CO OBSERVATIONS OF ULTRALUMINOUS INFRARED GALAXIES AND QUASARS

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ABSTRACT. Recent millimeterwave observations of CO emission from ultraluminous infrared galaxies ($L_{ir} > 10^{12}$ $L_\odot$) and quasars suggest that abundant supplies of molecular gas may be a common property of both types of object. Current published CO detections are summarized, and the possibility of an evolutionary connection between infrared galaxies and quasars is discussed.

1. Introduction

One of the most important results of the IRAS survey has been the discovery of a significant number of ultraluminous galaxies ($L_{bol} > 10^{12} L_\odot$, H_o = 75 km $s^{-1}Mpc^{-1}$, q_o = 0) that emit the bulk of their energy at infrared wavelengths (Soifer *et al.* 1986; Lawrence *et al.* 1986). These objects meet the generally accepted minimum bolometric luminosity criteria for quasars (Schmidt and Green 1983; Soifer *et al.* 1987). Luminous infrared galaxies represent an important class of extragalactic objects, exceeding even the space density of quasars at comparable bolometric luminosities (see Figure 1). The initial detection of CO emission from the prototype ultraluminous infrared galaxy Arp 220 (Young *et al.* 1984) showed that these objects can be extremely rich in molecular gas, and has led to the suggestion by several groups that molecular clouds may play a fundamental role in fueling the extreme infrared activity. These objects appear to be currently undergoing powerfull bursts of star-formation (c.f. Joseph and Wright 1985), and may possibly contain a dust-obscurred Active Galactic Nucleus (c.f. Sanders *et al.* 1988a).

The most extensive observations of CO emission from ultraluminous infrared galaxies have been for those objects in the IRAS BGS, a sample of ~700 objects with F_ν(60 μm) > 5.2 Jy (Soifer *et al.* 1987, 1989; Sanders *et al.* 1990). As the brightest infrared objects, the BGS galaxies have been the most amenable to studies at other wavelengths. CO(1→0) observations are essentially complete for a sample of 21 ultraluminous BGS galaxies at redshift z < 0.8. In addition, approximately 10 CO(1→0) detections at redshift z < 0.17 have been reported of 'warm' ultraluminous infrared galaxies, objects with properties intermediate between those of the cooler 60 μm selected objects and UV-excess quasars. Many of these objects are similar to 'infrared quasars', objects with Seyfert 1 type optical spectra, and a point-like appearance on the Palomar Sky Survey prints that were first discovered either serindipitously in the IRAS data (e.g. Beichman *et al.* 1986; Vader and Simon 1987; Kleinmann and Keel 1987), or through systematic searches for objects with 'warm' infared colors (e.g. deGrijp, Miley, and Lub 1988; Low *et al.*

F. Combes and F. Casoli (eds.), Dynamics of Galaxies and Their Molecular Cloud Distributions, 417–424.

1988; Sanders *et al.* 1988b). The few reported CO detections of previously identified quasars have been for quasars detected in IRAS pointed observations at 60 μm and 100 μm (Neugebauer *et al.* 1986).

All of the currently available CO data for ultraluminous infrared galaxies and quasars is summarized below. The molecular gas properties are derived and the role of molecular gas in these galaxies is discussed in the context of a more complete description of these objects using extensive ground-based observations at other wavelengths.

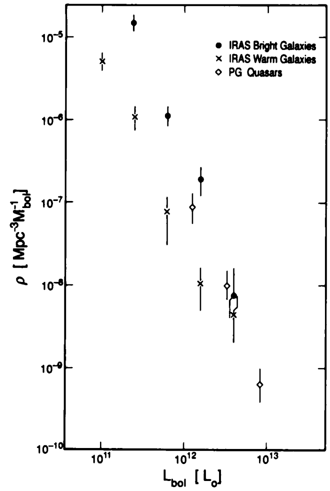

Figure 1. The luminosity functions of luminous infrared galaxies and optically selected quasars normalized to the same Hubble constant and plotted in units of bolometric luminosity. The solid line represents the best fit to the IRAS Bright Galaxy (•) luminosity function (Soifer *et al.* 1987). (×) represent IRAS 'warm' galaxies from the survey of Sanders *et al.* (1988b). (◇) represent optically selected quasars taken from the Palomar-Green Bright Quasar Survey (Schmidt and Green 1983).

2. Infrared Properties

The majority of ultraluminous infrared galaxies observed in CO are from the IRAS BGS. Although a typical BGS galaxy has an infrared emission peak longward of 100 μm, the majority of the ultraluminous BGS objects have an emission peak near 60 μm. Figure 2 shows the mean energy distribution for all 21 ultraluminous BGS objects indicating that typically 60-90% of the bolometric luminosity from these objects is emitted at wavelengths longward of 10 μm.

