Chapter 5

Molecular Gas in Double Barred Galaxies

III. A Lack of CO Emission?

Nuclear bars in barred galaxies have been proposed as a mechanism for transporting molecular gas interior to Inner Linblad Resonances where it may fuel a variety of nuclear activity. Models of these galaxies suggest that the molecular gas component is crucial for maintaining long-lived nuclear bars, and the resulting gas morphology can reveal important information regarding properties such as main bar pattern speed and the location of resonances that are not directly observable. We have undertaken a CO survey in an attempt to locate double barred galaxies that have strong CO emission that could be candidates for high resolution mapping. We observed ten galaxies in CO J=2$-$1 and J=3$-$2 and do not detect any new galaxies that have not already been detected in previous CO surveys. We preferentially detect emission from galaxies containing some form of nuclear activity. Simulations of these galaxies require that they contain 2 to 10% gas by mass in order to maintain long-lived nuclear bars. The fluxes for the galaxies for which we have detections suggest that the gas mass fraction is in agreement with these models requirements. The lack of emission in the other galaxies suggests that they contain as little as a few $\times 10^6$ $M_\odot$ of molecular material which corresponds to at least $\sim$0.1% gas by mass. This result suggests that the models may be underestimating the dissipative properties of the molecular gas.

keywords Galaxies: starburst – galaxies: active

5.1 Introduction

Recent near infrared (NIR) surveys reveal isophote twists in the central regions of barred galaxies which are thought to be the signature of a bar within a bar (e.g. Mulchaey, Regan, & Kundu 1997). Recent models of double barred galaxies have had success in reproducing relatively long lived nuclear features that can explain these isophote twists. Shaw et al. (1993) model galaxies as collisionless stars and dissipative gas clouds and find that the NIR isophote twists are caused by viscous and gravitational torques that drag the nuclear regions of the main bar out of alignment with the rest of the bar. Friedli & Martinet (1993) suggest that the NIR isophote twists are the result of a kinematically distinct nuclear bar that can rotate with up to six times the pattern speed of the large scale bar. The one thing these two models have in common is the need for dissipation: both groups must include substantial amounts of molecular gas for the models to be able to reproduce the observed features. To date, the best observational test of how accurately these models are taking into account the gaseous component is the assumed gas mass to total mass ratio (usually adopted as 5 to 10%, in agreement with observations of regular disk galaxies; Young & Devereux 1991). The models of barred galaxies containing a gaseous component by Combes & Gerin (1985), Shaw et al. (1993), and Friedli & Martinet (1993) produce nuclear morphologies very different than the purely stellar models. In fact, Combes (1994) find the simulations exhibit different results by simply changing only the *viscosity* of the gas. Thus, detailed observations of the molecular gas morphologies and physical conditions will make an excellent probe of the accuracy of these models.

In Paper I (Petitpas & Wilson 2001a) we used high resolution CO observations to search for the molecular gas components of these galaxies that the models of Friedli & Martinet (1993) and Shaw et al. (1993) require to be present. We found that in NGC 2273 the molecular gas emission takes the form of a nuclear bar that is aligned with the NIR isophote twists. In NGC 5728, we observed a rather disorderly molecular gas morphology that did not align with the NIR morphology, nor did it align with any features seen at other wavelengths in the nuclei of this galaxy. When comparing the CO maps of NGC 2273, NGC 5728 and other double barred galaxies with their star formation activity, we found evidence that the galaxies with nuclear CO bars may represent younger stages of barred galaxy evolution. The central concentrations of molecular gas may be exhausted and/or dispersed by vigorous star formation in the nuclei of the older double barred galaxies, which results in their more disordered appearance.

The similarity in the NIR images of these galaxies suggests that the galactic potentials may be similar. The variety of molecular gas morphologies suggests that the molecular gas may have different properties in each galaxy allowing it to respond differently to these similar potentials. In Paper II (Petitpas & Wilson 2001b), we performed a multi-transition CO survey of the nuclei of double barred galaxies for which high resolution CO maps exist. We found that the molecular gas was cooler in galaxies with more centrally concentrated gas distributions (i.e. nuclear molecular bars) and warmer in galaxies where the CO was scattered about the nucleus. When comparing this result with the evolutionary hypothesis of Paper I, we believe that the molecular gas has been heated by the past star formation, perhaps reducing its viscosity and resulting in a highly dispersed morphology.

The seven galaxies discussed in Papers I and II represent a small fraction of the total number of galaxies known to have nuclear bars (as indicated by NIR isophote twists). In order to strengthen the hypotheses of those papers, we need to study a larger sample of galaxies. Of the 93 galaxies studied by Jarvis et al. (1988), Shaw et al. (1993), Wozniak et al. (1995), Elmegreen et al. (1996), Mulchaey, Regan, & Kundu (1997), only 23 contain isophote twists on scales large enough to be resolved by the Caltech Millimeter and BIMA Arrays. Since the larger NIR surveys mentioned above were performed using southern observatories (i.e. La Silla, Chile), most of the candidates are located in the southern hemisphere. Of those 23 galaxies with resolvable bars, only 13 are at a declination $> -30°$.

Six of these (NGC 470, NGC 2273, NGC 4736, NGC 5850, NGC 5728, and NGC 6951) have high resolution CO maps published or soon to be published (Jogee 1998; Petitpas & Wilson 2001a; Wong & Blitz 2000; Leon, Combes, & Friedli 2000; Kohno, Kawabe, & Vila-Vilaró 1999).

We have performed a CO survey of the nuclei of 10 galaxies known to have strong NIR isophote twists in an attempt to find CO-bright double barred galaxies that would make good candidates for high resolution CO mapping. Five of these galaxies (NGC 2273, NGC 3081, NGC 4736, NGC 5728, and NGC 6951) are discussed in detail in papers I and II. In §5.2 we discuss the observations and data reduction techniques. In §5.3 we discuss our detections (and non-detections) in more detail, and compare our observations to previous studies of these galaxies. We also determine the molecular gas masses, and discuss the implications of these masses to the double barred galaxy models. This work is summarized in §5.4.

