# CO IN ULTRALUMINOUS AND HIGH Z GALAXIES

N.Z. SCOVILLE, M.S. YUN, AND P.M. BRYANT
*Owens Valley Radio Observatory*
*Caltech 105-24, Pasadena, CA 91125*

**Abstract.**

Dense molecular clouds are critical to the activity occurring in galactic nuclei. They are the active component from which starbursts arise, and this dense interstellar gas may be the fuel for AGNs. In the ultraluminous IRAS galaxies, high resolution millimeter line mapping has shown extremely high gas surface densities in the central kpc, and often a significant fraction ($> 25\%$) of the total molecular line emission from the galaxy arises from these central regions. New maps at resolutions down to $0.8''$ in the ultraluminous IRAS galaxies reveal kinematic gradients parallel to the major axis of the CO intensity distribution, suggesting that the gas is situated in a central rotating disk. The most extreme central concentrations are seen in Arp 220 and Mrk 231 (Sey 1) which have now been mapped in both the 2.6 and 1.3 mm CO transitions. In both galaxies, the high observed CO brightness temperatures indicate large area filling factors with mean $H_2$ densities exceeding $10^4 cm^{-3}$. To produce the observed luminosities, the star formation rates must be $\sim$100 $M_\odot$ yr$^{-1}$ within the central 500 pc radius. Estimated time scales for both the dynamical evolution and the exhaustion of the observed central ISM are typically $2\times10^8$ years. At higher redshift, CO emission has been unambiguously detected in two objects, FSC 10214+4724(z=2.3) and H1413+117(z=2.5), both of which are probably graviationally lensed. High resolution mapping of FSC 10214+4724 reveals two components: an unresolved core with 2/3 of the emission and an extended "disk"($9\times24$ kpc). In H1413+117 our CO(7-6) maps at $0.8''$ show a morphology similar to the cloverleaf pattern seen in the optical and the relative fluxes of the four components varies with velocity. Models for the CO lensing are consistent with the molecular emission arising from a disk within about 1 kpc in radius of the quasar. These high redshift systems may therefore be early universe counterparts of the ultraluminous IRAS galaxies.

## 1. INTRODUCTION

The IRAS survey provided a complete sample of luminous starburst galaxies out to moderate cosmological distances ($z < 0.1$); however, high resolution observations of that gas are vital to understand the differences in starburst activity from one galaxy to another. Without such molecular line data, it is not known if the high luminosities are simply due to a large quantity of gas, a more concentrated distribution of molecular gas, or a more efficient trigger for stimulating gas to form stars. It now appears as though all three factors may be at work to varying degrees. Single dish molecular line surveys of samples of IRAS bright galaxies (eg, Sanders, Scoville & Soifer 1991, Tinney *et al* 1988, Sage & Solomon 1988) clearly indicated that the more luminous infrared bright galaxies have greater CO luminosities and thus greater overall masses of dense molecular gas. On the other hand, at the highest luminosities ($> 10^{11} L_{\odot}$), the ratio $L_{IR}/M_{H_2}$ is enhanced by a factor of 5-50 over that measured in normal spiral galaxies like the Milky Way or M51. At high $L_{IR}$ there is also a higher frequency of interacting and merger systems and an increasing fraction of galaxies with the optical emission line ratios indicative of a relatively hard ionizing spectrum, possibly from an active galactic nucleus (see Sanders *et al* 1990). The increasing luminosity-to-mass ratio can be interpreted as a greater efficiency for forming stars in those galaxies or an additional non-stellar source of luminosity.

The peaking of quasar density at $z \sim 2$ as well as the stellar population analysis of galaxies in the local universe suggest that most galaxies must have formed near or prior to the redshift of 2. The identification of the IRAS FSC 10214+4724 with a z=2.3 galaxy ($L > 3 \times 10^{14} L_{\odot}$, Rowan-Robinson et al. 1991) and the subsequent detection of CO emission ($M_{H_2} > 10^{11} M_{\odot}$ – Brown & Vanden Bout 1991, Solomon et al. 1992) have substantiated the hypothesized existence of luminous gas-rich galaxies in the early epochs forming stars at prodigious rates. Given that there has been reasonable heavy element production, CO rotational transitions are excellent probes of cold interstellar medium (ISM) in very distant galaxies. For objects of constant CO brightness temperature in the different rotational transitions, the observed line flux is almost independent of redshift at z = 1-6 due to the factor $(1+z)^2$ in angular size distance. These molecular transitions are also unambiguous tracers of cold, dense molecular gas where stars are forming.