Although the majority of BGS objects do have similar far-infrared excesses, there is a range of energy distributions with the warmest objects having energy distributions similar to that shown for 'warm' infrared galaxies. Samples of 'warm' galaxies such as that from sanders *et al.* (1988b) contain objects which span the range of energy distributions shown for the 60 μm sample and for the UV-excess quasars. For 'warm' infrared galaxies the peak has shifted to wavelengths near 40μm, and typically ~20-30% of the bolometric luminosity emerges at wavelengths between 1 and 40 μm.

For UV-excess quasars the energy distribution appears to be composed two broad peaks, a 'big blue bump' at wavelengths 0.1 to 1 μm containing typically 60-80% of the bolometric luminosity, and a second infrared bump at wavelengths 1 to 100 μm containing 20-40% of the bolometric luminosity with a peak in the infrared near 10-20 μm. There is no overlap between objects in the BGS and the UV-excess quasars.

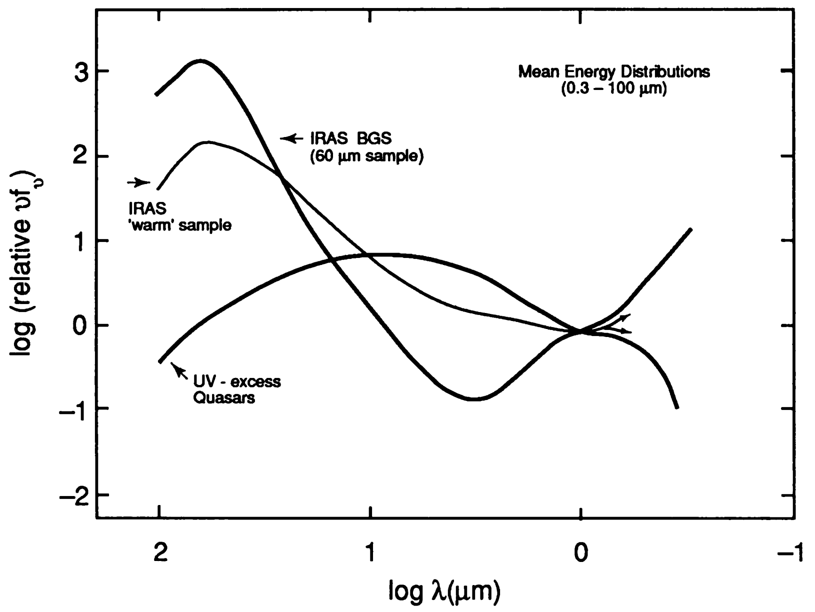

Figure 2. Mean energy distributions for ultraluminous infrared galaxies and optically selected quasars. The IRAS 60 μm curve is the mean for the 21 objects in the BGS (Soifer *et al.* 1989; Sanders *et al.* 1990; see also Table 1). The IRAS 'warm' galaxy curve is the mean for the 12 objects listed in Sanders *et al.* 1988b (see also Table 2). The curve for UV-excess quasars is the mean energy distribution for the 92 quasars in the Palomar-Green BQS (see Sanders *et al.* 1989a).

3. CO Observations and H_2 Masses

All of the currently published CO(1→0) detections of ultraluminous infrared galaxies and quasars are summarized in Tables 1 and 2. Observing coordinates are taken from the literature and typically represent the IRAS position, although in the case of the X-Ray quasar E1821+643, the optical position was used. The redshift is that measured from the centroid of the CO emission line. CO linewidths, although not given, range from 200 - 700 km s^{-1} (FWHM). The dust temperature corresponds to the 60/100 μm color temperature assuming a λ^{-1} dust emissivity law. L_{ir} corresponds to the (8-1000 μm) luminosity determined from the IRAS data using the prescription given in Perault *et al.* (1990). All infrared quantities use fluxes determined from IRAS coadded data that are more accurate than fluxes from the *IRAS Point Source Catalog.*

H_2 masses have been computed in a consistent manner using the published integrated CO intensities and the prescription given in Appendix A of Sanders, Scoville, and Soifer (1991) that attempts to take into account the source-beam coupling factor to obtain a more accurate measure of the CO luminosity, L_{CO}. The total mass of H_2 is given by $M(H_2) = 4.78\ L_{CO}\ [M_\odot]$, assuming a CO→$H_2$ conversion factor of 3×10^{20} H_2 (K km $s^{-1})^{-1}$.