5.2 Observations and Data Reduction

5.2.1 NRAO Spectra

The nuclei of nine double barred galaxies were observed in ^{12}CO J=2−1 using the National Radio Astronomy Observatory (NRAO)[1] 12-m Telescope. Observations were taken in remote observing mode over a 14 hour period on 15 February, 2000. The half-power beamwidth of the NRAO 12-m was 29″ at 230 GHz (^{12}CO J=2−1). All observations were taken in 2IF mode with the Millimeter AutoCorrelator (MAC). The pointing was found to be accurate to 6″ for the first half of the evening when we observed our galaxies with

---

[1] The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

NGC < 4736. This is poorer than the normal value for the NRAO 12-m, likely due to the high winds. In the second half of the evening the winds diminished, and the pointing improved to the more normal value of $5''$ for observations of galaxies with NGC ≥ 4736. The calibration was also monitored by observing spectral line calibrators and planets and the spectral line calibrators agreed with the published values. Thus, we adopt the normal main beam efficiency from the NRAO Users Guide of 0.29 at 230 GHz.

5.2.2 JCMT Spectra

Previous CO studies of double barred galaxies show CO J=3−2/J=2−1 line ratios $\gtrsim 1$ (Petitpas & Wilson 2001b) so for galaxies that were not detected with the NRAO, we obtained higher resolution ^{12}CO J=2−1 and ^{12}CO J=3−2 spectra using the James Clerk Maxwell Telescope (JCMT)[2]. These observations were taken over the period of 1999 - 2000, mostly as part of bad weather backup projects. The half-power beamwidth of the JCMT is $21''$ at 230 GHz (^{12}CO J=2−1) and $14''$ at 345 GHz (^{12}CO J=3−2). All observations were obtained using the Digital Autocorrelation Spectrometer. The calibration was monitored by frequently observing spectral line calibrators. The spectral line calibrators showed very little scatter from the published values with individual measurements differing by typically $< 15\%$ from standard spectra. Thus, we adopt the normal main beam efficiencies from the JCMT Users Guide of 0.69 at 230/220 GHz and 0.63 at 345 GHz. A detailed observing summary for the JCMT and NRAO observations is given in Table 5.1.

---

[2] The JCMT is operated by the Joint Astronomy Centre in Hilo, Hawaii on behalf of the parent organizations Particle Physics and Astronomy Research Council in the United Kingdom, the National Research Council of Canada and The Netherlands Organization for Scientific Research.

Table 5.1: Observing Parameters

Galaxy	α (2000)	δ (2000)	$V_{\rm lsr}$ (km s^{-1})	Line (^{12}CO)	Tele.	t$_{\rm int.}$ (h:m)	T$_{\rm sys}$ (K)	r.m.s. (mK)
NGC 2273	6:50:09.8	60:50:48.9	1870	J=2−1	NRAO	1:46	516	5
NGC 2859	9:24:19.5	34:30:42.5	1687	J=2−1	NRAO	1:58	467	4
NGC 2859	...	...	1687	J=3−2	JCMT	2:20	630	4
NGC 2950	9:42:35.1	58:51:05.0	1337	J=2−1	JCMT	0:30	254	4
NGC 3081	9:59:30.6	-22:49:40.7	2385	J=2−1	NRAO	2:09	1012	8
NGC 4340	12:23:35.8	16:43:16.4	950	J=2−1	NRAO	1:58	199	4
NGC 4340	...	...	950	J=3−2	JCMT	2:00	485	3
NGC 4371	12:24:55.5	11:42:10.0	943	J=2−1	NRAO	1:58	511	4
NGC 4371	...	...	943	J=3−2	JCMT	2:00	503	3
NGC 4736	12:50:53.4	41:07:02.1	308	J=2−1	NRAO	0:35	468	7
NGC 5728	14:42:23.8	-17:15:02.6	2788	J=2−1	NRAO	1:58	605	5
NGC 5850	15:07:07.5	1:32:42.7	2556	J=2−1	NRAO	1:58	453	4
NGC 6951	20:37:11.6	66:06:11.6	1424	J=2−1	NRAO	3:20	424	3

The beam size for the NRAO 12-m at CO J=2−1 is 29″. The beam size for the JCMT is 21″ at CO J=2−1 and 14″ at J=3−2.

5.2.3 Reduction

Similar data sets were averaged together using the software package SPECX for the JCMT data and the Bell Labs data reduction package COMB for the NRAO data. The data were binned to 10 km s^{-1} resolution (13.0 and 8.7 MHz at 230 and 345 GHz respectively) and zeroth (horizontal) or first order (linear sloped) baselines were removed. The emitting regions we detected were quite wide ($>$ 300 km s^{-1}) but the spectrometer bandwidth was 800, 800, and 1200 km s^{-1} for the NRAO and JCMT J=3−2and J=2−1, respectively, which allowed for accurate baseline determination. For the galaxies where we have no detections, the baseline levels were set using the region of the spectrometer outside a 400 km s^{-1} range centered on the rest velocity of the galaxies (i.e. $V_{lsr} \pm 200$ km s^{-1}) in order to maximize our changes of detecting any weak signal. The NRAO spectra for each galaxy are shown in Figure 5.1 and the JCMT spectra are shown in Figure 5.2. The spectral line intensities are summarized in Table 5.2.