Many of the most active starburst galaxies are subject to strong dynamical perturbations: they are either interacting galaxy systems or show evidence of a central bar-like mass distribution. In both instances there will be strong non-axisymmetric gravitational forces which disturb the circular rotation. The interstellar gas is fundamentally different from the stars – the ISM is extremely dissipative (due to the fact that the gas clouds have much

larger cross-section relative to their mean separation and in cloud collisions the gas radiates strongly in shock fronts). The dissipation of orbital energy (and transfer of angular momentum) leads to transfer of gas towards the galactic center, resulting in high central concentrations of active star-forming molecular clouds. The studies of ultraluminous IRAS galaxies in the local universe are highly relevant to the search for and our understanding of primeval galaxies since both starbursts and galactic merging must have been prevalent in the early universe.

## 2. LUMINOUS IRAS GALAXIES

A major direction of extra galactic molecular line research has been measurement of the molecular gas properties and distributions in luminous IRAS galaxies. The IRAS bright galaxy survey (Soifer *et al* 1987) included 238 objects in the northern hemisphere, and approximately 150 of these have had single dish CO measurements. The resulting $H_2$ masses, assuming the same CO emissivity per unit mass for the Milky Way GMCs, show a clear trend for increasing masses of molecular gas with increasing far infrared luminosity. For the most luminous objects, the total $H_2$ masses are in the range 2-50$\times 10^9 M_\odot$, that is 1-20 times the $H_2$ content of our Galaxy. CO aperture synthesis mapping has been done on approximately 30 of these galaxies. Early aperture synthesis maps at 4-6″ resolution showed that this gas is also much more concentrated in the galactic nuclei than in normal galaxies (see Scoville *et al* 1991, Okumura *et al* 1991). Typically 50% of the molecular gas was found within radii less than or equal to 1 kpc, and the gas mass fractions in the central regions ($M_{H2}/M_{dyn}$) often exceed 50% (as compared with typical values of 5% near the centers of normal galaxies). Recently, several of these galaxies have been observed at 2 ″ resolution in CO (1-0) and at 1″ resolution in the CO (2-1) transition. We describe three of these objects (VV 114, Mrk 231, and Arp 220) in more detail below.

### 2.1. VV 114

VV 114 is an early merger system with $L_{IR} = 6 \times 10^{11} L_\odot$ and a very large gas content, $M_{H_2} = 5 \times 10^{10} M_\odot$. The two galaxy nuclei are seperated by 6 kpc, and CO (1-0) images show the molecular peak between the optical and infrared nuclei (Yun, Scoville, & Knop 1994). The CO is shown superposed on an r-band image in Figure 1. The molecular gas is extended over $\sim$ 5 kpc between the two galaxy nuclei. In fact, the CO distribution is quite similar to that of the non-thermal radio continuum. In this system, the gas is clearly more concentrated toward a central peak than are the two stellar systems. This is interesting because more rapid merging is expected for the gas than for the stars in interacting systems due to the greater dissipation

