MOLECULAR GAS IN CANDIDATE DOUBLE-BARRED GALAXIES. III.
A LACK OF MOLECULAR GAS?

GLEN R. PETITPAS
University of Maryland
College Park MD 20742; petitpas@astro.umd.edu

AND

CHRISTINE D. WILSON
McMaster University
1280 Main Street West, Hamilton ON L8S 4M1, Canada; wilson@physics.mcmaster.ca

Received 2003 March 5; accepted 2003 November 21

ABSTRACT

Most models of double-barred galaxies suggest that a molecular gas component is crucial for maintaining long-lived nuclear bars. We have undertaken a CO survey in an attempt to determine the gas content of these systems and to locate double-barred galaxies with strong CO emission that could be candidates for high-resolution mapping. We observed 10 galaxies in CO J = 2–1 and J = 3–2 and did not detect any galaxies that had 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%–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 $7 \times 10^6 M_\odot$ of molecular material, which corresponds to $\leq 0.1$% gas by mass. This result combined with the wide variety of CO distributions observed in double-barred galaxies suggests the need for models of double-barred galaxies that do not require a large, well-ordered molecular gas component.

Subject headings: galaxies: active — galaxies: ISM — galaxies: nuclei — radio lines: galaxies

1. INTRODUCTION

Double-barred galaxies have been proposed as a means of transporting molecular gas interior to inner Lindblad resonances (ILRs), where it may fuel starbursts or other forms of nuclear activity (Shlosman, Frank, & Begelman 1989). Thus far, double-barred galaxies have been identified predominantly through the analysis of near-infrared (NIR) images (e.g., Mulchaey, Regan, & Kundu 1997) and manifest themselves as variations in the position angles and ellipticity with galactic radius. A variety of models have been proposed to explain the nature of these nuclear bars, with origins varying from kinematically distinct nuclear bars to nuclear agglomerations that corotate at the same speed as the large-scale bar (Friedli & Martinet 1993; Shaw et al. 1993). To allow long-lived nuclear bars, these models usually require substantial amounts of dissipative gas to prevent the nuclear stellar populations from suffering rapid kinematic heating and subsequent bar destruction.

There is another class of models that attempt to explain nuclear bars using purely stellar orbits. It is known that there are different classes of orbits in a barred potential. The two important ones are the $x_1$ family, which runs parallel to the bar major axis, and the $x_2$ family, which runs perpendicular to it (e.g., Athanassoula 1992). It was thought that the $x_2$ orbits of the large-scale bar near the nucleus could form the $x_1$ orbits of the smaller nuclear bar and the corotation radius of the nuclear bar could correspond to the ILR of the large-scale bar. In this picture, the nuclear bar must always be aligned perpendicular to the main bar. Friedli & Martinet (1993) rule out this model by studying a larger sample of double-barred galaxies, since they found that not all of the observed offsets between the nuclear bar and the main bar can be explained by inclination effects. Recently, Maciejewski & Sparke (2000) found that there exist orbits in which particles in a double-barred potential (where the inner bar rotates faster than the large-scale bar) remain on closed orbits and may form the building blocks of long-lived double-barred galaxies without the need for a gaseous component.

High-resolution observations of the dynamics of these galaxies will allow us to test these competing models and learn the true nature of nuclear bars. Of the currently known double-barred galaxies, only a few have been studied in detail using high-resolution observations of the molecular gas (e.g., Petitas & Wilson 2002; Jogee, Kenney, & Smith 1999). In Petitas & Wilson (2002, hereafter Paper I) we used high-resolution CO observations to compare the molecular gas distributions of two candidate double-barred galaxies with the models of Friedli & Martinet (1993) and Shaw et al. (1993). We found that in NGC 2273 the molecular gas emission takes the appearance of a barlike feature 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.

