3.5 ± 1.0 higher than for the mean of all galaxies in the observed intermediate luminosity sample, and a factor of 4.8 ± 0.8 higher than the isolated and mildly

TABLE 3

MEAN $L_{\text{FIR}}/L_{\text{CO}}$ FOR PAPER I SAMPLE ABOVE $L_{\text{FIR}} = 10^{11} L_{\odot}$

DISTANCE	MEAN $L_{\text{FIR}}/L_{\text{CO}}^a$	
	$L_{\text{FIR}} = 10^{11}$ – $10^{12} L_{\odot}$	$L_{\text{FIR}} > 10^{12} L_{\odot}$
$d > 100$ Mpc.....	106 ± 11 (18)	296 ± 110 (5)
$70 < d < 100$ Mpc.....	97 ± 26 (9)	— ^b (1)
$20 < d < 70$ Mpc.....	138 ± 45 (7)	—

^a Each entry gives the mean ratio, the standard error in the mean and (in parenthesis) the number of galaxies in each luminosity/distance bin.

^b There is only one galaxy in this luminosity/distance bin, with $L_{\text{FIR}}/L_{\text{CO}} = 340$.

TABLE 4

MEAN $L_{\text{FIR}}/L_{\text{CO}}$ VS. INTERACTION CLASS

Class ^{a,c}	Mean $L_{\text{FIR}}/L_{\text{CO}}^b$
(1) Isolated	24 ± 4 (15)
(2) Disturbed	18 ± 2 (8)
Classes 1–2	22 ± 3 (23)
(3) Interacting	74 ± 34 (3)
(4) Merger	$220, 15$ (2) ^d
Classes 3–4	91 ± 42 (5)
All Classes	30 ± 8 (28)

^a See text for description of morphology class criteria.

^b Each entry gives the mean ratio, the standard error in the mean and (in parenthesis) the number of galaxies in each class.

^c All galaxies from the intermediate luminosity sample are included, except the upper limit for NGC 3395/Arp 270.

^d $L_{\text{FIR}}/L_{\text{CO}}$ ratio shown for both galaxies in this class (NGC 3310 and NGC 2782, respectively).

disturbed intermediate luminosity galaxies. This is also true for galaxies closer than 100 Mpc, though less certain due to the undersampling effects discussed above. (The uncertainties quoted here are based on the standard errors of the means, as shown in Tables 3 and 4, as the cosmic scatter in our results is larger than that expected from our estimate of the measurement uncertainties.)

Even within the Paper I sample it can be seen that for the well-sampled galaxies ($d > 100$ Mpc), the $L_{\text{FIR}}/L_{\text{CO}}$ ratio is significantly higher for galaxies at $L_{\text{FIR}} > 10^{12} L_{\odot}$ than for galaxies with $L_{\text{FIR}} = 10^{11}$ – $10^{12} L_{\odot}$. It is thus clear that the ratio of infrared luminosity to molecular gas mass is significantly greater for more luminous *IRAS* galaxies.

Recall that our intermediate luminosity sample is biased toward more luminous galaxies—if we consider our result here in that light, it becomes clear that a complete sample could be expected to show an even larger difference between the intermediate luminosity and Paper I $L_{\text{FIR}}/L_{\text{CO}}$ ratios.

b) Variation of $L_{\text{FIR}}/L_{\text{CO}}$ with Morphology

Clearly an interesting comparison to make, then, would be between the galaxies of the intermediate luminosity sample and a sample of normal galaxies. Unfortunately a statistically well defined class of such objects (i.e., an unbiased sample of *fully mapped* isolated field galaxies) does not exist—we are forced to make rather arbitrary assumptions as to what constitutes normal. We have, therefore, included for comparison in Figure 3 the ratio between L_{FIR} and L_{CO} found for the Milky Way (Scoville and Good 1989), and the 45° line corresponding to the mean of a sample of Virgo Spirals (Kenney and Young 1988). For the relation discussed above between L_{CO} and M_{H_2} for Virgo spirals, this line corresponds to a ratio of $L_{\text{FIR}}/M_{\text{H}_2} = 2.1 \pm 0.4 L_{\odot} M_{\odot}^{-1}$. For our sample of intermediate luminosity galaxies, the mean $L_{\text{FIR}}/M_{\text{H}_2} = 6.2 \pm 1.6 L_{\odot} M_{\odot}^{-1}$. Thus, the mean luminosity-to-mass ratio for this sample of galaxies is 3.0 ± 0.9 times that obtained for normal gas-rich spiral galaxies.