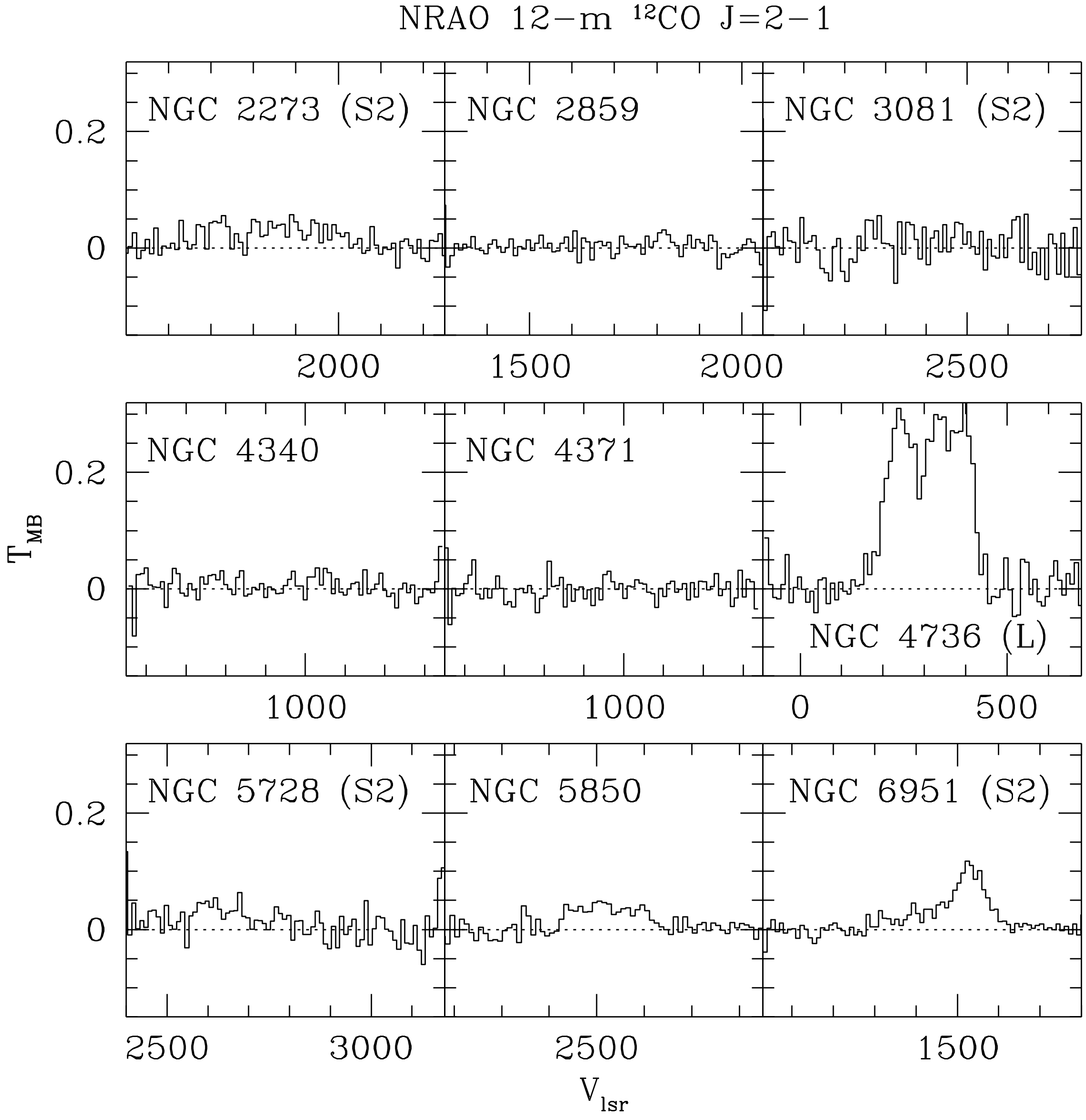

Figure 5.1: NRAO 12-m Spectra of Double Barred Galaxy Nuclei
^{12}CO J=2−1 spectra taken at the NRAO 12-m of a sample of galaxies thought to contain double bars. The spectra cover the inner 29″ of the galaxy nuclei, which is predicted to be gas rich by the models of Shaw et al. (1993) and Friedli & Martinet (1993). The type of nuclear activity exhibited is shown after the galaxy name (S2 = Seyfert 2; L = LINER). Note that we detect CO emission mostly galaxies from with some form of nuclear activity. The large tickmarks on the velocity axis correspond to 500 km s^{-1} intervals, while the smaller tickmarks are every 100 km s^{-1}. Higher recession velocities are to the right.

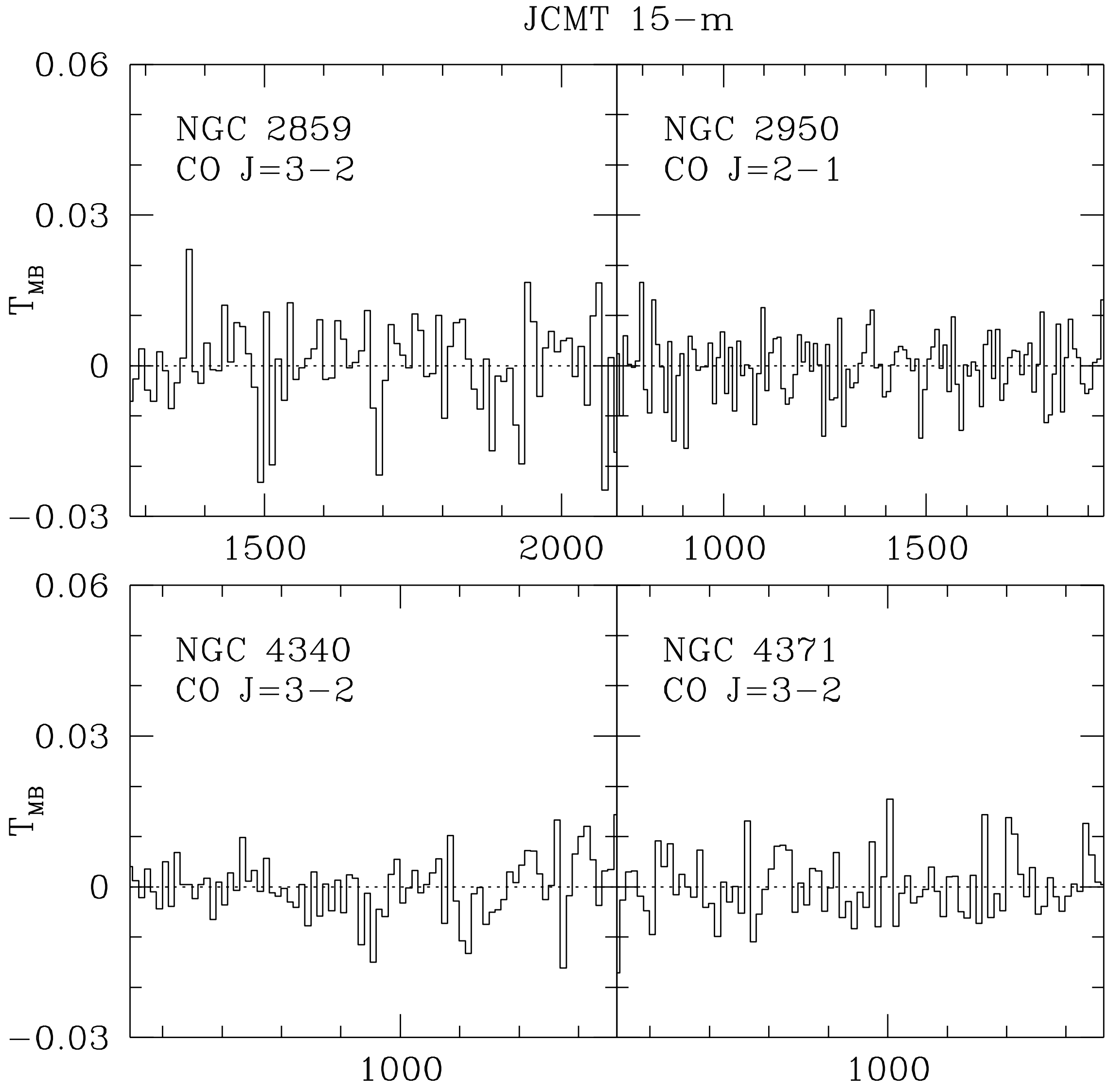

Figure 5.2: JCMT Spectra of Double Barred Galaxy Nuclei
^{12}CO J=2−1 and ^{12}CO J=3−2 spectra taken at the JCMT of a sample of galaxies thought to contain double bars. The J=2−1 spectra cover the inner 21″ while the J=3−2 spectra cover 14″. Note that despite the rather low noise, we still do not detect any emission from these galaxies.

