The Central kpc of Starbursts and AGN
ASP Conference Series, Vol. xxx, 2001
J. H. Knapen, J. E. Beckman, I. Shlosman, and T. J. Mahoney

Molecular Gas in The Central Kpc of Starbursts and AGN

Shardha Jogee[1], Andrew J. Baker[2], Kazushi Sakamoto[3], Nick Z. Scoville[1], and Jeffrey D. P. Kenney[4]

Abstract. With the recent advent of large interferometric surveys, we can now probe the physical conditions, dynamics, and star-forming properties of molecular gas in the central kpc of starbursts and active galactic nuclei. We present results from the high-resolution ($\sim$ 100 pc) interferometric survey of molecular gas in the inner kpc of nearby starbursts (Jogee, Kenney, & Scoville 2001a) and the ongoing multi-transition survey of cold, warm, and dense molecular gas in a broad range of active and inactive galactic nuclei (Jogee, Baker, Sakamoto, & Scoville 2001b).

1. Survey of molecular gas in the inner kpc of starbursts

Using the Owens Valley Radio Observatory (OVRO) in the past five years, a high resolution ($\sim$ 100 pc) interferometric CO (J=1->0) survey of molecular gas in the inner kpc of eleven circumnuclear starbursts and non-starbursts has been conducted (Jogee 1999; Jogee et al. 2001a) The sample shows an order of magnitude variation in circumnuclear molecular gas content and star formation efficiency (SFE), defined as the star formation rate per unit mass of molecular gas. The circumnuclear starbursts, characterized by a high SFE, include the brightest nearby starbursts comparable to M82. The survey investigates the physical conditions, dynamics, and star-forming properties of molecular gas in the inner kpc. Selected results are outlined in § 1.1-1.2.

1.1. The molecular environment

Molecular gas in the inner kpc differs markedly from the the outer disk (see Table 1). In the inner kpc, gravitational instabilities can only be triggered at high gas densities (few 100-1000 $M_\odot$ pc^{-2}) due to the large Coriolis and pressure forces resulting from the large epicyclic frequency and velocity dispersion. Gravitational instabilities can promote star formation by agglomerating molecular clouds into complexes where they can grow by collision, coalescence, and accretion. In the inner kpc, the growth timescale (t_{GI}) of gravitational instabilities can be so short (a few Myrs) that it is comparable to the lifetime of OB

[1]California Institute of Technology, MS 105-24, Pasadena, CA 91125

[2]MPI für extraterrestrische Physik, Postfach 1312, 85741 Garching,Germany

[3]Harvard-Smithsonian Center for Astrophysics, SMA, P. O. Box 824, Hilo, HI 96721

[4]Yale University Astronomy Department, New Haven, CT 06520-8101

Table 1. Molecular gas properties in the inner kpc

Quantities	Outer Disk of Sa-Sc	Inner r=500 pc of sample starburst	Inner r=500 pc of Arp 220
(1) $M_{\rm gas-m}$ $[M_\odot]$	$\leq$ few $\times 10^9$	Few $\times$ (10^8-10^9)	3×10^9
(2) $M_{\rm gas}/M_{\rm dyn}$ [%]	< 5	10 to 30	40 to 80
(3) SFR $[M_\odot$ yr$^{-1}]$	-	0.1-11	> 100
(4) $\Sigma_{\rm gas,m}$ $[M_\odot$ pc$^{-2}]$	1-100	500-3500	4×10^4
(5) σ [km s^{-1}]	6-10	10-40	90
(6) κ [km s^{-1} kpc^{-1}]	< 100	800-3000	> 1000
(7) $\Sigma_{\rm crit}$ $[M_\odot$ pc$^{-2}]$	< 10	500-1500	> 2000
(8) $t_{\rm GI}$ [Myr]	>10	0.5-1.5	< 1
(9) $\lambda_{\rm J}$ [pc	Few $\times$ (100-1000)	100-300	90