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 Petitpas & Wilson (2003, hereafter Paper II) 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 (and less dense) in galaxies with more centrally concentrated gas distributions and warmer and denser in galaxies with CO emission scattered about the nucleus. The star formation rates in the galaxies with non-centrally concentrated gas distributions tended to be higher than in the galaxies with strong central concentrations. This result suggests either that the gas distribution is influencing the star formation activity or that the star formation may be affecting the gas properties.

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 to date (Jarvis et al. 1988; Shaw et al. 1993; Wozniak et al. 1995; Elmegreen et al. 1996; Mulchaey et al. 1997), only 23 contain isophote twists with size scales and position angle offsets large enough to be resolved by the Caltech Millimeter and BIMA (Berkeley-Illinois-Maryland Association) Arrays. Since the larger NIR surveys mentioned above were performed using southern observatories, most of the candidates are located in the southern hemisphere. Of those 23 galaxies with resolvable bars, only 13 are at a declination greater than −30°. Six of these (NGC 470, NGC 2273, NGC 4736, NGC 5850, NGC 5728, and NGC 6951) have high-resolution CO maps published (Paper I; Jogee 1998; Wong & Blitz 2000; Leon, Combes, & Friedli 2000; Kohno, Kawabe, & Vila-Vilaró 1999). Only NGC 3945 was not included in our sample, because of time and source availability constraints.

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 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 § 2 we discuss the observations and data reduction techniques. In § 3 we discuss our detections (and nondetections) in more detail and compare our observations with 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 § 4.

2. OBSERVATIONS AND DATA REDUCTION

2.1. NRAO Spectra

The nuclei of nine double-barred galaxies were observed in 12CO $J = 2 \rightarrow 1$ using the National Radio Astronomy Observatory (NRAO) 12 m telescope. Observations were taken in remote observing mode over a 14 hr period on 2000 February 15. The half-power beam width of the NRAO 12 m telescope was 29'' at 230 GHz (12CO $J = 2 \rightarrow 1$). 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 NGC < 4736. This is poorer than the normal value for the NRAO 12 m telescope, likely because of 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 nominal main-beam efficiency from the NRAO Users Guide of 0.29 at 230 GHz.

2.2. JCMT Spectra

Previous CO studies of double-barred galaxies show CO $J = 3 \rightarrow 2$ and $J = 2 \rightarrow 1$ line ratios ≥1 (Paper II), so for galaxies that were not detected with the NRAO Telescope we obtained higher resolution 13CO $J = 2 \rightarrow 1$ and 12CO $J = 3 \rightarrow 2$ spectra using the James Clerk Maxwell Telescope (JCMT). These observations were taken over the period of 1999–2000, mostly as part of a bad weather backup project. The half-power beam width of the JCMT is 21'' at 230 GHz (12CO $J = 2 \rightarrow 1$) and 14'' at 345 GHz (12CO $J = 3 \rightarrow 2$). 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 less than 15% from standard spectra. Thus, we adopt the nominal 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 1.

2.3. Reduction

Similar data sets were averaged together using the software package SPEXC 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 (7.7 and 11.5 MHz at 230 and 345 GHz, respectively) and zeroth- or first-order baselines were removed. The emitting regions that we detected were quite wide (>300 km s$^{-1}$), but the spectrometer bandwidth

| Galaxy | Line (12CO) | Telescope | $t_{int}$ (h:m) | $T_{mb}$ (K) | rms (mK $T_{mb}$) |
|--------|-------------|-----------|----------------|-------------|-----------------|
| NGC 2273 | $J = 2 \rightarrow 1$ | NRAO | 1:46 | 516 | 16 |
| NGC 2859 | $J = 2 \rightarrow 1$ | JCMT | 0:30 | 322 | 8 |
| NGC 2950 | $J = 2 \rightarrow 1$ | JCMT | 3:20 | 630 | 6 |
| NGC 3081 | $J = 3 \rightarrow 2$ | NRAO | 2:09 | 1012 | 28 |
| NGC 4340 | $J = 2 \rightarrow 1$ | NRAO | 1:58 | 467 | 14 |
| NGC 4371 | $J = 3 \rightarrow 2$ | JCMT | 2:00 | 485 | 5 |
| NGC 4736 | $J = 2 \rightarrow 1$ | NRAO | 3:20 | 424 | 10 |
| NGC 5728 | $J = 3 \rightarrow 2$ | JCMT | 0:50 | 503 | 5 |
| NGC 6951 | $J = 2 \rightarrow 1$ | NRAO | 1:58 | 453 | 13 |

