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DENSE MOLECULAR GAS AND STARBURSTS IN ULTRALUMINOUS GALAXIES

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ABSTRACT

With the IRAM 30 m telescope we observed HCN($1 \rightarrow 0$) emission from five ultraluminous galaxies, three lower luminosity interacting systems, and two gas-rich normal galaxies. There are huge masses of high-density gas ($2 \times 10^{10}\ M_{\odot}$) in the ultraluminous galaxies, which shows star formation, rather than active galactic nuclei, generates their infrared luminosity. HCN traces H_2 at a much higher density, $\sim 10^4$ cm^{-3}, than CO (~ 500 cm^{-3}). The ultraluminous galaxies Mrk 231, Arp 193, Arp 220, and NGC 6240 have HCN($1 \rightarrow 0$) luminosities greater than the CO($1 \rightarrow 0$) luminosity of the Milky Way. Mrk 231 has $3 \times 10^{10}\ M_{\odot}$ of H_2 at a density near 10^4 cm^{-3}, ~ 300 times the mass of dense H_2 in the Milky Way. We also detected $HCO^+(1 \rightarrow 0)$ emission from Mrk 231 and Arp 220 at half the strength of HCN($1 \rightarrow 0$). The ratio of HCN to CO luminosity is 1/6 for ultraluminous galaxies, but only 1/80 in normal spiral galaxies. A large fraction of the molecular gas in ultraluminous galaxies, perhaps 50%, is in very dense regions similar to star-forming cloud cores, rather than in the envelopes of giant molecular clouds. The ratio of far infrared to HCN luminosity is similar in both ultraluminous galaxies and normal spirals, including the Milky Way, which suggests the star formation rate per mass of *dense* gas is independent of the infrared luminosity or the state of interaction. The molecular gas density in the central regions of the ultraluminous galaxies, $\sim 500\ M_{\odot}$ pc^{-3}, is similar to the stellar density in the centers of elliptical galaxies, consistent with the idea some mergers may eventually become ellipticals.

Subject headings: galaxies: individual (Arp 193, Arp 220, Arp 299, Mrk 231, NGC 520, NGC 828, NGC 1530, NGC 3147, NGC 3690, NGC 6240, NGC 7771) — galaxies: interstellar matter — infrared: galaxies — ISM: molecules

Ultraluminous infrared galaxies ($L_{FIR} \sim 10^{12}\ L_{\odot}$) are rich in molecular gas, $M(H_2) \approx 2 \times 10^{10}\ M_{\odot}$. Although this is 10 times the H_2 content of the Milky Way, some normal spirals have as much molecular gas in their inner disks. Ultraluminous galaxies have, however, $L_{FIR}/M(H_2)$ ratios 10 times greater than those of normal spirals (Sanders et al. 1986; Solomon & Sage 1988), and their molecular gas is often concentrated in the central 1–3 kpc, rather than spread throughout the inner disk (Scoville et al. 1991). Until now CO has been the only molecule observed in ultraluminous galaxies, and molecular hydrogen masses have been estimated with the Galactic $M(H_2)/L_{CO}$ ratio, which is derived for regions where $n(H_2) \approx 10^2$–10^3 cm^{-3}. While this density characterizes most of the H_2 mass in Galactic disk GMC's (Scoville et al. 1987; Solomon et al. 1987), it is much less than the ambient density, $n(H_2) \approx 10^4$–10^6 cm^{-3}, in cloud cores where stars form, particularly high-mass OB stars.

To measure the mass of *dense* molecular gas and, therefore, the star formation potential of luminous IR galaxies, we have observed HCN and CS line emission. These molecules both trace higher density gas than CO, since they have large dipole moments and require $n(H_2) \geq 10^4$ cm^{-3} for significant excitation. The CS($3 \rightarrow 2$) luminosity of Arp 220, shows this galaxy has $\approx 10^{10}\ M_{\odot}$ of dense gas (Solomon, Radford, & Downes 1990). HCN($1 \rightarrow 0$) and $HCO^+(1 \rightarrow 0)$ emission from Arp 220 have been mapped with the IRAM interferometer (Radford et al. 1991a). Here we report observations of HCN($1 \rightarrow 0$) and CO($1 \rightarrow 0$) from five ultraluminous galaxies classed as advanced mergers, three interacting systems, and two gas-rich galaxies with normal infrared luminosity.