Rows are : (1) $M_{\rm gas-m}$, the molecular gas mass (2) $M_{\rm gas,m}/{\rm M_{dyn}}$, the ratio of molecular gas mass to dynamical mass; (3) SFR, the star formation rate; (4) $\Sigma_{\rm gas,m}$ the surface density; (5) σ, the velocity dispersion; (6) $\Sigma_{\rm crit}$, the critical density for the onset of gravitational instabilities (7) κ, the epicyclic frequency; (8) $t_{\rm GI} = {\rm Q}/\kappa$, the growth timescale of the most unstable wavelength (9) $\lambda_{\rm J}$, the Jeans length

stars which destroy molecular clouds. One may therefore expect the fraction of gas converted into stars before cloud disruption to be higher in circumnuclear starbursts than in the outer disk. Detailed studies are required to further investigate this possibility. Another special feature of the inner kpc is the presence of a high pressure, high turbulence molecular ISM. Such an ISM is believed to favor the formation of more massive clusters (e.g., Elmegreen 1993) and may explain why bright super star clusters in non-interacting spirals tend to occur preferentially in the inner kpc. Table 1 also shows that the prototypical ultra luminous infrared galaxy (ULIRG) Arp 220 looks like a scaled-up version of the nearby circumnuclear starbursts. This raises the possibility that ULIRGs may be starbursts which have built an extreme molecular environment (density and linewidths) in the central part of deep potential well, through major mergers or interactions.

1.2. Molecular gas distribution and triggers of star formation

The molecular gas shows a wide variety of morphologies (Fig. 1) ranging from relatively axisymmetric annuli or disks (NGC 4102, NGC 3504, NGC 4536, and NGC 4314), elongated double-peaked and spiral morphologies (NGC 2782, NGC 3351, and NGC 6951) to extended distributions elongated along the large-scale bar (NGC 4569). We find large gas concentrations inside the outer inner Lindblad resonance (ILR) of the bar, consistent with theory (e.g., Combes & Gerin 1985). Assuming the epicycle theory for a weak bar, it is estimated that in the sample galaxies, typically the bar pattern speed is > 40–$115\,\mathrm{km\ s^{-1}\ kpc^{-1}}$, the radius of the outer ILR is $> 500\,\mathrm{pc}$, and the radius of the inner ILR is $< 300\,\mathrm{pc}$. (Jogee et al. 2001a).

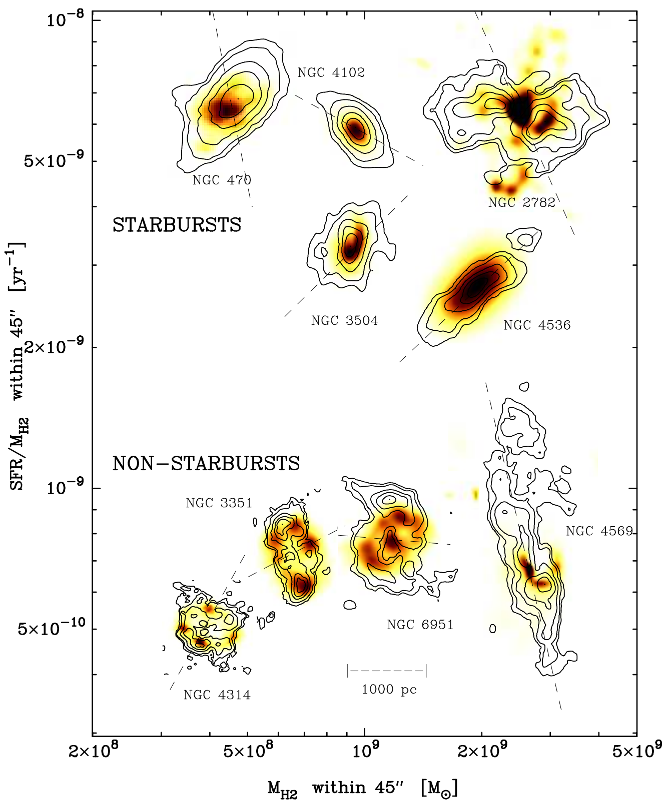

Figure 1. In the SFR/M_{H2} vs. M_{H2} plane, the CO intensity (contours) is overlaid on the star formation (greyscale), as traced by RC and Hα. The dotted line is the P.A. of the large-scale stellar bar/oval. The synthesized CO beam is 100–200 pc.

The starbursts and non-starbursts have circumnuclear SFR of 3–11 and 0.1–2 $\mathrm{M_\odot\,yr^{-1}}$, respectively. For a given CO-to-H_2 conversion factor, the starbursts have a larger peak gas surface density $\Sigma_{\mathrm{gas-m}}$ in the inner 500 pc radius than non-starbursts with a similar circumnuclear gas content (Fig. 2a). In the regions of intense star formation, $\Sigma_{\mathrm{gas-m}}$ remains close to the Toomre (1964) critical density (Σ_{crit}) for the onset of gravitational instabilities, despite an order of magnitude variation in Σ_{crit} (Fig. 3b and e). In the non-starbursts, there are gas-rich regions with no appreciable star formation, for instance, at the CO peaks in NGC 6951 and inside the ring of HII regions in NGC 3351 and NGC 4314. The gas surface density, although high, is still sub-critical in regions of inhibited star formation, as illustrated for NGC 4314 in Fig. 3e–f.