Using the $T_{\rm R}^{*}$ temperature scale would ensure that our observed line strengths are as close to the true radiation temperatures as possible (Kutner & Ulich 1981). However, conversion to $T_{\rm R}^{*}$ from $T_{\rm A}^{*}$ requires knowledge of the forward scattering and spillover ($\eta_{\rm FSS}$), which is difficult to measure and was not attempted during the JCMT observing runs. On the other hand, we do have good values for the main beam efficiencies and so an accurate conversion to main beam temperature ($T_{\rm MB}$= $T_{\rm A}^{\star}/\eta_{\rm MB}$) is possible. Therefore, we will display our spectra using the main beam temperature scale. For ease of calculations, we report our fluxes in Table 5.2 in $T_{\rm A}^{\star}$.

5.3 Discussion

Figure 5.1 shows the spectra taken at the NRAO 12-m in ^{12}CO J=2−1. At first glance it appears that we have only detected three of the galaxies: NGC 4736, NGC 5850, and NGC 6951. These galaxies were all previously detected and detailed studies are published in Petitpas & Wilson (2001b), Sakamoto et al. (1999), Leon, Combes, & Friedli (2000), and Kohno, Kawabe, & Vila-Vilaró (1999). Observations of these galaxies were taken primarily for cross-calibration. The line profiles and peak strength for NGC 4736 agree well with those published in Petitpas & Wilson (2001b). The line profile of NGC 6951 is single peaked which is noticeably different than the JCMT ^{12}CO J=2−1 spectra for this galaxy (see Paper II). The profile of the NRAO spectrum more closely resembles the CO J=3−2 spectra taken with the JCMT at an offset of (0″,−7″) as part of our 5-point mapping procedure discussed in Petitpas & Wilson (2001b). In addition to this, the peak line strength in the NRAO spectrum is much lower than the JCMT ^{12}CO J=2−1 spectrum, suggesting that pointing inaccuracies may have resulted in pointing the telescope too far south, missing the strongest emission in the northern part of the nucleus (Kohno, Kawabe, & Vila-Vilaró 1999) with the most sensitive part of the beam. There are no published single dish CO spectra for NGC 5850, but interferometric maps are published in Leon, Combes, & Friedli (2000).

For NGC 2273, we have JCMT J=2−1 spectra with a strong detection (Petitpas & Wilson 2001b), so despite the weak emission in the NRAO spectrum for this region we expect to see emission over the velocity range from 1600 to 2000 km s^{-1}. While there are no clear emission peaks visible in the NGC 2273 spectrum of Figure 5.1, we do see an increase in the baseline that can likely be attributed to the faint spectral line. The emission in NGC 5728 is known to cover a wide range of velocities from less than 2600 km s^{-1} to greater than 3050 km s^{-1} and is very clumpy (Petitpas & Wilson 2001a; Schommer et al. 1988). The line would nearly cover the entire spectrometer which makes it difficult to determine the baseline for the spectra of NGC 5728 shown in Figure 5.1. We have used the very ends of the spectrometer to determine the baseline level, and the result is a lumpy spectra with no strong noticeable peaks, but a general tendency for the noise to remain slightly greater than zero. We have JCMT CO J=2−1 spectra for NGC 3081 that show emission over a region from 2200 to 2500 km s^{-1}, while in the NRAO spectrum, we see no detectable line. The significance of these marginal detections is discussed in more detail in §5.3.1.

Despite our rather high sensitivity ($T_{\rm MB}$(rms) $\approx$ 14 mK) we have failed to detect CO J=2−1 lines in NGC 2859, NGC 4340, or NGC 4371. In addition, Figure 5.2 shows that we do not detect the CO J=3−2 emission line in NGC 2859, NGC 4340, or NGC 4371, despite higher sensitivity ($T_{\rm MB}$(rms) $\approx$ 6 mK). For the single J=2−1 spectra taken at the JCMT, we do not detect emission in NGC 2950 despite reaching the 5 mK rms limit. In short, we do not detect any galaxies that have not been previously detected in the CO surveys of Braine & Combes (1992), Mauersberger et al. (1999), and Young et al. (1995).

Beside the galaxy names in Figures 5.1 and 5.2 are codes (in parentheses) that indicate the types of nuclear activity found in these galaxies. Seyfert 2s are marked as "S2" and LINERs are flagged with "L". Galaxies without any detected nuclear activity are not flagged and show no signs of Seyfert, LINER, or starburst activity. If we neglect the higher sensitivity spectra published in Petitpas & Wilson 2001b for now and use only Figures 5.1 and 5.2, we would see convincing detections in NGC 2273 (Seyfert 2), NGC 4736 (LINER) and NGC 5850 (quiescent) and NGC 6951 (Seyfert 2). We would see no detections for NGC 2859 (quiescent), NGC 2950 (quiescent), NGC 3081 (Seyfert 2), NGC 4340 (quiescent), NGC 4371 (quiescent), and NGC 5728 (Seyfert 2). Thus three out of four (75%) of our detected galaxies show signs of some form of nuclear activity. Four out of six (67%) of our un-detected galaxies show no signs of activity. These rather small number statistics are enhanced when we include the CO detections published in Petitpas & Wilson (2001b). Inclusion of these data moves the Seyfert 2 galaxies NGC 3081 and NGC 5728 into the 'detected' bin. Now, five of the six galaxies (83%) that we have detected show signs of nuclear activity. Of the four galaxies that we have not detected CO emission, none of them show any signs of nuclear activity.

We note that in performing a literature search, the galaxies that we have not detected are quite a bit less studied than NGC 4736 and NGC 6951, for example, and may harbor yet undetected nuclear activity, which could change our small number statistics noticeably.