The ultraluminous galaxies Arp 220 ($L_{FIR} = 10^{12}\ L_{\odot}$) and Mrk 231 ($L_{FIR} = 1.7 \times 10^{12}\ L_{\odot}$) both have $L_{CO} \approx 5 \times 10^9$ K km s^{-1} pc^2, so for these galaxies $L_{FIR}/L_{CO} = 210 - 290\ L_{\odot}$ (K km s^{-1} pc^2)$^{-1}$ (Table 1). If the standard Galactic $M(H_2)/L_{CO}$ ratio is applicable, then $M(H_2) \approx 2 \times 10^{10}\ M_{\odot}$ and $L_{FIR}/M(H_2) \approx 50\ L_{\odot}\ M_{\odot}^{-1}$ (Solomon & Sage 1988; Radford et al. 1991b). Arp 193 and NGC 6240 are about half as luminous, but equally gas rich. Arp 299 is a luminous merger with three concentrations of molecular gas and IR emission (Gehrz, Sramek, & Weedman 1983; Sargent & Scoville 1991; Wynn-Williams et al. 1991). All five of these systems have high L_{FIR}/L_{CO} ratios. NGC 520 and NGC 828 are mergers with disturbed morphologies and L_{FIR}/L_{CO} ratios intermediate between ultraluminous and normal galaxies (Solomon & Sage 1988 and references therein). The gas-rich edge-on galaxy NGC 7771 and its close companion are interacting, but their shapes are only mildly disturbed; it also has intermediate L_{FIR}/L_{CO}. We included two galaxies in our sample as controls, NGC 1530 and NGC 3147, which have large molecular masses but normal infrared luminosities and low L_{FIR}/L_{CO} ratios. The large Sb galaxy NGC 3147 has a CO ring extending from a radius of 2–9 kpc (Downes et al. 1991). NGC 1530 is an SBb galaxy with a pronounced bar extending out to a radius of ~ 5 kpc. Our 13″ resolution CO($2 \rightarrow 1$) map (Solomon, Downes, & Radford 1989) shows a strong nuclear disk of radius 1.5 kpc, weak emission along the bar, and secondary weak maxima at the ends of the bar.

The observations were made between 1988 and 1991 at the IRAM 30 m telescope with the techniques reported earlier (Radford et al. 1991b). For all but one galaxy the HCN was observed over a region covering at least 80% of the CO emis-