* Given for a velocity resolution of 10 km s$^{-1}$, which corresponds to 7.68 MHz at 230 GHz and 11.5 MHz at 345 GHz.

1 More recent studies suggest that NGC 6951 does not currently contain a nuclear bar but may have had one in the past (Pérez et al. 2000). See § 3 for more details.
2 The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
3 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.
was 800, 800, and 1200 km s$^{-1}$ for the NRAO and JCMT $J = 3-2$ and $J = 2-1$ data, 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., $V_{\text{lsr}} \pm 200$ km s$^{-1}$) in order to maximize our chances of detecting any weak signal. The NRAO spectra for each galaxy are shown in Figure 1, and the JCMT spectra are shown in Figure 2. In the cases where the NRAO spectra show no convincing detections, we have included when available the $^{12}$CO $J = 3-2$ spectrum taken at the JCMT and published in Paper II (Fig. 3).

The type of nuclear activity exhibited is shown after the galaxy name (S2 = Seyfert 2; L = LINER). Note that we detect CO emission primarily from galaxies with some form of nuclear activity. The large tick marks on the velocity axis correspond to 500 km s$^{-1}$ intervals, while the smaller tick marks are every 100 km s$^{-1}$. Higher recession velocities are to the right.

3. DISCUSSION

3.1. Individual Galaxies

NGC 2273.—The NRAO 12 m detection of this galaxy is not strong. Given the velocity width of the emission and the fact that all the emission is located in the central few arcseconds (Petitpas & Wilson 2002) the large beam of the 12 m telescope dilutes the emission substantially.

NGC 2859.—Despite our rather high sensitivity, this galaxy was not detected in $^{12}$CO $J = 2-1$ with the NRAO 12 m telescope, nor in $^{12}$CO $J = 3-2$ with the JCMT. A literature search shows that it was detected with the 3 A$^5$ beam of Arecibo and contains $2 \times 10^8 M_\odot$ of H i (Bieging & Biermann 1977; Wardle & Knapp 1986).

NGC 2950.—Because of the similarity in local sidereal time with NGC 2859, we were unable to attempt an NRAO 12 m observation of this galaxy. It was observed with the JCMT but was not detected in $^{12}$CO $J = 2-1$. A literature search shows that H i was not detected in the galaxy (Wardle & Knapp 1986).

NGC 3081.—We have JCMT CO $J = 2-1$ spectra for NGC 3081 (Fig. 3) that show emission over a region from 2200 to 2500 km s$^{-1}$, while in the NRAO spectrum we see no detectable line. This is likely due to the high noise level in the NRAO spectra of NGC 3081 due to its low declination.

We have JCMT CO $J = 2-1$ and $J = 3-2$ spectra with strong detections (Paper II, Fig. 3) 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$^{-1}$. For completeness we include the $^{12}$CO $J = 3-2$ spectrum of this galaxy from Petitpas & Wilson (2003) in Figure 3.

**Fig. 1.** $^{12}$CO $J = 2-1$ spectra taken at the NRAO 12 m telescope of a sample of galaxies with NIR isophote twists and thought to contain double bars. The spectra cover the inner 29$''$ regions of the galaxy nuclei, which are 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 primarily from galaxies with some form of nuclear activity. The large tick marks on the velocity axis correspond to 500 km s$^{-1}$ intervals, while the smaller tick marks are every 100 km s$^{-1}$. Higher recession velocities are to the right.