5.3.1 Molecular Gas Mass

The double barred galaxy models of Friedli & Martinet (1993) and Shaw, Combes, Axon, & Wright (1993) suggest that there needs to be substantial amounts of molecular gas in double barred galaxies. In fact, the molecular gas inflow in these double barred galaxies may accumulate enough mass so that the nuclear bar can become kinematically distinct (Friedli & Martinet 1993; Pfenniger & Norman 1990). Thus, we may expect to see high molecular gas masses in the centers of these double barred galaxies.

The intensity of the CO emission can be related to the molecular mass using the equation

$$M_{\rm mol} = 1.61 \times 10^4 \left(\frac{\alpha}{\alpha_{\rm Gal}}\right) \left(\frac{115 \text{ GHz}}{\nu}\right)^2 d^2_{\rm Mpc} \, \frac{S_{\rm CO}}{R} \, {\rm M}_\odot \tag{5.1}$$

(Wilson & Scoville 1990; Wilson 1995) where $S_{\rm CO}$ is the ^{12}CO J=2−1 flux in Jy km s^{-1}, R is the ^{12}CO J=2−1/J=1−0 line ratio, ν is the frequency of the emission (230 GHz for the J=2−1 transition), $d_{\rm Mpc}$ is the distance to the galaxy in Mpc, α is the CO-to-H$_2$ conversion factor for that galaxy, and $\alpha_{\rm Gal}$ is the Galactic value ($3 \pm 1 \times 10^{20}$ cm^{-2}(K km s^{-1})$^{-1}$, Strong et al. 1988; Scoville & Sanders 1987). We use 24.7 Jy K^{-1}, 27.8 Jy K^{-1} ($\eta_{\rm ap}$= 0.63, 0.56) and 70.6 Jy K^{-1} to convert our JCMT (J=2−1,J=3−2) and NRAO J=2−1 data (respectively) from Kelvins ($T^\star_{\rm A}$) to Janskys (Kraus 1986; JCMT Users Guide; NRAO 12-m Users Manual). We assume a coupling efficiency ($\eta_{\rm c}$) of 0.7 to correct our observed fluxes to true fluxes. The CO-to-H$_2$ conversion factor (α) is a globally averaged property of the galaxy and hence there are uncertainties involved in its use in one specific region of the galaxy and it is only accurate to within $\sim$ 30%. Our fluxes are typically accurate to about 10%. The distances for these relatively nearby galaxies is likely uncertain by at least 30%. We therefore adopt a total uncertainty of 50% in our mass estimates.

For the galaxies where we have CO detections with other telescopes or at other frequencies, we integrate over the velocity range where the emission line was seen. For galaxies with no previous detections, we integrate over a 400 km s^{-1} range centered on the rest velocity of the galaxy (this region was excluded from the baseline subtraction). In the cases where the integrated intensity is greater than the rms noise, we give both the integrated intensity and the noise regardless of how insignificant. We are not claiming these as detections, but are simply using these as a more realistic value for the detection cut-off limit. If the integrated intensity is less than or equal to the rms noise the noise value is given as an upper limit. The results are summarized in Table 5.2.

Table 5.2 shows that there is a wide variety of molecular gas masses in the inner regions of these galaxies. For the galaxies in our sample that have been detected with the JCMT, we find that the masses determined here are typically lower than the masses determined with CO J=2−1 data in Petitpas & Wilson (2001b) by less than a factor of two. The exception

Table 5.2: CO Fluxes and Molecular Gas Masses

Galaxy	Transition (^{12}CO)	V limits (km s^{-1})	Flux (K km s^{-1} $T_A^\star$)	Distance (Mpc)	Gas Mass (M$_\odot$)
NGC 2273	J=2−1	1600-2020	2.83 ± 0.30	25	8.2×10^8
NGC 2859	J=2−1	1490-1890	(0.76 ± 0.25)	22	2.0×10^8
NGC 2859	J=3−2	1490-1890	< 0.25	22	$< 2.9 \times 10^7$
NGC 2950	J=2−1	1140-1540	< 0.23	18	$< 1.8 \times 10^7$
NGC 3081	J=2−1	2200-2550	(1.05 ± 0.52)	32	6.2×10^8
NGC 4340	J=2−1	750-1150	(0.83 ± 0.24)	13	8.1×10^7
NGC 4340	J=3−2	750-1150	< 0.20	13	$< 8.2 \times 10^6$
NGC 4371	J=2−1	740-1140	< 0.28	13	$< 2.7 \times 10^7$
NGC 4371	J=3−2	740-1140	< 0.18	13	$< 7.3 \times 10^6$
NGC 4736	J=2−1	100-450	17.9 ± 0.4	4	1.7×10^8
NGC 5728	J=2−1	2500-3050	2.16 ± 0.37	37	1.3×10^8
NGC 5850	J=2−1	2400-2650	1.99 ± 0.19	34	1.3×10^9
NGC 6951	J=2−1	1250-1620	3.90 ± 0.18	19	2.9×10^8

All distances are taken from the NASA-IPAC Extragalactic Database (NED) and assume a Hubble Constant of 75 km s^{-1} (Mpc)$^{-1}$. For calculating gas masses for NGC 2273, NGC 5728, NGC 6951 we adopt CO J=2−1/J=1−0 ratios of 0.88, 0.7, and 1.96 respectively (Petitpas & Wilson 2001b). For the other galaxies we have assumed a ^{12}CO J=2−1/J=1−0 ratio of 0.7 and (where necessary) a J=3−2/J=2−1 line ratio of 1 similar to the values found for other double barred galaxies (Petitpas & Wilson 2001b). The flux values for the questionable detections are enclosed in parentheses.

is NGC 6951 which is lower here by more than a factor three. This discrepancy can likely be attributed to the pointing offset discussed in §5.3. It is interesting that the masses derived here for NGC 2273 and NGC 5728 using NRAO fluxes agree more closely (within 25-70%) with the masses derived using CO J=1$-$0 interferometric fluxes which are known to miss large scale emission (Petitpas & Wilson 2001a). This may reflect the differences in pointing accuracy between the JCMT and NRAO. Since the emission in these galaxies is confined to a small region of the nucleus, the larger pointing errors of the NRAO may have resulting in the most sensitive part of the main beam missing the emission peak. It may also reflect the higher dish surface precision of the JCMT. In any case, the similarities between the masses obtained with the weaker NRAO 12-m spectra (even in the cases where no obvious lines are visible such as NGC 3081 and NGC 5728) and the masses obtained with the JCMT J=2$-$1 spectra gives us confidence that our mass estimates and upper limits are accurate to at least a factor of two.