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TABLE 1

HCN(1 → 0) AND CO(1 → 0) LINE INTENSITIES, LUMINOSITIES, AND H_2 MASSES OF IR LUMINOUS GALAXIES

Galaxy	R.A. (1950)	Decl. (1950)	cz (km s^{-1})	I_{HCN}[a] (K km s^{-1})	I_{CO}[a] (K km s^{-1})	L_{FIR}[b] (10^{10} $L_\odot$)	L_{CO}[c] ($10^8 L_l$)	L_{HCN}[c] ($10^8 L_l$)	$M_{HCN}(H_2)$[d] (10^{10} $M_\odot$)	L_{FIR}/L_{CO} ($L_\odot/L_l$)	L_{FIR}/L_{HCN} ($L_\odot/L_l$)	L_{CO}/L_{HCN}
Mrk 231	$12^h54^m05^s.0$	+57°08′39″	12650	3.3	22	170	59	14	3	290	1200	4.2
Arp 220	15 32 46.9	+23 40 08	5450	8.5	109	107	51	6.5	1	210	1600	8
NGC 6240	16 50 27.7	+02 28 58	7340	5.9	63	56	56	8.5	2	89	600	6.5
Arp 193	13 18 17.0	+34 24 07	7000	5.7	36	40	31	8.0	1.6	130	500	3.7
Arp 299 A	11 25 44.1	+58 50 17	3100	3	60	39	18[e]	1.5[e]	0.3	217	2600	11
Arp 299 C	11 25 41.3	+58 50 20	3160	2.8	62							
NGC 7771	23 48 52.1	+19 49 57	4280	6.0[f]	105[f]	14	63[g]	4.5[g]	0.9	23	305	13
NGC 828	02 07 06.8	+38 57 23	5350	0.8[h]	80	14	36	0.9	0.2	39	1540	40
NGC 520	01 21 59.3	+03 31 47	2270	3.4	48	4.9	14[i]	0.5	0.1	35	1000	40
NGC 3147	10 12 41.0	+73 38 50	2990	1.8[j]	16	4.0	59[i]	0.9[k]	0.2	6	500	90
NGC 1530	04 17 03.6	+75 10 43	2500	2.0	57	3.0	23[i]	0.3	0.06	13	1000	60
Milky Way[l]	...	...	...	...	...	0.71[m]	4[n]	0.04	0.01	18	1800	100
IC 342-1 kpc[o]	...	...	...	...	...	0.06	0.2	0.014	0.003	29	430	15

[a] T_{mb}; 4.4 Jy K^{-1} for point sources.
[b] L_{FIR} calculated from the IRAS 60 and 100 μm fluxes.
[c] L_l = K km s^{-1} pc^2.
[d] Mass of H_2 at $n(H_2) \approx 10^4$ cm^{-3}.
[e] Total for both components.
[f] Central intensities.
[g] Luminosities from maps of both CO(1 → 0) and HCN(1 → 0).
[h] Marginal detection.
[i] Solomon & Sage 1988.
[j] Strongest position. HCN(1 → 0) also observed in three other points.
[k] Luminosity estimated from HCN/CO ratios at observed points and CO map.
[l] Mostly from the molecular ring.
[m] Cox & Mezger 1989.
[n] Rivolo & Solomon 1988.
[o] Central 1 kpc of IC 342 (Downes et al. 1992).

