MOLECULAR GAS IN GALACTIC NUCLEI

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 both the nearby infrared bright galaxies (e.g., M82, NGC 253, and IC342) and the ultraluminous IRAS galaxies, high resolution millimeter line mapping has shown extremely high gas surface densities in the central kpc. 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 $0.8''$ of 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 $10^4 \mathrm{cm}^{-3}$. 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 2×10^8 years.

1. INTRODUCTION

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 that disturb the circular rotation. The interstellar gas is fundamentally different from the stars—the ISM is extremely dissipative (because the gas clouds have much larger cross-sections 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.

In the last few years there have been major advances in observations of molecular gas in the nuclei of galaxies. There are now a number of galaxies that have been mapped at resolutions of 2–4″ in CO, ^{13}CO, and high dipole moment molecules (CS and HCN which trace the higher density molecular gas). As a result of continued improvements in receiver sensitivity and expansions of the mm interferometer arrays, capabilities have improved to the point where such observations can now be done out to systemic velocities of 10,000 km s^{-1}. The most spectactular observational results have been achieved on the infrared bright galaxies.

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 (e.g., 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 ($> 10^{11}\mathrm{L}_{\odot}$) the ratio $\mathrm{L}_{\mathrm{IR}}/M(\mathrm{H}_2)$ 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 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.

2. Nearby Galactic Nuclei

2.1. M82

The M81/M82/NGC 3077 group is at a distance of only 3.3 Mpc and is thus the closest interacting/starburst galaxy group. The entire group has been mapped in HI at 60″ resolution by Yun, Ho, & Lo (1994) and extensive tidal tails are seen extending well beyond the optical disks of the galaxies. In M82, the molecular gas is strongly concentrated towards the center with the total molecular gas mass being as much as 25% of the dynamical mass (Young & Scoville 1984). The nucleus of M82 has been mapped at high resolution in

CO, HCN, and HCO^+ by Lo et al. (1987); Nakai et al. (1987); Carlstrom (1988); and most recently by Shen & Lo (1995). The earlier studies indicated that a substantial fraction of the molecular gas was contained in a torus at radius ~ 150 pc and mass $\sim 10^8 M_\odot$; the relatively strong emission from high dipole moment molecules indicates that the physical conditions are quite different than those of typical Galactic giant molecular clouds. Derived kinetic temperatures are 50 K and the volume densities within the clouds are approximately $10^5 \mathrm{cm}^{-3}$. The most recent observations at $2.5''$ (38 pc) resolution by Shen & Lo (1995) resolve the molecular gas into spiral arms at 125 and 390 pc radii. They also indicate outflow motion at 230 km s^{-1} normal to the plane of the galaxy; however, the galaxy is nearly edge on and thus there is a large inclination correction for motions perpendicular to the disk. The earlier investigations had noted that the bulk of the starburst activity was interior to the molecular gas ring/arms and hence concluded that the starburst had propagated outwards in the central disk of the galaxy. However, Shen & Lo find substantial molecular gas within the starburst region and thus propose that the starburst may be propagating inwards. Modelling of the infrared, optical, and radio data from M82 by Rieke et al. (1993) suggests two bursts of star formation occurring 5×10^6 and 3×10^7 years ago.

2.2. IC 342 AND BARRED SPIRALS

At a distance of 3 Mpc, IC 342 is one of the closest barred spiral galaxies. In fact, the barred nature of this galaxy was first discovered by low resolution aperture synthesis observations (Lo et al. 1984). High resolution CO and ^{13}CO 2.6 and 1.3 mm maps have been obtained by Turner, Hurt, & Hudson (1993) and Turner & Hurt (1993). They find the strongest molecular emission arising from two ridges or spiral arms (along the leading edges of the bar), radial streaming towards the center, and a molecular gas mass fraction $\sim 50\%$ in the inner 100 pc. The high CO (2–1)/(1–0) ratios at the interfaces of the molecular and ionized gas suggest substantial external UV heating of the molecular clouds.

Kenney et al. (1992) have mapped four galaxies in which the bar potential is probably stronger than that in IC 342. In all cases, the molecular gas is strongly concentrated towards the nucleus of the galaxy. In three of the galaxies (M101, NGC 3351, and NGC 6951), the central gas concentration is resolved into twin peaks near the center but positioned perpendicular to the direction of the large-scale stellar bar. In general, the orbits in a bar potential will be elongated parallel to the bar; however, if there is a Lindblad resonance within the bar, orbits inside this ILR are elongated perpendicular to the bar. Kenney et al. (1992) suggest that the twin concentrations of

CO emission are due to orbit crowding where the inner perpendicular orbits meet the outer parallel orbits. At these locations, cloud-cloud collisions and gravitational instabilities could lead to massive accumulations of gas.