**Fig. 2.** $^{12}$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 do not detect any emission from these four galaxies.

**Fig. 3.** JCMT $^{12}$CO $J = 2-1$ spectra from Paper II of three galaxies where the $^{12}$CO $J = 2-1$ detections with the NRAO were not convincing (see Fig. 1).
NGC 4340.—No emission was detected in $^{12}$CO $J = 2–1$ with the NRAO 12 m telescope, so follow-up observations were taken at the JCMT in $^{12}$CO $J = 3–2$ with the same result. This galaxy was not detected in H$\text{I}$ with Arecibo (Giovanardi, Krumm, & Salpeter 1983).

NGC 4371.—This galaxy is also not detected with the NRAO 12 m telescope in $^{12}$CO $J = 2–1$, JCMT in $^{12}$CO $J = 3–2$, or Arecibo in H$\text{I}$ (Giovanardi et al. 1983).

NGC 4736.—This nearby galaxy was easily detected with the NRAO 12 m telescope in $^{12}$CO $J = 2–1$. The line profiles and peak strength for NGC 4736 agree well with those published in Paper II.

NGC 5728.—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 2002; 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 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 with a general tendency for the noise to remain slightly greater than zero. NGC 5728 is clearly detected in the JCMT spectrum shown in Figure 3.

NGC 5850.—This galaxy is clearly detected in the NRAO 12 m spectrum. There are no published single-dish CO spectra for NGC 5850, so we cannot compare line profiles. Single-dish fluxes and interferometric maps are published in Leon et al. (2000), and they find single-dish gas masses comparable with ours, suggesting that our pointing and calibration are correct.

NGC 6951*.—The NRAO 12 m line profile of NGC 6951 (Fig. 1) is single-peaked, which is noticeably different than the JCMT $^{12}$CO $J = 2–1$ spectrum for this galaxy (see Paper II). The profile of the NRAO spectrum more closely resembles the CO $J = 3–2$ spectrum taken with the JCMT at an offset of $(0''$, $-7''$) as part of our five-point mapping procedure discussed in Paper II. 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 et al. 1999) with the most sensitive part of the beam.

We also point out here that after the inclusion of this galaxy in our sample, more recent studies have suggested that it does not contain a double bar as indicated by the earlier NIR surveys. Pérez et al. (2000) find evidence that NGC 6951 may have contained a nuclear bar at one point, but gas accumulates. Pe´rez et al. (2000) find evidence that NGC 6951 may have contained a nuclear bar at one point, but gas accumulates.

### 3.2. Cumulative Results

Despite our rather high sensitivity [$T_{\text{MB}}(\text{rms}) = 14$ mK], we have failed to detect CO $J = 2–1$ lines in NGC 2859, NGC 4340, or NGC 4371. 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). Looking at Table 3 suggests that we are predominantly detecting CO in later type galaxies, which is a result known from previous studies (Young et al. 1995), but there is also an apparent trend with nuclear activity.