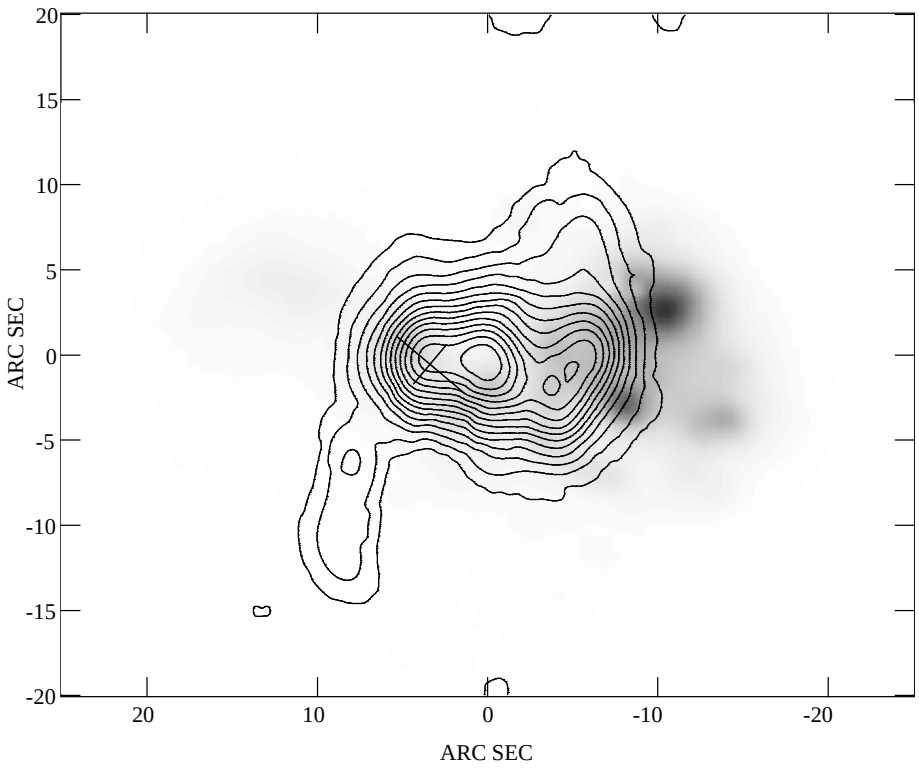


*Figure 1.* The integrated CO (1-0) emission ($3''$ resolution) is shown superposed on an r-band image of the interacting system VV 114 (Yun, Scoville, & Knop 1994). The position of the eastern nucleus which is brightest at $2\mu$m is indicated by the cross. The molecular gas is distributed in a bar-like configuration between the two galaxy nuclei.

in the gas.

### 2.2. MRK 231

Mrk 231 (at 174 Mpc) is one of the few ultraluminous IRAS galaxies in which there is general consensus on the existence of a dust-embedded high luminosity Sey 1 AGN (Boksenberg *et al* 1977). New CO (1-0) and (2-1)

images at 0.8-2″ resolution resolve the CO source and reveal a velocity gradient parallel to the major axis of the CO distribution (Bryant & Scoville 1995). Virtually all of the single dish CO emission is contained within a radius of 420 pc, and the CO brightness temperatures exceed 30K, indicating nearly complete area filling factors for the molecular gas within this radius. The CO conversion factor in such galactic nuclei was extensively analyzed (Bryant & Scoville 1995) and was found to be within a factor of a few of the Galactic value for Mrk 231. Assuming the Galactic value, the nuclear disk of Mrk 231 must be within 22° of face-on, in order to reconcile the dynamical mass with the mass from the CO line emissivity. This is consistent with the modest extinction measured for the Seyfert/quasar nucleus.

### 2.3. ARP 220

Arp 220 at 77 Mpc has been imaged in CO (1-0) (Scoville *et al* 1991), HCN (Radford *et al* 1991) and most recently in CO (2-1) (Scoville, Yun & Bryant 1995). The CO (2-1) maps at 1″ clearly reveal three components in the dense molecular gas: peaks corresponding to each of the double nuclei (separated by 0.9″ at pa = 101°) seen in the near infrared (Graham *et al* 1990) and radio continuum and a more extended disk like structure elongated southwest-northeast, similar to the dust lane seen in optical images. In Figure 2, the CO (2-1) line emission integrated over all velocities is shown superimposed on a H$\alpha$ image of Arp 220. The elongated disk feature exhibits a monotonic velocity gradient parallel to the major axis of the CO intensity distribution, and the dynamical mass determined from the CO is approximately $3\times10^{10}M_{\odot}$ within 0.9″ (360 pc) radius. Bright peaks are also seen in the channel maps coincident with the locations of the two infrared nuclei. The observed kinematics of the molecular gas are consistent with the radial distribution of the CO emissivity in the sense that a rotation curve derived, assuming that the total mass is dominated by the molecular gas (with little contribution from the stars) is consistent with the observed CO line profiles (Scoville, Yun, & Bryant 1995). The CO to $H_2$ conversion ratio which gives best correspondence between the CO kinematics and the dynamical mass distribution is 40% of the standard Galactic value (Scoville, Yun & Bryant 1995).