Examining Figure 3 and Table 4 it can be seen that evidence for a trend in the $L_{\text{FIR}}/L_{\text{CO}}$ ratio with morphology class within our sample is marginal. Although the mean $L_{\text{FIR}}/L_{\text{CO}}$ ratio is larger for Class 3 and 4 galaxies (9 ± 4 times larger than that

found for the Virgo sample), the scatter is also very large and the number statistics are not good. However, it should be noted that Young *et al.* (1986b) and Solomon and Sage (1988) have found evidence for a trend in $L_{\text{FIR}}/L_{\text{CO}}$ with degree of interaction—further study of this question with a larger sample of well-mapped galaxies is clearly indicated.

V. SPATIAL DISTRIBUTION OF MOLECULAR GAS

The spatial resolution of our data is sufficient in most cases to assess crudely the relative contributions of the central galactic point source and an extended disk to CO emission. The emission, in general, is *not* consistent with that due to a dominant central point source, and in most cases is adequately fit by a 3–4 kpc exponential disk. This extended emission is inconsistent with the strong central condensations seen in more luminous *IRAS* galaxies, where $\sim 50\%$ of the gas is found in the central few kpc (e.g., Arp 220, Scoville *et al.* 1987; NGC 7469, Sanders *et al.* 1988; Mrk 331, Scoville *et al.* 1989).

However, some galaxies were not well fit by a gas disk due to a pronounced nonaxisymmetry (e.g., NGC 157, NGC 2633, NGC 2782, NGC 3310, NGC 6217, NGC 7678). It is interesting to note that both galaxies classed as advanced mergers (NGC 3310/Arp 217 and NGC 2782/Arp 215) have CO emission which is offset from their optical centers—a fact which supports their classification as galaxies strongly affected by a galactic collision. Clearly, therefore, if more than a first-order assessment of the properties of these galaxies is desired, it does not suffice to assume a disk structure for all galaxies—mapping of the extended emission, both to determine its form and extent, is *essential* if luminosities are to be accurately determined.

VI. CONCLUSIONS

For this sample of 40 intermediate luminosity *IRAS* galaxies we find that;

1. The total H_2 masses span the range $5 \times 10^8 - 2 \times 10^{10}$

$M_{\odot}$, with the generally higher molecular gas masses obtained in the higher infrared luminosity galaxies.

2. An intermediate stage is seen in the sequence of far-infrared and molecular gas properties which extends from normal spiral galaxies, through the intermediate sample studied here, to the high- and ultraluminous galaxies studied in Paper I. In particular, the mean ratio of far-infrared to molecular mass (assuming a standard galactic CO-to- H_2 conversion) is $6 \pm 2 L_{\odot}/M_{\odot}$, i.e., approximately three times that found for the sample of normal Virgo spiral galaxies, and one-third that of the sample of more infrared-luminous galaxies.

3. Within the sample of galaxies observed, there is a large range in the ratio of far-infrared luminosity to molecular mass—there is marginal evidence to indicate that the mean value is enhanced for galaxies classified as being interacting or advanced merger systems. In isolated or loosely interacting systems the far-infrared luminosity to molecular gas mass ratio is 2.2 ± 0.7 times that found for nearby spiral galaxies, but in the five interacting/advanced merger systems studied this ratio is a factor of 9 ± 4 higher than normal.

4. The enhanced luminosity to mass ratios found for the interacting/advanced merger systems in our sample are similar to those measured in luminous and ultra-luminous *IRAS* galaxies (Paper I). This similarity in the luminosity to mass ratios may be accounted for by the fact that a large proportion of the luminous and ultraluminous galaxies are, in fact, advanced merger systems (Sanders *et al.* 1988).

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