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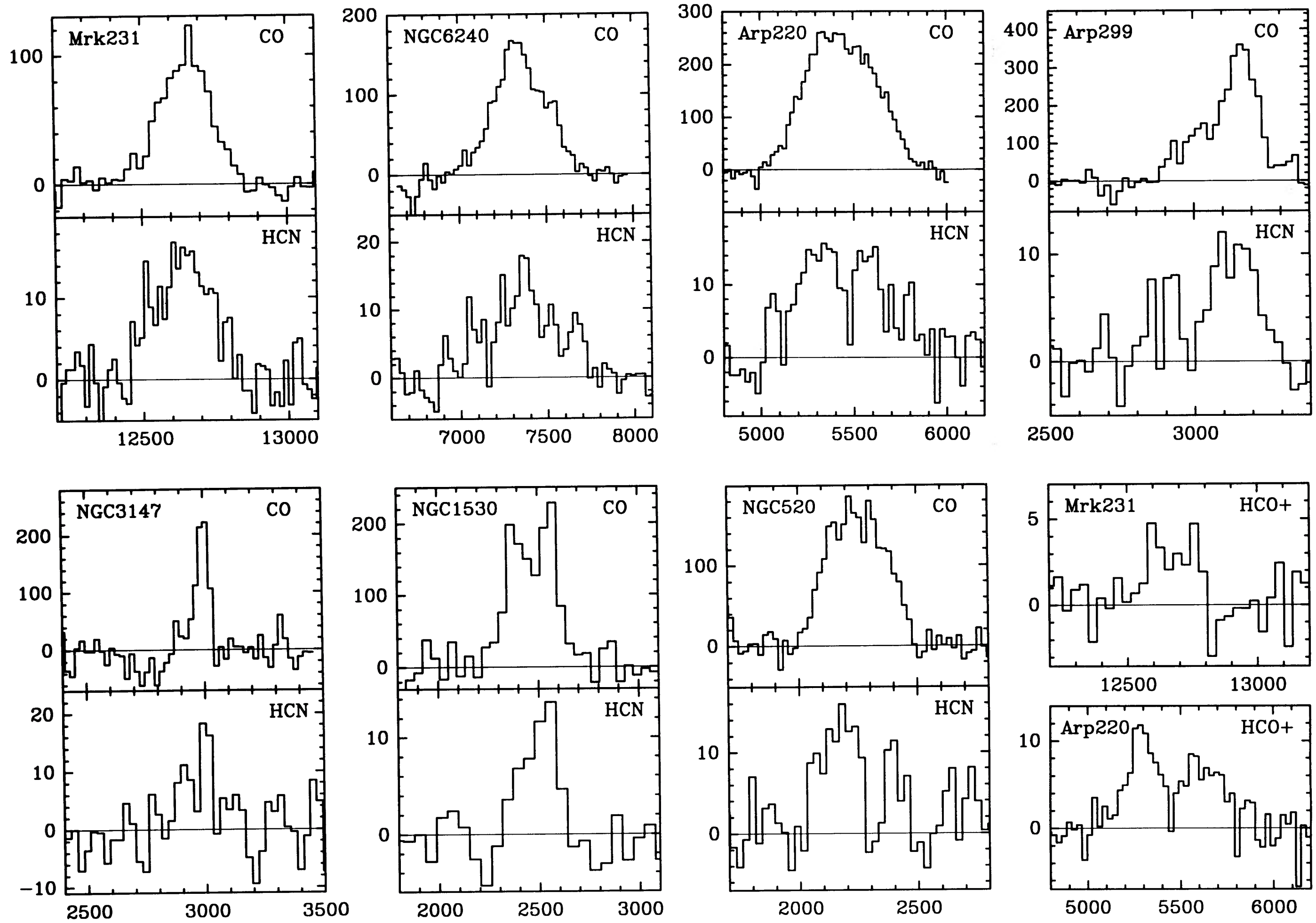

FIG. 1.—CO(1 → 0) (*upper*) and HCN(1 → 0) spectra (*lower*) at 8 MHz resolution of the ultraluminous galaxies Mrk 231, Arp 220, and NGC 6240, the mergers Arp 299 = (NGC 3690 and IC 694) and NGC 520, and the gas-rich normal spirals NGC 1530 and NGC 3147. Our HCO^+(1 → 0) spectra of Mrk 231 and Arp 220 are shown at lower right. Vertical scale is main beam brightness temperature in mK (4.4 Jy K^{-1} for point sources), horizontal scale is radial velocity (*cz*) in km s^{-1}, and linear baselines were subtracted.

sion, which except as noted in Table 1 required only one observation with the beam (28″ FWHM at 3.4 mm). In NGC 3147, four positions were sampled and the total HCN luminosity estimated from the HCN/CO ratios.

All 10 galaxies have similar HCN and CO line shapes (Fig. 1). Table 1 lists the integrated intensities, $I = \int T_{\rm mb}\, dv$ and line luminosities, $L_{\rm HCN} = I_{\rm HCN} D^2 \Omega$, where $D = cz/H_0$ is the distance to the galaxy, $H_0 = 75$ km s^{-1} Mpc^{-1}, and Ω is the solid angle of the beam convolved with the source. We also detected HCO^+(1 → 0) emission from Mrk 231 and Arp 220, which probably traces gas at a density similar to that traced by HCN. We searched for another high-density tracer, CS, in some of these galaxies, but without success except for Arp 220, where we detected CS(3 → 2) (Solomon et al. 1990) and CS(2 → 1). Our limits show the CS(3 → 2) luminosities are less than half those of HCN(1 → 0). The lack of CS detections is not surprising, since CS traces even higher density gas (10^5 cm^{-3}) than HCN, and in the Galaxy the CS lines are usually weaker.