Of particular interest is the galaxy NGC 5850, whose spectrum indicates that there is more than 10^9 M$_\odot$ of molecular gas in the inner 29$''$. This comparable to the amount of gas in the entire Milky Way, but now contained in its inner 2.5 kpc radius. The optical size of this galaxy is $4'.3\times3'.7$ ($D_{25} \times d_{25}$), which corresponds to the 43×37 kpc at its distance of 34 Mpc (NED). This clearly makes it the largest galaxy in our sample (the second runner up is NGC 5728 at 33×19 kpc). Given its rather strong bar, it is possible that the large quantity of gas in the inner regions of this galaxy may have been transported inward by the inflow mechanisms known to be associated with bar perturbations. The high resolution CO maps of this galaxy (Leon, Combes, & Friedli 2000) detect only 6.7×10^7 M$_\odot$ of molecular gas, mostly concentrated in a small off-center peak of emission approximately 8$''$ north of the galactic center. On the other hand, their single dish IRAM 30-m CO J=1$-$0 maps of the entire primary bar detects 3.4×10^9 M$_\odot$. Leon, Combes, & Friedli (2000) point out that this galaxy is surprisingly quiescent given the large amounts of molecular gas, and propose that the reason for this is that the molecular gas is below the critical surface density for gravitational instabilities (Kennicutt 1989).

The large size of NGC 5850 and the fact that it is the only quiescent galaxy with a strong detection lead us to wonder if we are detecting emission lines in predominantly the largest galaxies (with possibly the largest molecular gas reservoirs). All the other galaxies are in the 15 to 20 kpc (major axis) size range with the exception of NGC 2859, NGC 5728, and NGC 5850 who have major axes of 28, 33, and 43 kpc respectively. The strongest line occurs in the closest galaxy, NGC 4736, which is incidentally one of the smallest in our sample with major axis of $\sim$14 kpc. So it seems that we are not detecting CO emission preferentially in larger galaxies. Since NGC 5850 is the second most distant galaxy in our sample, it also appears that we are not preferentially detecting emission from the closest galaxies.

Since we are searching for emission with the CO J=2$-$1 line, our lack of success in finding bright candidates may not be the result of a lack of molecular gas, but that the gas in these galaxies is very cool and possibly at a low density. Is it possible that all of the molecular emission is dominated by J=1$-$0 emission and it is not excited into the J=2$-$1 levels enough to be detected? In our mass calculation, we assume a J=2$-$1/J=1$-$0 line ratio of 0.7. In the Local Thermodynamic Equilibrium approximation, in order to achieve this line ratio, the gas must be at a temperature of only 7 K. This temperature is low enough that it can be maintained by cosmic ray heating (Goldsmith & Langer 1978). Higher values of the J=2$-$1/J=1$-$0 line ratio will act to decrease our molecular gas mass, meaning that the mass values quoted here are likely upper limits.

Another possible explanation for the low molecular gas mass may be that the gas is just not located in the inner 29$''$. There are observations of other galaxies that contain large molecular rings that seem to have prevented any of the molecular gas from reaching the nucleus (e.g. NGC 7331; Sheth et al. 2000). We will need spectra covering a wider field of view to verify if this is happening in any of these galaxies.

5.3.2 Implications to Double Barred Galaxy Models

Recall that all of the galaxies in this survey were chosen because they are known to contain the NIR isophote twists believed to be the signature of a double barred galaxy. As mentioned in §5.1, the models of double barred galaxies by Shaw et al. (1993) and Friedli & Martinet (1993) require large amounts of molecular gas in the nuclear regions of these galaxies in order to sustain long-lived double bars. The gas requirements vary from 4 to 6% globally (Shaw et al. 1993; Friedli & Martinet 1993) to as little as 2% molecular gas in the nucleus (Friedli & Martinet 1993). This gas is required to provide the dissipation needed to prevent the stellar component from dynamically heating so much that the nuclear bar is destroyed. We point out that we are studying the molecular gas properties in *only the nuclear region* so we expect to see gas mass fractions on the order of 2% or more.

The molecular gas content of the galaxies for which we have detections are in agreement with the model requirements and are discussed elsewhere (Leon et al. 2000; Petitpas & Wilson 2001a; Sakamoto et al. 1999). We will focus our attention here on the galaxies where we have failed to detect a strong molecular gas component. These are the galaxies that are difficult to explain in light of the current models of double barred galaxies.

As mentioned in §5.3, the galaxies where we have not detected any CO emission are in general less well studied. As such, we are not able to find direct measurements of the masses of all the galaxies in our sample in the literature. We have estimated the mass for these galaxies from their blue magnitude (extrapolated to infinity; $m_{B(T)}$ in de Vaucouleurs et al. 1991). Table 5.3 shows the apparent blue magnitudes for our sample of galaxies, the absolute magnitude, and the luminosity in solar luminosities. We have assumed the absolute

Table 5.3: Galaxy Masses Estimated from Blue Light

Galaxy	$m_{B(T)}$ (app.)	M_B (abs.)	L_B ($L_\odot$)	Mass ($M_\odot$)
NGC 2273	12.55	−19.44	8.7×10^9	2.6×10^{10}
NGC 2859	11.83	−19.87	13×10^9	3.9×10^{10}
NGC 2950	11.84	−19.87	13×10^9	3.9×10^{10}
NGC 3081	12.85	−19.68	11×10^9	3.3×10^{10}
NGC 4340	12.10	−18.47	3.6×10^9	1.1×10^{10}
NGC 4371	11.79	−18.78	4.7×10^9	1.4×10^{10}
NGC 4736	8.99	−19.18	6.9×10^9	2.1×10^{10}
NGC 5728	12.57	−20.27	19×10^9	5.7×10^{10}
NGC 5850	11.54	−21.18	43×10^9	13×10^{10}
NGC 6951	11.64	−19.75	12×10^9	3.6×10^{10}

$m_{B(T)}$ is the apparent blue magnitude of the galaxy extrapolated to infinite radius (RC3). We adopt +5.41 for the suns absolute blue magnitude (Allen 1964) and note that variations of ~0.3 in either the galactic or solar magnitude result in a factor of ~2 variation in the luminosity. The last column assumes a mass to light ratio of 3, which is typical for barred spiral galaxies (Forbes 1992).