In Arp 220 the measured mm-wavelength continuum provides a strong constraint on starburst models since any free-free contribution from the HII associated with a starburst must be less than the measured continuum minus the expected dust contribution. The limit on the free-free continuum implies $Q\leq 7.5\times10^{54}s^{-1}$. For a standard Miller-Scalo initial mass function with lower and upper stellar mass cutoffs ($m_l$ and $m_u$), a constant rate of

star formation ($\dot{M}$) and a burst timescale ($t_B$), the ratio of luminosity to Lyman continuum photon production rate (Q) is

$$L/Q = 7.2 \times 10^{-44} \left(\frac{m_l}{5M_\odot}\right)^{-0.37} \left(\frac{m_u}{45M_\odot}\right)^{-0.96} \left(\frac{t_B}{5 \times 10^7 yr}\right)^{0.37} \mathrm{L}_\odot\mathrm{sec}.$$

Combining this constraint with the dynamical mass limit derived from the CO kinematics, Scoville, Yun & Bryant (1995) find that $m_l = 5M_\odot$, $m_u = 23M_\odot$, and $\dot{M} = 90M_\odot yr^{-1}$ (with a burst timescale of $5 \times 10^7 yr$). The narrow range of permissable stellar masses suggests that a starburst origin for a major fraction of the luminosity in Arp 220 is unlikely, although not ruled out. Starbursts with low mass stars ($m_l = 0.1M_\odot$) are categorically ruled out since they violate the $L/M_*$ constraint by more than an order of magnitude; similarly starbursts with only high mass OB stars are easily ruled out since they violate the L/Q constraint.

## 3. HIGH REDSHIFT GALAXIES

The Owens Valley Millimeter Array is very well-suited for detecting gas-rich high redshift systems. The six 10.4-m diameter telescopes in the array provide an effective collecting area of 2040 $m^2$ – comparable to a 25.5-m diameter telescope. Cross-correlation of the signals as is done in interferometry also significantly reduces the instrumental effects that often plague the single dish observations. The OVRO observations also yield spectral map cubes with typical spatial resolution of 2-5″, providing spatial information and, when resolved, kinematic information.

### 3.1. FSC 10214+4724

The CO (3–2) emission region in z=2.3 IRAS galaxy FSC 10214+4724 is resolved by our 2″ resolution observations (see Figure 3). About 1/3 of the total CO flux originates from an extended structure with a narrow line width while the majority of molecular gas belongs to an unresolved structure (Scoville et al. 1995). The small line width for the extended component may be explained if a kinematically distinct section of the galaxy is strongly amplified and the angular extent is increased by gravitational lensing. Since the molecular and far infrared emission probably arise from the same extended gas and dust distribution in the host galaxy, it is likely the both emissions have undergone similar magnifications. If this is the case, then the true luminosity to molecular mass ratio is similar to the apparent ratio ($\simeq 10^3 L_\odot\ M_\odot^{-1}$)– this is approximately 200 times greater than that in the Galaxy! At such high luminosity-to-mass ratios, radiation pressure acting

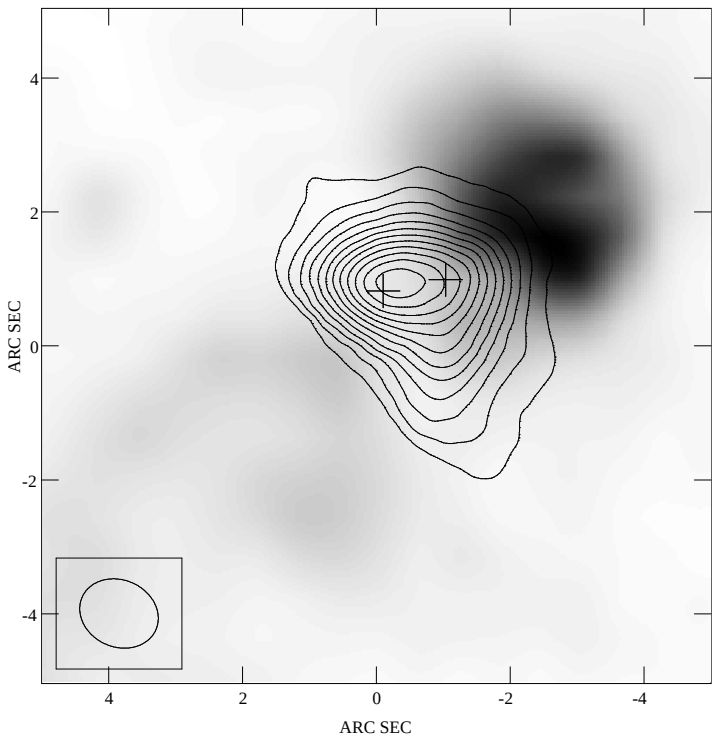


*Figure 2.* CO (2-1) line emission ($1''$ resolution) integrated over all velocities in Arp 220 is shown superimposed on an H$\alpha$ image (Scoville, Yun, & Bryant 1995). The CO emission in the central 500 pc of the galaxy peaks between the two infrared nuclei (spacing $0.95''$) and is elongated in the outer contours parallel to the dust lane crossing the H$\alpha$ emission distribution.