The ultraluminous galaxies Mrk 231, Arp 193, Arp 220, and NGC 6240 have extraordinary HCN(1 → 0) luminosities, greater than the CO(1 → 0) luminosity of the Milky Way, $L_{\rm CO} = 4 \times 10^8$ K km s^{-1} pc^2. In particular, the *Seyfert 1 QSO Mrk 231 has an* HCN(1 → 0) *luminosity 4 times the Milky Way's* CO(1 → 0) *luminosity*. For these sources, the mean CO(1 → 0)/HCN(1 → 0) luminosity ratio is six, which indicates much of the molecular gas is in a dense phase. By contrast, the fraction of dense gas in our Galaxy is much smaller. Although there are no large-scale HCN surveys of the Milky Way, observations of CS(2 → 1) are a guide, since CS and HCN in Galactic disk GMCs both trace cloud cores, not the larger CO-emitting cloud envelopes. Extensive observations (Mooney 1992; Lee, Snell, & Dickman 1990) of Galactic GMC's show the average CS(2 → 1)/CO(1 → 0) intensity ratio is ∼1/300. Since HCN(1 → 0) is usually 1.5 or 2 times stronger than CS(2 → 1) and has slightly larger source sizes, we adopt an HCN(1 → 0)/CO(1 → 0) ratio ∼1/100 for the Galactic disk (molecular ring), which gives an HCN luminosity for the Milky Way of $\sim 4 \times 10^6$ K km s^{-1} pc^2, 500 times smaller than that of Mrk 231. The central 1 kpc region of the nearby spiral galaxy IC 342 has luminosity ratios (Downes et al. 1992) that suggest a moderate starburst, intermediate between our Galaxy and ultraluminous ones.

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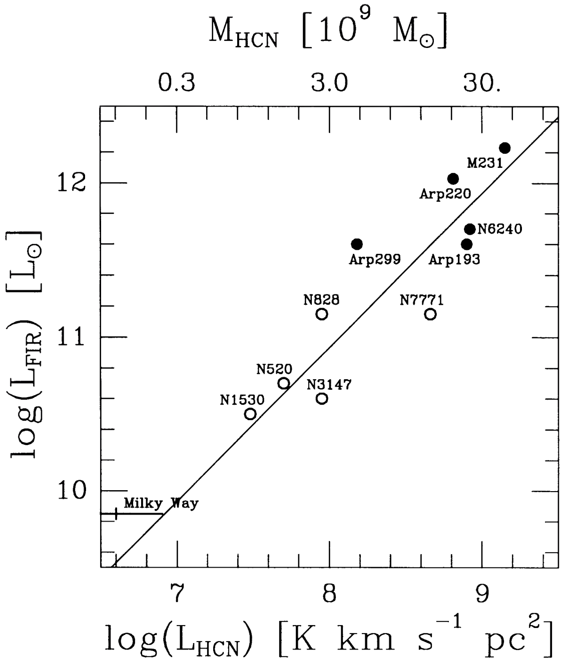