blue magnitude of the sun to be +5.43 (Allen 1964) and note that variations in magnitude of ~0.3 result in variations in luminosity of a factor of ~2. Table 5.3 shows that all of these galaxies (except NGC 5850) have masses of approximately a few $\times 10^{10}$ $M_\odot$. Independent measurements for the masses of some galaxies in our sample exists in the literature. Rubin (1980) determined the dynamical mass of the disk (the dominant source of the blue light) of NGC 5728 to be $\sim 8 \times 10^{10}$ $M_\odot$; Marquez & Moles (1993) find the mass of NGC 6951 to be 1.3×10^{11} $M_\odot$; Smith et al. (1991) determine the mass of NGC 4736 to be 4×10^{10} $M_\odot$. These masses are in acceptable agreement with our estimates considering the uncertainties associated with our technique. It seems though, that our method is underestimating the galaxy mass by a factor of 2 to 4, whichs is likely the result of the blue light missing much of the older, redder stellar population of stars in these galaxies. Our estimate therefore provides a lower limit to the true galaxy mass, and thus, an upper limit to the gas mass fraction.

The limits on the molecular gas masses for the undetected galaxies in our sample range from as high as 2×10^8 $M_\odot$(for NGC 2859) down to 8×10^6 $M_\odot$ for NGC 4371. Using the galaxy masses shown in Table 5.3, this corresponds to a molecular gas mass fraction of 0.08% and 0.05% for NGC 2859 and NGC 4371, respectively. Recall that the models of Shaw et al. (1993) and Friedli & Martinet (1993) require 4% to 10% gas mass fractions to maintain long lived nuclear bars. Friedli & Martinet (1993) state that the molecular gas requirements for the inner kpc of these galaxies can be as low as 2%. The gas mass fractions obtained here suggest that some of these galaxies do not contain enough molecular gas to be able to support nuclear bars.

There are four possible explanations that can bypass this perceived problem. The first possibility is that the gas in our galaxies is not in molecular form. The gaseous components of the models are basically a dissipation mechanism that acts to prevent the stellar components from being dynamically heated. Models of these galaxies generally treat this gas as being primarily molecular, contained in regions of high density and low filling factor (e.g. Combes & Gerin 1985). Molecular gas also has a higher cooling capacity, since it contains many more emission lines available to it compared to atomic gas. It would take much more HI gas to dissipate as much energy as molecular gas. There are currently no HI maps of NGC 4340 in the literature, but Burstein, Krumm, & Salpeter (1987) have detected very weak HI emission in NGC 2859 using Arecibo, so it is unlikely that the HI gas contributes greatly to the galactic cooling.

Another possibility is that the molecular gas is not confined to the nuclei of these galaxies. A circumnuclear CO morphology is seen in other galaxies (e.g. NGC 7331; Sheth et al. 2000), so it is possible that the molecular gas is outside of the inner $29''$covered by the NRAO beam for the seemingly gas deficient galaxies in our sample. We will need CO observations over a larger area in order to determine if this is the case, but the models of Friedli & Martinet 1993 still require that the inner kpc contain at least 2% gas. If we assume similar disk and bulge profiles for NGC 2859 as those adopted for NGC 5738 by Rubin (1980), we estimate that roughly one tenth of the stellar mass (bulge + disk) is contained in the inner 29″ of NGC 2859. This translates into a gas to mass ratio of *0.8% for the inner 3 kpc* of NGC 2859, so the lack of CO in this galaxy is still a problem for the Friedli & Martinet (1993) model. Even if the gas is located in a large circumnuclear ring, it will not have much of an impact on the cooling of the nuclear regions.

The third possibility is that the NIR isophote twists are not correlated with the gas properties at all. It is possible that the NIR isophote twists are caused by a triaxial stellar bulge, as originally proposed by Kormendy 1979. In this scenario, the lack of molecular gas is not a problem, because there is not much molecular gas in the bulges of galaxies anyway. Evidence against the triaxial bulge model is discussed in Petitpas & Wilson (2001a) where the existence of a nuclear molecular bar that aligns with the isophote twists confirms the existence of a true nuclear bar in the disk of NGC 2273. It has also been proposed that the NIR isophote twists are the result of the stars following the stable x_2 orbits that exist inside the inner Lindblad resonance of barred galaxies (e.g. Maciejewski & Sparke 2000). Again, in this scenario, the molecular gas is not required, so the weak CO emission is not a problem. It is difficult to get the x_2 orbits (which tend to be perpendicular to the x_1 orbits that dominate the main galactic bar) to become misaligned from the large-scale bar as is seen in many galaxies (see discussion in Shaw, Combes, Axon, & Wright 1993, for example).

It is possible that different mechanisms are at work in different galaxies, and they need to be studied on a case by case basis to determine if the isophote twists are the result of a nuclear bar or a triaxial stellar bulge. In either case, we will need either more sensitive arrays or a sub-millimeter interferometer in the southern hemisphere in order to obtain high resolution CO maps for a larger number of these galaxies.

The final possibility is that the models are underestimating the dissipative properties of the molecular gas. Since the molecular gas basically acts as an energy dissipation agent, if the dissipation in the models were increased, it should take less gas to sustain the long-lived nuclear bars. This counters the findings of Paper I, which propose that the dissipation properties of the molecular gas may be overestimated. In any case, it is clear that the study of the dissipative properties of molecular gas will greatly increase the accuracy of these galaxy models.

5.4 Summary

In an attempt to find double barred galaxies that are bright in CO emission, we have obtained ^{12}CO J=2$-$1 spectra for nine galaxies with the NRAO 12-m Telescope. We detect emission in four (perhaps five) of these galaxies. Three of the four galaxies detected exhibit some form of nuclear activity, while of the galaxies that were not detected, four out of six are quiescent, showing no signs of any nuclear activity. Thus, within our small sample, the CO emission seems to be detected predominantly in galaxies that harbor some form of nuclear activity (e.g. Seyfert, LINER). If we include CO detections from a previous study (Petitpas & Wilson 2001b), this result becomes slightly more convincing. We note that the quiescent galaxies are less well studied than the active galaxies in our sample, so it may be that they harbor some form of nuclear activity that has yet to be discovered.