on the dust may provide significant support against gravity, thus alleviating for the problem that the dynamical mass is apparently less than the molecular gas mass (without resorting to a nearly face-on inclination).

### 3.2. H1413+117 (THE CLOVERLEAF)

The CO (7–6) emission from H1413+117 (the Cloverleaf quasar) is also resolved by our $0.8''$ beam (Yun *et al.* 1995). The morphology of the integrated CO emission (shown in Figure 4) is remarkably similar to that of

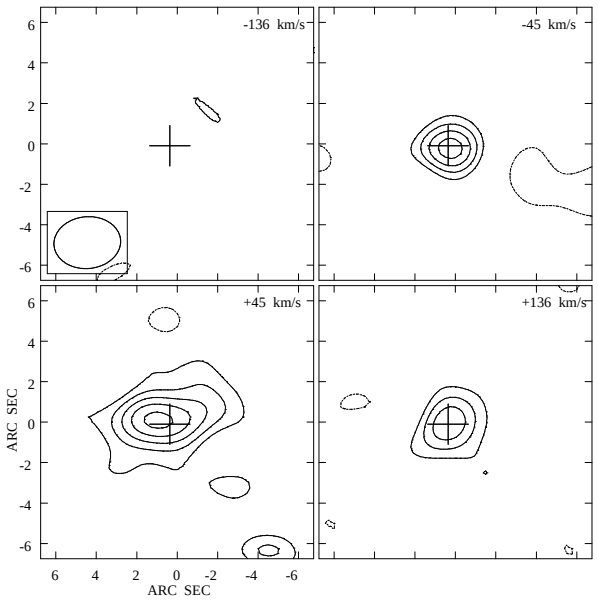


*Figure 3.* New 2″ resolution CO (3–2) maps of FSC 10214+4724 with 90 km s$^{-1}$ velocity channels (Scoville et al. 1995). The cross marks the VLA radio source position. An extended component with a narrow line width is found in V=+45 km/s channel.

optical light, suggesting the CO emitting region is very compact and arises close to the quasar. In CO, the relative brightnesses of the four images seen in the optical varies as a function of velocity and thus the CO enables one to "map" the molecules within the host galaxy, given a suitable model for the lensing. The model presented by Yun *et al* (1995) places the molecular gas in a disk within 1 kpc of the quasar nucleus.

The inferred total $H_2$ mass, $2.3 \times 10^{11} {A_g}^{-1} h^{-2} M_\odot$ ($A_g$ is amplification factor), is nearly identical to the CO (3–2) measurement by Barvainis et al. (1994), and the CO (3–2) emission must arise from high excitation gas ($n > 10^5$ cm$^{-3}$, $T > 50\ K$).

The dust masses estimated from the continuum emission are about $2 \times 10^8$ and $3 \times 10^8 {A_g}^{-1} h^{-2} M_\odot$ for FSC 10214+4724 and H1413+117 (see Downes et al. 1992, Rowan-Robinson et al. 1993, Barvainis et al. 1992). The inferred gas-to-dust ratios are therefore 500 and 800, respectively – similar to the IR luminous systems in the local universe (e.g. Sanders, Scoville, & Soifer 1991). The dust continuum and CO emission are likely co-spatial in distribution and thus similarly amplified by lensing.