The detection of CO(2→1) emission from Arp 220 with a I_{CO}(2→1)/(1→0) ratio of 0.4 - 0.7 (Casoli *et al.* 1988; Radford, Solomon, and Downes 1990) suggests a rather low gas temperature,

Table 1

Bright Ultraluminous Infrared Galaxies

Galaxy	RA ($^{h\ m\ s}$)	Dec ($^{\circ}\ '\ ''$)	CZ_{co} (km s^{-1})	T_d ($L_\odot$)	log L_{ir} ($M_\odot$)	log $M(H_2)$ ($L_\odot\ M_\odot^{-1}$)	L/M (°K)	Tel [a]	Ref [b]
VII Zw31	50822.7	793649	16245	38	11.93	10.73	16	I	1
IR0518-25*	51858.6	-252440	12816	50	12.12	10.44	48	N	2
IR0603-71	60334.6	-710258	23888	44	12.19	10.55	44	S	3
IR0857+39*	85713.0	391540	17469	59	12.09	9.77	209	I	4
IR0911-10	91111.1	-100701	16273	39	12.01	10.44	37	S	3
UGC 5101	93204.8	613437	11807	38	11.97	10.50	29	N	2
IR1056+24	105635.5	244843	12895	42	12.00	10.37	43	N	2
IR1211+03	121112.2	030520	21788	45	12.25	10.68	37	N	2
Mrk 231*	125404.8	570838	12660	49	12.51	10.21	200	N	2
Mrk 273	134251.6	560813	11132	47	12.08	10.25	67	N	2
IR1434-14	143452.3	-144724	24723	46	12.26	10.85	26	N	2
IR1437-36	143753.4	-365134	20444	46	12.17	10.29	77	S	3
Arp 220	153246.9	234008	5542	45	12.13	10.42	51	I	5
IR1720-00	172048.2	-001417	12854	45	12.38	10.71	47	S	3
IR1925-72*	192527.8	-724539	18479	42	12.05	10.58	30	S	3
IR2055-42	205509.3	-425038	12940	51	12.00	10.36	43	S	3
IR2249-18	224909.6	-180821	23170	50	12.10	10.52	39	N	2
IR2312-59	231250.6	-591938	13403	47	12.00	10.18	65	S	3

Note: The IRAS Bright Galaxy Surveys are complete to a 60 μm flux limit of 5.2 Jy over 90% of the sky. There are 21 BGS objects with $L_{bol} > 10^{12}$ $L_\odot$, 18 of which have been observed and detected in CO(1→0). Three objects (IRAS 15250+3609, IRAS 19297-0406, IRAS 23365+3604) have not been observed in CO(1→0). (∗) denotes objects also included in the IRAS 'warm' galaxy survey (see Table 2).

[a] I - IRAM 30m; N - NRAO 12m; S - SEST 15m

[b] 1 - Sage and Solomon (1987); 2 - Sanders, Scoville, and Soifer 1991; 3 - Mirabel *et al.* (1990); 4 - Sanders *et al.* (1989b); 5 - Solomon, Radford, and Downes (1990)

T_K = 10 - 15 °K, and moderate H_2 densities of a few hundred per cm^{-3} similar to what is found for galactic giant molecular clouds, suggesting that the CO→H_2 conversion factor used here for ultraluminous infrared galaxies is appropriate.

The H_2 masses listed in Tables 1 and 2 are probably uncertain by 20-30% due both to an uncertainty in the measured CO integrated intensity and to the assumed source-beam coupling. Hear we have assumed that the CO source size is smaller than 0.5 θ_{mb}, which is probably a good approximation for most of the reported detections. Total H_2 masses are typically in the range $1 - 7 \times 10^{10}$ $M_\odot$, or 5 - 35 times the total H_2 mass of the Milky Way. The ratio $L_{ir}/M(H_2)$ ranges from $\sim$ 20-200 $L_\odot M_\odot^{-1}$ compared to the value 4 $L_\odot M_\odot^{-1}$ for normal isolated spirals like

https://doi.org/10.1017/S0074180900244732 Published online by Cambridge University Press