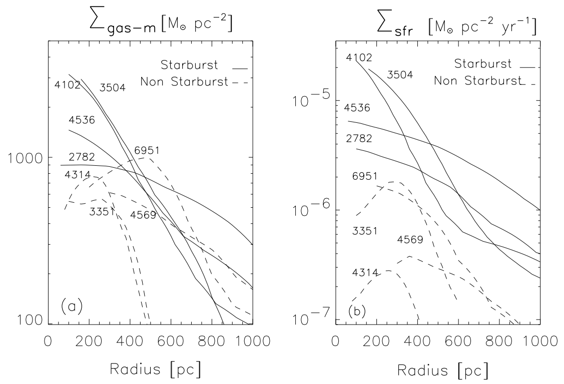

Figure 2. **(a)** The azimuthally-averaged molecular gas surface density and **(b)** the extinction-corrected SFR per unit area.

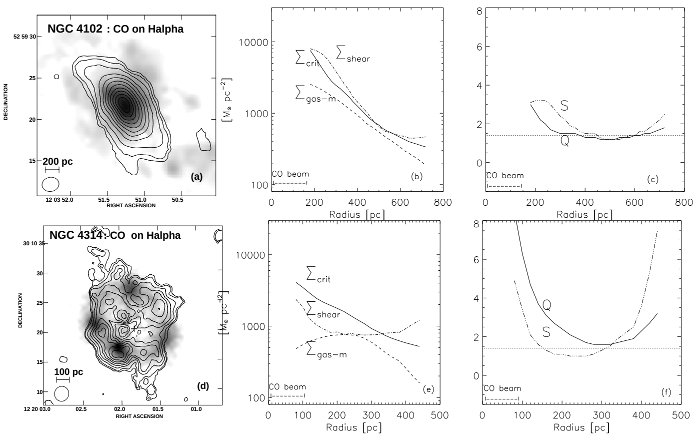

Figure 3. **(a, d)** CO (contours) on Hα (greyscale) distributions. **(b, e)** $\Sigma_{\rm gas-m}$, $\Sigma_{\rm crit}$, and $\Sigma_{\rm shear}$. **(c, f)** Toomre Q and shear S parameters (Jogee et al 2001a). Quantities are plotted starting at a radius equal to the CO beam size ($\sim 2''$). See text for details.

2. Survey of cold, warm, and dense gas in active and inactive nuclei

We present the ongoing multi-transition high-resolution ($\sim$ 100 pc) interferometric survey of cold, warm, and dense molecular gas in a broad range of nearby active (AGN) and inactive (IGN) galactic nuclei by Jogee, Baker, Sakamoto, and Scoville. The sample consists of AGN and IGN whose optical types encompass Seyfert, LINER, and HII-regions, and whose star formation efficiency varies by an order of magnitude. The survey aims at exploring the physical conditions and dynamics of the molecular gas in AGN and IGN, and constraining the drivers of activity levels in galactic nuclei. When completed, the survey will cover forty galactic nuclei with high resolution CO(1–0) observations and fifteen nuclei with multiple line observations, thus constituting one of the largest multi-transition interferometric surveys of galactic nuclei to date. It will complement ongoing multiple line surveys of nuclei with the Plateau de Bure (NuGA; Garcia-Burillo & Combes, private communication) and Nobeyama Radio Observatory (Kohno