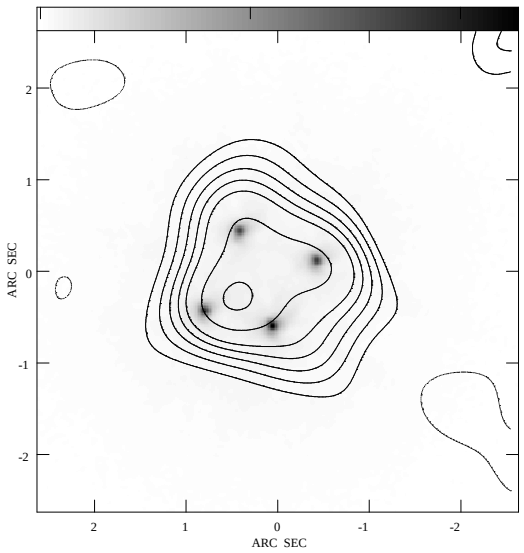


*Figure 4.* CO (7–6) map of H1413+117 at 0.8″ resolution in contours overlaid on the grey scale HST F555W image (Falco 1993).

### 3.3. SUMMARY OF OBSERVATIONS

The results of the OVRO CO observations on other high redshift systems are summarized in Table 1. In the majority of cases, the $H_2$ mass sensitivity is sufficient to detect the more gas-rich galaxies in the local universe. In all cases, any FSC 10214+4724 like objects should have been detected. To improve the detection statistics, more IR-selected candidates need to be searched. Detecting the progenitors of $L_*$ galaxies probably requires an order of magnitude improvement in sensitivity. We note that neither 4C 41.17 (a z=3.8 radio galaxy with dust continuum detection – Chini & Krügel 1994) nor B2 0902+34 (a z=3.4 "protogalaxy" – Eales et al. 1993) were detected in CO. The upper limit on the gas-to-dust ratio is 750 for 4C 41.17. We find the 650$\mu$m (rest) continuum emission from B2 0902+34 dominated by non-thermal emission rather than by dust emission.

## 4. SUMMARY

Important general characteristics of the molecular gas in starburst and high infrared luminosity galactic nuclei include: (1) extremely high gas surface

TABLE 1. Summary of the OVRO CO Observations

| Name | $z$ | Transition | $S_{CO}$ (mJy) | $\Delta V$ (km s$^{-1}$) | $M_{H_2}$ ($h^{-2}10^{10}M_\odot$) |
|---|---|---|---|---|---|
| H1413+117 | 2.56 | CO (7–6) | $120 \pm 12$ | 340 | $23 \pm 2$ |
| FSC10214+4724 | 2.29 | CO (3–2) | $14 \pm 2^a$ | 250 | $12 \pm 2$ |
| 3C 48 | 0.37 | CO (1–0) | $7.7 \pm 1.9^b$ | 250 | $3.9 \pm 0.8$ |
| B2 0902+34 | 3.40 | CO (4–3) | $< 4.1^c$ | $(300)^d$ | $< 3.3^d$ |
| 4C 41.17 | 3.80 | CO (4–3) | $< 4.5$ | (300) | $< 4.2$ |
| 3C 368 | 1.13 | CO (2–1) | $< 8.1$ | (300) | $< 4.5$ |
| TX 1243+036 | 3.58 | CO (4–3) | $< 6.9$ | (300) | $< 5.5$ |
| PC 1033+4750 | 3.68 | CO (4–3) | $< 6.1$ | (300) | $< 5.5$ |
| MG 1019+0535 | 2.77 | CO (3–2) | $< 6.2$ | (300) | $< 6.4$ |
| TX 0211−122 | 2.34 | CO (3–2) | $< 9.1$ | (300) | $< 7.3$ |
| 4C 28.58 | 2.95 | CO (3–2) | $< 7.4$ | (300) | $< 8.5$ |
| H0836+113 | 2.47 | CO (3–2) | $< 13$ | (300) | $< 11$ |
| PC 1643+4631A | 3.14 | CO (3–2) | $< 10$ | (300) | $< 13$ |
| PC 1406+123 | 2.25 | CO (3–2) | $< 12$ | (300) | $< 13$ |

Notes: (a) Scoville et al. (1995); (b) Scoville et al. (1993); (c) all $3\sigma$ upper limits; (d) $\Delta V$=300 km s$^{-1}$ is assumed.

densities exceeding $10^3 M_\odot$ pc$^{-2}$; (2) strong non-circular gas motion often accreting radially along a stellar bar potential or two merging galactic nuclei; (3) high molecular gas mass fractions in the central 500 pc with the gas constituting greater than 50% of the total mass.

The strong non-circular gas motions and high central gas concentrations may be driven by non-axisymmetric gravitational forces from stellar bars or the merging of comparable mass galactic nuclei. Large nuclear gas concentrations can then arise and set off the starburst activity which becomes non-linear due to cloud-cloud collisions and stimulated star formation effects such as high pressure HII regions and supernova blast waves.