Models of double barred galaxies suggest that they should be gas rich in order provide a means of dissipating energy that would otherwise heat the stellar population and subsequently destroy the nuclear bars. We use the CO fluxes to estimate the amount of molecular gas in the centers of these galaxies and we find gas masses that range from less than a few $\times 10^6$ M$_\odot$ to more than $\sim 10^9$ M$_\odot$. The one quiescent galaxy that was detected with the NRAO 12-m (NGC 5850) contains a very large amount of molecular gas: 10^9 M$_\odot$. This is equivalent to all the molecular gas in the Milky Way being contained within a radius of 2.5 kpc. (Leon, Combes, & Friedli 2000) find that the gas in this galaxy is below the critical surface density required for star formation to occur, which would explain the absence of activity despite the very large fuel reservoir.

In the cases where no emission was found with the NRAO 12-m, we obtained higher resolution ^{12}CO J=3−2 and J=2−1 spectra with the James Clerk Maxwell Telescope. There are no detections in the JCMT spectra of these galaxies despite reaching sensitivities of 4 mK ($T_{\rm A}^{\star}$). The lack of detections in these galaxies places very strict limits on the amounts of molecular gas in these galaxies. For some galaxies, there must be less than a few $\times 10^6$ M$_\odot$ of molecular gas, which (assuming these galaxies are typical disk galaxies) corresponds to 0.05 to 0.08% of the total mass of the galaxy. This is a lower mass fraction than required by the models of double barred galaxies to create long lived nuclear bars. This result suggests that either the NIR isophote twists are the result of a triaxial stellar bulge in these CO weak galaxies, or the dissipative properties of the molecular gas in the simulations have been underestimated.

This research has been supported by a research grant to C. D. W. from NSERC (Canada). This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We wish to thank Rob Ivison, Susie Scott, Tracy Webb, and the staff of the JCMT for their help with the observations taken remotely during non-cosmology weather. GRP wishes to thank the extremely helpful staff at the NRAO 12-m for all their assistance in the remote observing run in February 2000, which went more smoothly than many observing runs for which he himself was present.

Bibliography

Allen, C. W., 1964. *Astrophysical Quantities.* Astrophysical Quantities, London: Athlone Press (2nd edition), 1964.

Braine, J. & Combes, F., 1992. *A&A* **264**, 433.

Burstein, D., Krumm, N., & Salpeter, E. E., 1987. *AJ* **94**, 883.

Combes, F., 1994. Nuclear gas flows in barred galaxies. In *Mass Transfer Induced Activity in Galaxies*, pp. 170. ed. I. Shlosman, Cambridge Univ. Press.

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

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Buta, R. J., Paturel, G., & Fouque, P., 1991. *Third Reference Catalogue of Bright Galaxies.* Volume 1-3, XII, 2069 pp. 7 figs.. Springer-Verlag Berlin Heidelberg New York.

Elmegreen, D. M., Elmegreen, B. G., Chromey, F. R., Hasselbacher, D. A., & Bissell, B. A., 1996. *AJ* **111**, 1880.

Forbes, D. A., 1992. *A&AS* **92**, 583.

Friedli, D. & Martinet, L., 1993. *A&A* **277**, 27.

Goldsmith, P. F. & Langer, W. D., 1978. *ApJ* **222**, 881.

Jarvis, B. J., Dubath, P., Martinet, L., & Bacon, R., 1988. *A&AS* **74**, 513.

Jogee, S., 1998. *Molecular Gas and Starbursts in the Circumnuclear Regions of Spiral Galaxies.* Ph.D. Thesis, Yale University.

Kennicutt, R. C., 1989. *ApJ* **344**, 685.

Kohno, K., Kawabe, R., & Vila-Vilaró, B., 1999. *ApJ* **511**, 157.

Kormendy, J., 1979. *ApJ* **227**, 714.

Kraus, J. D., 1986. *Radio astronomy.* Powell, Ohio: Cygnus-Quasar Books, 1986.

Kutner, M. L. & Ulich, B. L., 1981. *ApJ* **250**, 341.

Leon, S., Combes, F., & Friedli, D., 2000. Single co peak in the double bar galaxy ngc 5850. In *ASP Conf. Ser. 197: Dynamics of Galaxies: from the Early Universe to the Present*, pp. 61.

Maciejewski, W. & Sparke, L. S., 2000. *MNRAS* **313**, 745.

Marquez, I. & Moles, M., 1993. *AJ* **105**, 2090.

Mauersberger, R., Henkel, C., Walsh, W., & Schulz, A., 1999. *A&A* **341**, 256.

Mulchaey, J. S., Regan, M. W., & Kundu, A., 1997. *ApJSS* **110**, 299.

Petitpas, G. R. & Wilson, C. D., 2001a. *ApJ submitted.*

Petitpas, G. R. & Wilson, C. D., 2001b. *ApJ to be submitted.*

Pfenniger, D. & Norman, C., 1990. *ApJ* **363**, 391.

Rubin, V. C., 1980. *ApJ* **238**, 808.

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

Schommer, R. A., Caldwell, N., Wilson, A. S., Baldwin, J. A., Phillips, M. M., Williams, T. B., & Turtle, A. J., 1988. *ApJ* **324**, 154.

Scoville, N. Z. & Sanders, D. B., 1987. H2 in the galaxy. In *ASSL Vol. 134: Interstellar Processes*, pp. 21.

Shaw, M. A., Combes, F., Axon, D. J., & Wright, G. S., 1993. *A&A* **273**, 31.

Sheth, K., Regan, M. W., Vogel, S. N., & Teuben, P. J., 2000. *ApJ* **532**, 221.

Smith, B. J., Lester, D. F., Harvey, P. M., & Pogge, R. W., 1991. *ApJ* **373**, 66.

Strong, A. W., Bloemen, J. B. G. M., Dame, T. M., Grenier, I. A., Hermsen, W., Lebrun, F., Nyman, L. ., Pollock, A. M. T., & Thaddeus, P., 1988. *A&A* **207**, 1.

Wilson, C. D., 1995. *ApJL* **448**, L97.

Wilson, C. D. & Scoville, N., 1990. *ApJ* **363**, 435.

Wong, T. & Blitz, L., 2000. *ApJ* **540**, 771.

Wozniak, H., Friedli, D., Martinet, L., Martin, P., & Bratschi, P., 1995. *A&AS* **111**, 115.

Young, J. S. & Devereux, N. A., 1991. *ApJ* **373**, 414.

Young, J. S., Xie, S., Tacconi, L., Knezek, P., Viscuso, P., Tacconi-Garman, L., Scoville, N., Schneider, S., Schloerb, F. P., Lord, S., Lesser, A., Kenney, J., Huang, Y., Devereux, N., Claussen, M., Case, J., Carpenter, J., Berry, M., & Allen, L., 1995. *ApJSS* **98**, 219.