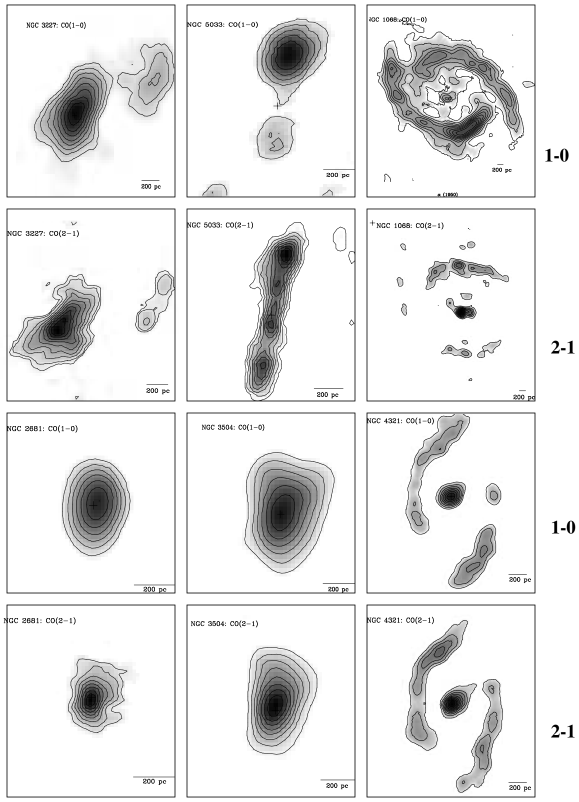

Figure 4. CO(1–0) and CO(2–1) emission in the inner kpc of select AGN (NGC 3227, NGC 1068, NGC 2681, and NGC 5033) and IGN (NGC 3504 and NGC 4321)

et al. 2001, these proceedings) interferometers. We built the survey database by pooling together new OVRO CO (1–0), C0(2–1), and HCN(1–0) observations with existing data from three high resolution surveys: the Jogee (1999) CO(1–0) survey of starbursts and non-starbursts, the Sakamoto et al. (1999) CO(1–0) survey of CO-luminous spirals, and the Baker (2000) CO(1–0) and CO (2–1) survey of AGN with broad Hα emission.

We are investigating the physical properties of the cold, warm, and dense molecular gas in AGN and IGN with different levels of star formation, nuclear activity, and radiation fields. Fig. 4 shows CO(2-1) and CO(1-0) emission in the inner kpc of several AGN and IGN in our sample. The distributions of the cold and warm gas are similar in several HII nuclei (e.g., NGC 3504, NGC 4321), but several AGN (e.g., NGC 5033, NGC 2681, NGC 1068) show bright or enhanced CO (2-1) emission near the central engine. Baker (2000) found that the integrated intensity ratio of CO(2-1) to CO(1-0) in temperature units exceeds one in several AGN (e.g., NGC 1068, NGC 2681). Such high ratios can result from optically thick gas in a two-zone model where CO(2-1) comes from warm outer layers of externally heated clouds. By comparing AGN and IGN in

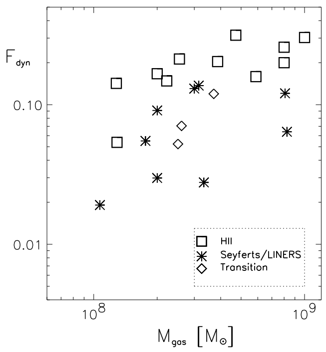

Figure 5. Preliminary plot of the molecular gas mass fraction $F_{\rm dyn}$ and mass $M_{\rm gas}$ in the inner 500 pc.

our sample, we are investigating whether hard X-rays constitute the dominant heating mechanism in AGN. We also hope to constrain the CO-to-H_2 conversion factor by comparing our line ratios with those from surveys of the Galaxy.

We are also testing if nuclear types are correlated with the molecular gas mass fraction in the inner 500 pc. Despite mounting evidence that most galaxies contain a black hole, a large fraction of galaxies do not show evidence for an AGN, as characterized by high-excitation optical lines produced by a hard accretion-disk spectrum. One hypothesis is that in some systems, a high circumnuclear gas mass fraction ($F_{\rm dyn}$) can trigger efficient circumnuclear star formation which starves a black hole or washes out its accretion spectrum. The low Q in circumnuclear regions with high SFE (e.g., Jogee 1999), and the low $F_{\rm dyn}$ in several AGN (e.g., Sakamoto et al. 1999) lend some support to this hypothesis. Preliminary results from the half of the survey data (Fig. 5) suggest the HII nuclei have larger gas mass fractions than the Seyfert and LINERS. We emphasize that the results are preliminary and an ongoing analysis of the entire sample will further investigate this apparent correlation.

References

Baker, A. J. 2000, Ph.D. thesis, California Institute of Technology

Combes, F., & Gerin, M. 1985, A&A, 150, 327

Elmegreen, B. G. 1993, ApJ, 411, 170

Jogee, S. 1999, Ph.D. thesis, Yale University

Jogee, S., Kenney, J. D. P., & Scoville, N. Z. 2001a, in preparation

Jogee, S. Baker, A. J., Sakamoto, K., & Scoville N. Z. 2001b, BAAS, AAS Meeting 198, 74.04

Sakamoto, K., Okumura, S. K., Ishizuki, S., & Scoville, N. Z. 1999, ApJ, 525, 691

Toomre, A. 1964, ApJ, 139, 1217