FIG. 2*a*

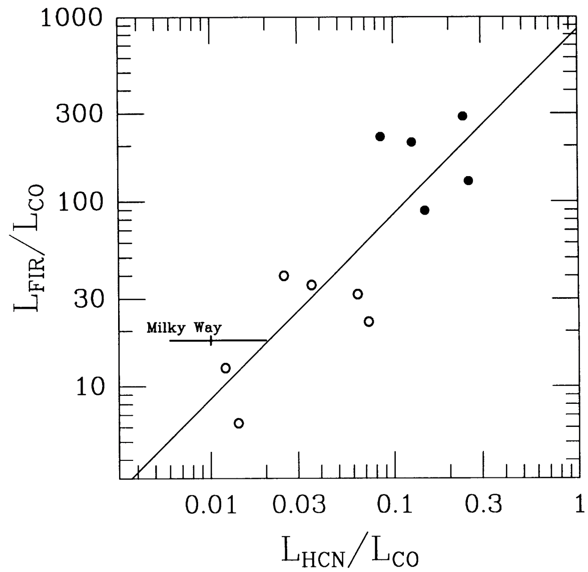

FIG. 2*b*

FIG. 2.—(*a*) The correlation between FIR and HCN luminosities for the 10 galaxies in the sample and for the Milky Way. The solid line is the best fit with the slope fixed at 1.0. A fit with the slope as a free parameter gives a slope of 1.03. The upper scale gives the mass of molecular hydrogen at a density $\approx 10^4$ cm^{-3}, $M_{HCN}(H_2) = 20\, L_{HCN}$ (see text).

FIG. 2.—(*b*) The FIR luminosity and HCN luminosity for the sample galaxies, normalized by the CO luminosity. The vertical axis has units of $L_\odot$ (K km s^{-1} pc^2)$^{-1}$. The HCN/CO luminosity ratio correlates well with the FIR/CO luminosity ratio, which suggests the HCN/CO luminosity ratio is a good indicator of star formation.

In our sample, we find a much tighter correlation between far-IR and HCN($1 \rightarrow 0$) *luminosities than between far-IR and* CO($1 \rightarrow 0$) *luminosities.* For example, while the control galaxy NGC 3147 has the same CO luminosity as Mrk 231, it has only 1/40 the FIR luminosity and 1/15 the HCN luminosity. For our 10 galaxies the range of CO luminosities is only a factor of 3, but the HCN and FIR luminosities both range over a factor of 50. In a plot of L_{FIR} versus L_{HCN} (Fig. 2*a*), normal gas-rich galaxies, the Milky Way, *and* luminous IR galaxies all lie near the same line, unlike the diagram of L_{FIR} versus L_{CO} (Sanders, Scoville, & Soifer 1991; Solomon & Sage 1988) where luminous IR galaxies have L_{FIR}/L_{CO} ratios 10–30 times higher than for normal spirals or the Milky Way. Young et al. (1986) stressed the good correlation of L_{FIR} with L_{CO}, but only after segregating the sample by dust temperature. Actually the L_{FIR}–L_{CO} correlation is poor when all galaxies, including interacting systems, are included. *Unlike* the CO luminosity, the HCN luminosity scales with FIR luminosity, regardless of the FIR luminosity or the degree of interaction with companion galaxies. On average, mergers have the same L_{FIR}/L_{HCN} ratio as ordinary galaxies.

Figure 2*b* shows L_{FIR} and L_{HCN} normalized by L_{CO} to eliminate effects of distance and galaxy size on the correlation. The L_{HCN}/L_{CO} ratio indicates the fraction of molecular gas at the high densities, $n(H_2) \geq 10^4$ cm^{-3}, characteristic of star-forming cloud cores. If L_{FIR}/L_{CO} measures the efficiency of converting molecular gas into OB stars, then Figure 2*b* suggests this efficiency is proportional to the fraction of molecular gas in dense cloud cores. Differences in star formation activity between luminous IR galaxies and normal spirals, reflected in different L_{FIR}/L_{CO} or $L_{FIR}/M(H_2)$ ratios, are then due to differences in the fraction of interstellar gas in dense cloud cores.