The statistics from the IRAS survey indicate that approximately 0.2% of the present epoch spiral galaxies are undergoing high luminosity global starbursts; however, given the short duration of this activity ($2\times10^8$ years) and the fact that standard cosmological evolution would indicate that the interaction rate was higher in the past, nearly all galaxies would be undergoing such merger induced starbursts at z=1-2 (see Scoville & Soifer 1990). Although only a small fraction of present day galaxies are highly luminous in the infrared, the star formation rates are typically enhanced by factors of 10-100, thus a significant fraction of the overall star formation may occur during such brief periods of activity.

Our research is supported in part by NSF Grant AST 93-14079.

## References

Antonucci, J., & Miller, J.S. 1985, *Ap.J.*, 297, 621
Barvainis et al. 1994, Nature, 371. 586
Barvainis, R., Antonucci, R., Coleman, P. 1992, ApJ, 399, L19
Boksenberg, A., Carswell, R.F., Allen, D.A. Fosbury, R.A.E., Penston, M.V., & Sargent, W.L.W. 1977, *M.N.R.A.S.*, 178, 451
Brown, R.L., Vanden Bout, P.A. 1991, AJ, 102, 1956
Bryant, P.M. & Scoville, N.Z. 1995, *Ap.J.*, in press
Chini, R., Krügel, E. 1994, A&A, 288, L33
Downes et al. 1992, ApJ, 398, L25
Eales et al. 1993, Nature, 363, 140
Falco E.E. 1993, in *Gravitational Lenses in the Universe*, eds. Surdej et al. (Universite de Liege, Liege), p.127
Graham, J.R., Carico, D.P., Matthews, K., Neugebauer, G., Soifer, B.T., & Wilson, T.D. 1990, *Ap.J. Letters*, 354, L5
Okumura, S.K., Kawabe,R., Ishiguro,M. Kasuga, T., & Morita, K.I. 1991 in IAU Symposium No. 146, 425
Planesas, P., Scoville, N.Z. & Myers, S.T. 1991, *Ap.J.*, 369, 364
Radford, S.J.E., Delannoy, J., Downes, D. Guelin. M. & Guilloteau, S. 1991, in IAU Symposium, 146, 303
Rieke, G.H., Loken, K., Rieke, M.J. & Tamblyn, P. 1993, *Ap.J.*, 412, 99
Rowan-Robinson et al. 1991, Nature, 351, 719
Rowan-Robinson et al. 1993, MNRAS, 261, 513
Sage, L., & Solomon, P.M. 1989. *Ap.J.*, 334, 613
Sanders D.B., Scoville, N.Z., & Soifer, B.T. 1991, *Ap.J.*, 370, 158
Sanders, D.B., Soifer, B.T., Elias, J.H., Madore, B.F., Matthews, K., Neugebauer, G., & Scoville, N.Z. 1988, *Ap.J.*, 325, 74
Scoville, N.Z., Matthews, K., Carico, D.P. & Sanders, D.B. 1988, *Ap.J.*, 327, L61
Scoville, N.Z., Sargent, A.I., Sanders, D.B., & Soifer, B.T. 1991, *Ap.J.*, 366, L5
Scoville, N.Z. & Soifer, B.T. 1990, in Massive Stars in Starbursts, ed. C. Leitherer (Cambridge: Cambridge Univ. Press), 233
Scoville, N.Z., Yun, M.S., Brown, R., Vanden Bout, P. 1995, ApJ, in press
Scoville, N.Z., Yun, M.S. & Bryant, P.M. 1995, *Ap.J.*, (in preparation)
Shen, J & Lo, K.Y. 1995, *Ap. J. Letters*, 445, L99
Soifer, B.T., & Wilson, T.D. 1990, *Ap. J. Letters*, 354, L5
Solomon, P.M., Downes, D., Radford, S.J.E. 1992, ApJ, 398, L29
Tinney, C.G., Scoville, N.Z., Sanders, D.B. & Soifer, B.T. *Ap.J.*, 362, 473
Yun, M.S., Scoville, N.Z. & Knop, R.A. 1994, *Ap. J. Letters*, 430, L109
Yun, M.S., Scoville, N.Z., Carasco, J.J. & Blandford, R.D. 1995, Nature, in preparation