Table 2

'Warm' Ultraluminous Infrared Galaxies and Quasars

Galaxy	RA ($^{h\ m\ s}$)	Dec ($^{\circ}\ '\ ''$)	CZ_{co} (km s^{-1})	T_d (°K)	log L_{ir} ($L_{\odot}$)	log $M(H_2)$ ($M_{\odot}$)	L M^{-1} ($L_{\odot}M_{\odot}^{-1}$)	Tel [a]	Ref [b]
I Zw1 †	05057.8	122520	18317	44	11.89	10.43	29	I	1
Mrk 1014 †	15716.6	000908	48913	47	12.56	10.66	81	I	2
IR0518-25*	51858.6	-252440	12816	50	12.12	10.44	48	N	2
IR0759+65 †	75952.9	650821	44621	46	12.45	10.87	38	I	4
IR0857+39*	85713.0	391540	17469	59	12.09	9.77	209	I	4
IR1207-04 †	120711.7	-044439	38600	51	12.35	10.67	49	I	5
Mrk 231*	125404.8	570838	12660	49	12.51	10.21	200	N	2
Pks 1345+12 †	134516.5	123221	36651	46	12.29	10.87	26	N	6
Mrk 463A/B †	135339.7	183658	15252	51	11.76	10.00	58	I	4
IR1520+33 †	152038.3	334212	37485	44	12.18	10.69	31	N	2
E1821+643	182144.	641932	90238	34	13.02	11.19	69	I	7
IR1925-72*	192527.8	-724539	18479	42	12.05	10.58	30	S	3

Note: 'Warm' infrared galaxies were selected on the basis of $f_\nu(25)/f_\nu(60) > 0.2$. (∗) denotes objects from the complete BGS as summarized in Table 1. (†) denotes objects from the complete 'warm' infrared galaxy survey of Sanders *et al.* (1988b), with $f_\nu(60) > 1.5$ Jy. E1821+643, with $f_\nu(60) = 1.0$ Jy, was taken from the list of *Quasars Detected by IRAS Astronomical Satellite* (Neugebauer *et al.* 1986).

[a] I - IRAM 30m; N - NRAO 12m; S - SEST 15m

[b] 1 - Barvainis, Alloin, and Antonucci (1989); 2 - Sanders, Scoville, and Soifer (1988); 3 - Mirabel *et al.* (1990); 4 - Sanders *et al.* (1989b); 5 - Sanders *et al.* (1990); 6 - Mirabel, Sanders, and Kazès (1989); 7 - Alloin *et al.* (1990), with $M(H_2)$ computed from their reported I_{co} = 1.1 km s^{-1}, and CO redshift of 0.301 .

the Milky Way.

The H_2 masses are displayed in Figure 3, where they are compared also with data from lower luminosity IRAS BGS galaxies. In general, ultraluminous infrared galaxies seem to be found among the most molecular gas-rich systems although there is substantial overlap with lower luminosity objects. The fact that all galaxies with $M(H_2) > 5 \times 10^{10}\ M_{\odot}$ are ultraluminous in the infrared is most likely an artifact of the flux-limited infrared surveys that are incapable of detecting lower luminosity objects at redshifts larger than ~0.05. Among ultraluminous galaxies from the complete IRAS BGS, the four 'warm' objects have a mean $L_{ir}/M(H_2)$ ratio of 120 $L_{\odot}M_{\odot}^{-1}$, a factor of 3 larger than for the sample of 14 cooler BGS objects. The ratio for all 12 'warm' galaxies drawn primarily from the survey of Sanders *et al.* (1988b) is 72 $L_{\odot}M_{\odot}^{-1}$, a factor of 2 larger than that for cooler ultraluminous objects.