If HCN traces gas in gravitationally bound or virialized clouds, the line luminosity tells us the total mass of dense molecular gas. Following the analysis of CS($3 \rightarrow 2$) (Solomon et al. 1990) and using HCN radiative transfer solutions (e.g., Kwan & Scoville 1974), we can determine a molecular mass to HCN luminosity ratio. For kinetic temperatures 20–60 K and an abundance ratio HCN/H_2/$(dv/dr) \approx 10^{-7}$–10^{-8} (km s^{-1} pc^{-1})$^{-1}$, the intrinsic HCN line brightness temperature $T_b =$ 3–40 K and $M_{HCN}(H_2)/L_{HCN} \approx 20^{+30}_{-10}\, M_\odot$ (K km s^{-1} pc^2)$^{-1}$, where $M_{HCN}(H_2)$ is the mass of H_2 at a density near 10^4 cm^{-3} traced by HCN($1 \rightarrow 0$). This is 4 times higher than the similar ratio for CO($1 \rightarrow 0$) in our Galaxy.

The mass of high-density gas in the most luminous galaxies exceeds $10^{10}\, M_\odot$ (Table 1). Mrk 231 has $\sim 3 \times 10^{10}\, M_\odot$ at high density, equal to the mass of lower density gas traced by CO. In giant molecular clouds in the Galactic disk, only a small fraction of the gas is sufficiently dense to form OB stars. Indeed, many Galactic GMCs have little or no O star formation (Mooney & Solomon 1988). The relevant parameter for star formation is not the mass of molecular gas derived from CO observations, $M_{CO}(H_2)$, but rather the mass fraction at high density, $dM(H_2)/d \log n(H_2)$. While the Milky Way and ordinary spiral galaxies have 20 times more mass at a density ~ 300 cm^{-3} than they do at 10^4 cm^{-3}, luminous IR galaxies have nearly equal masses in each decade of density between 10^2 and 10^4 cm^{-3}. The molecular gas in ultraluminous galaxies is more similar to that in active star-forming cloud cores than that in the envelopes of GMCs. Rather than CO, the best

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molecular tracer of star formation is a high-density diagnostic such as HCN.

Some luminous IR galaxies also have active nuclei (e.g., Mrk 231) and there may be an evolution from ultraluminous galaxies to quasars (Sanders et al. 1988). While molecular gas may represent *future* fuel for an AGN, there is no reason why the *present* luminosity of an AGN accretion disk, on a scale of 10^{14} cm, should be proportional to the mass of dense H_2 on a scale of 10^{21} cm, nor why an AGN should have $L_{FIR}/L_{HCN} \approx 1000$ $L_{\odot}$ (K km s^{-1} pc^2)$^{-1}$, the same ratio observed in normal galaxies and regions of O star formation in our Galaxy, such as Orion, M17, or Sgr B2. Massive cloud cores with high-density gas form O stars in our Galaxy and will do so in ultraluminous galaxies as well. From the HCN line, we can measure the mass of high-density gas in luminous IR galaxies, and multiplying this by the Galactic $L_{FIR}/M_{HCN}(H_2)$ ratio gives values remarkably close to the observed FIR luminosities of these galaxies. This strongly indicates active star formation is the main source of the high–FIR luminosity, even though AGNs may also be present.

The four most luminous galaxies in our sample are regarded as mergers. Our HCN data show they have $\sim 2 \times 10^{10}$ $M_{\odot}$ of H_2 at a density of $\sim 10^4$ cm^{-3}, or 500 $M_{\odot}$ pc^{-3}. At this density all the mass would fit in a sphere of diameter 500 pc, about the size of the HCN source in Arp 220 measured with the IRAM interferometer ($\leq 2''$, Radford et al. 1991a). The only stellar systems with a density this high, over this large a region are the central regions of elliptical galaxies. If most of the gas in the core of an ultraluminous merger eventually forms stars with a normal IMF, the region will evolve to look like the center of an elliptical galaxy. The high gas densities are consistent, therefore, with the idea that some ellipticals arise from galaxy mergers (Toomre 1977; Schweizer 1983). Whether or not elliptical galaxies are the eventual outcome, however, the large mass of high-density interstellar gas implied by the HCN luminosity is an extraordinary star forming environment, rare at present, but probably more common in galaxies in the early universe. The centers of ultraluminous galaxies are, therefore, evolving rapidly in conditions that resemble those when galaxies formed.

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