2.3. NGC 1068

NGC 1068 is the closest (18 Mpc) galaxy in which both starburst and AGN activity are occurring in the central regions. A total luminosity of $3 \times 10^{11} L_{\odot}$ is approximately equally divided between an extended starburst and a point-like Seyfert 2 nucleus. In addition, near infrared mapping revealed a strong stellar bar extending out to radius 1 kpc (Scoville et al. 1988). High resolution maps of the CO, ^{13}CO, and HCN emission have been obtained by Planesas, Scoville, & Myers (1991); Kaneko et al. (1992); Tacconi et al. (1994); Helfer & Blitz (1995); and Papadoupolus, Seaquist & Scoville (1996). The major features seen in the molecular gas are two strong spiral arms at radius $\sim 15''$(1.5 kpc) that originate from the ends of the stellar (2μm) bar and a compact source ($\sim 3''$) coincident with the Seyfert 2 nucleus. The maps by Heifer & Blitz (1995), which included both interferometric and single dish data, also reveal molecular gas flowing into the nucleus along the leading edges of the stellar bar. The total mass of molecular gas in the inner disk of NGC 1068 is approximately $4 \times 10^9 M_{\odot}$ and approximately 50% of this gas is in the discrete structures mapped interferometrically. Within the spiral arms the gas structures range in size up to 500 pc and their masses are in the range $2 \times 10^7 - 7 \times 10^8 M_{\odot}$ (Planesas et al. 1991). At present it is not clear if these are gravitationally bound structures or simply transient associations of gas clouds similar to those seen in M51 (Rand & Kulkarni 1990). The gas mass in the nuclear concentration is estimated to be $8 \times 10^7 M_{\odot}$ (within 130 pc radius, Planesas et al. 1991); however, relatively strong HCN emission is seen here (e.g., Tacconi et al. 1994) and it is, therefore, doubtful that the standard Galactic conversion ratio should be applied. The mass of gas and dust in this source is clearly sufficient to obscure the broad line Seyfert 1 nucleus as originally suggested by Antonucci & Miller (1985). NGC 1068 also contains a one-sided nuclear radio jet (Wilson & Ulvestad 1987) extending from the nucleus to the northeast at approximately the same position angle as the stellar/molecular bar. This alignment is surprising given the general model that the radio jets are oriented along the rotation axis of the galaxies. Clearly, investigations of the interaction of the radio jet with the molecular gas might be illuminating.

3. LUMINOUS IRAS GALAXIES

A major direction of extragalactic 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 as 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 ($M(H_2)/M_{\rm dyn}$) 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.

3.1. VV 114

VV 114 is an early merger system with $L_{\rm IR} = 6 \times 10^{11} L_\odot$ and a very large gas content, $M(H_2) = 5 \times 10^{10} M_\odot$. The two galaxy nuclei are separated by 6 kpc and CO (1–0) images show the molecular peak lies 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 ~ 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 in the gas.

3.2. 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 1996). 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.

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 2μm, is indicated by the cross. The molecular gas is distributed in a bar-like configuration between the two galaxy nuclei.

The CO conversion factor in such galactic nuclei was extensively analyzed (Bryant & Scoville 1996) 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.

3.3. ARP 220

Arp 220 at 77 Mpc has been imaged in CO (1–0) (Scoville et al. 1991), in HCN (Radford et al. 1991), and most recently in CO (2–1) (Scoville, Yun, & Bryant 1996). 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

Figure 2. CO (2–1) line emission (1″ resolution) integrated over all velocities in Arp 220 is shown superimposed on an Hα image (Scoville, Yun, & Bryant 1996). 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 Hα emission distribution.

elongated southwest-northeast, similar to the dust lane seen in optical images. In Figure 1, the CO (2–1) line emission integrated over all velocities is shown superimposed on a Hα 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 3×10^{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 1996).

4. SUMMARY

Important general characteristics of the molecular gas in starburst and high infrared luminosity galactic nuclei include: (1) extremely high gas surface 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; and (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 from the merging of comparable mass galactic nuclei. Large nuclear gas concentrations can then arise and set off the starburst activity that 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 starburst; however, given the short duration of this activity (2×10^8 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 in these galaxies are typically enhanced by factors of 10–100 so a significant fraction of the overall star formation may occur during such brief periods of activity.

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