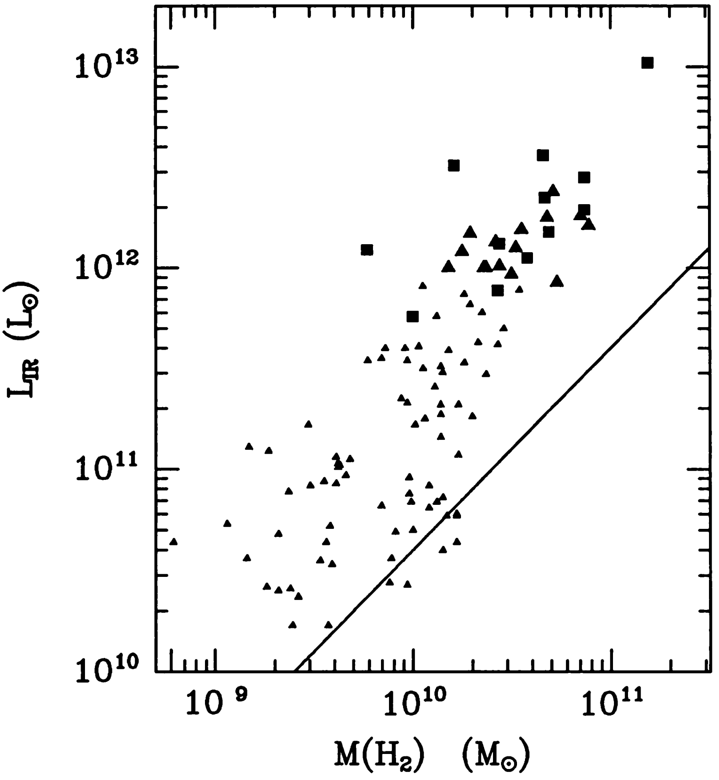

Figure 3. Infrared luminosity, $L_{ir}(8 - 1000\mu m)$, versus H_2 mass for luminous infrared galaxies. Large triangles represent ultraluminous objects from the complete IRAS BGS, large squares, ultraluminous 'warm' IRAS galaxies and quasars from surveys with known and unknown selection bias, and small triangles, lower luminosity objects in the IRAS BGS (see Sanders, Scoville, and Soifer 1991). The solid line represents a L/M value of 4.

4. Origin and Evolution

Ground-based optical and infrared observations suggest an evolutionary connection between ultraluminous infrared galaxies and optical quasars. Previous studies (Sanders *et al.* 1988a; Scoville and Norman 1988), using data primarily from the IRAS BGS and IRAS 'warm' galaxy surveys, have summarised the evidence that suggests that ultraluminous infrared galaxies represent the initial, dust-enshrouded stages of quasars triggered by the strong interaction/merger of two gas-rich spiral galaxies. More recent ground-based data covering the complete IRAS BGS and the larger collection of infrared and optical quasars discussed here strengthens this picture.

The extension of the IRAS BGS to the southern hemisphere has nearly doubled the number of nearby ($z < 0.08$) ultraluminous objects for study. Melnick and Mirabel (1990) and Mirabel (this volume) have shown that, like their northern counterparts, all of the ultraluminous BGS galaxies in the south appear to be strongly interacting/merging systems. Mirabel *et al.* (1990) have also shown that all of these objects are extremely rich in molecular gas.

Unfortunately, surveys for CO emission from a comparison sample of nearby UV-excess quasars have not been reported, although one object, I Zw 1, has been found to be rich in molecular gas, and at least one other, II Zw 136, has been shown to be extremely rich in H I (Condon, Hutchings, and Gower 1985). However, several more distant examples of infrared and UV-excess quasars have been shown to be rich in molecular gas (e.g. Mrk 1014), and it seems likely that further attempts to detect CO emission from quasars will be successful.

Current CO(1→0) data clearly indicates that molecular gas plays a central role in the energetics of ultraluminous infrared galaxies. Recent interferometer observations of several ultraluminous galaxies in the IRAS BGS show that strong concentrations of molecular gas are present in the centers of these galaxies (Scoville *et al.*, 1989, 1990; Okumura *et al.*, this volume; Planesas, Sanders, and Mirabel 1990). Such concentrations appear to be a natural consequence of the merger of two molecular gas-rich spirals (Noguchi, this volume; Hernquist 1989).

Further CO observations of complete samples of more distant infrared objects using new, more sensitive IRAS surveys (e.g. the all-sky $F_\nu(60) > 2$ Jy survey of Strauss *et al.* 1990, or the QMC- Cambridge-Durham survey, Saunders *et al.* 1990), and of UV-excess quasars are required before it will be possible to trace the evolution of the central gas concentration during the infrared excess phase through the evolution into optical quasars.

5. Summary

CO(→0) single dish observations of a complete sample of ultraluminous infared galaxies in the local universe ($z < 0.08$) show that:

1) For a sample of 14 ultraluminous BGS galaxies with a strong 60-100 μm excess, the mean H_2 mass is 3.7×10^{10} $M_\odot$, and the mean $L_{ir}/M(H_2)$ ratio is 43 $L_\odot M_\odot^{-1}$.

2) For four ultraluminous BGS galaxies with 'warm' infrared colors, $f_\nu(25)/f_\nu(60) > 0.2$, the mean H_2 mass is 2.2×10^{10} $M_\odot$ and the mean $L_{ir}/M(H_2)$ ratio is 120 $L_\odot M_\odot^{-1}$. The factor of approximately two lower H_2 gas mass and three higher L/M ratio than found for cooler objects suggests that the central heating source is slightly more intense while H_2 gas supplies are beginning to be depleted during the 'warm' infrared phase.

CO(1→0) observations of more distant objects (z = 0.8 - 0.3) have detected abundant molecular gas from objects which span the range of spectral types from infrared-excess to UV-excess quasars, demonstrating that large amounts of molecular gas may continue to be present during the evolution of ultraluminous infrared galaxies into optically selected quasars.

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