**TABLE 2**

| Galaxy | $V$ Limits (km s$^{-1}$) | Transition (telescope) | Flux$^a$ (K km s$^{-1}$ $T_{\text{MB}}$) | $r_{\text{int}}^b$ (kpc) | Gas Mass (M$_\odot$) |
|-------|------------------------|------------------------|-------------------------------|------------------|------------------|
| NGC 2273 | 1600–2020 | $J = 2–1$ (NRAO) | 9.8 ± 1.0 | 1.7 | $8.2 \times 10^8$ |
| NGC 2859 | 1490–1890 | $J = 2–1$ (NRAO) | 19.7 ± 0.5 | 1.3 | $1.3 \times 10^9$ |
| NGC 2950 | 1140–1540 | $J = 2–1$ (NRAO) | <0.40 | 0.8 | $<2.9 \times 10^7$ |
| NGC 3081 | 2200–2550 | $J = 2–1$ (NRAO) | 4.6 ± 0.3 | 1.7 | $6.5 \times 10^8$ |
| NGC 4340 | 750–1150 | $J = 2–1$ (NRAO) | <0.32 | 0.4 | $<7.7 \times 10^6$ |
| NGC 4371 | 740–1140 | $J = 2–1$ (NRAO) | <1.0 | 0.9 | $<2.7 \times 10^7$ |
| NGC 4736 | 100–450 | $J = 2–1$ (NRAO) | 61.7 ± 1.4 | 0.3 | $1.7 \times 10^8$ |
| NGC 5728 | 2500–3050 | $J = 2–1$ (NRAO) | 7.4 ± 1.3 | 2.6 | $6.1 \times 10^8$ |
| NGC 5850 | 2400–2650 | $J = 2–1$ (NRAO) | 6.9 ± 0.7 | 2.3 | $1.3 \times 10^9$ |
| NGC 6951* | 1250–1620 | $J = 2–1$ (NRAO) | 13.4 ± 0.6 | 1.3 | $9.7 \times 10^8$ |

**Notes.**—For calculating gas masses for NGC 2273, NGC 5728, and NGC 6951 we adopt CO $J = 2–1/J = 1–0$ ratios of 0.88, 1.96, and 0.59, respectively (Petitpas & Wilson 2003). 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 2003). The flux values for the questionable detections (where the integrated intensities are larger than 3 times the noise associated with that region) are enclosed in parentheses.

$^a$ The beam size for the NRAO 12 m telescope, so follow-up observations were taken at the JCMT in $^{12}$CO $J = 3–2$ with the same result. This galaxy was not detected in H$\text{I}$ with Arecibo (Giovanardi, Krumm, & Salpeter 1983).

$^b$ The radius interior to which the flux/mass has been measured.

$^c$ The pointing may have been off; see text for details.
of nuclear activity. Of the four galaxies that we have not detected in CO emission, none of them show any signs of nuclear activity.\(^4\) 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 as yet undetected nuclear activity, which could change our small number statistics noticeably.

3.3. Molecular Gas Mass

The double-barred galaxy models of Friedli & Martinet (1993) and Shaw et al. (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

\[
M_{\text{mol}} = 1.61 \times 10^3 \left( \frac{\alpha}{\alpha_{\text{Gal}}} \right) \left( \frac{115 \text{ GHz}}{\nu} \right)^2 d_{\text{Mpc}}^2 S_{\text{CO}} \frac{M_\odot}{R} \]

(Wilson & Scoville 1990; Wilson 1995), where \(S_{\text{CO}}\) is the \(^{12}\text{CO} J = 2-1\) flux in Jy km s\(^{-1}\), \(R\) is the \(^{12}\text{CO} J = 2-1/J = 1-0\) line ratio, \(\nu\) is the frequency of the emission (230 GHz for the \(J = 2-1\) transition), \(d_{\text{Mpc}}\) is the distance to the galaxy in Mpc, \(\alpha\) is the CO-to-H\(_2\) conversion factor for that galaxy, and \(\alpha_{\text{Gal}}\) is the Galactic value \(\left[ 3 \pm 1 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1} \right]\), Strong et al. 1988; Scoville & Sanders 1987). We use 24.7 Jy K\(^{-1}\), 27.8 Jy K\(^{-1}\) \((\tau_{\text{ap}} = 0.63, 0.56)\), and 70.6 Jy K\(^{-1}\) \((\tau_{\text{ap}} = 0.35)\) to convert our JCMT \((J = 2-1, J = 3-2)\) and NRAO \(J = 2-1\) data (respectively) from Kelvins (\(T_b^*\)) to Janskys (Kraus 1986; JCMT Users Guide; NRAO 12 m Users Manual). We assume a coupling efficiency \((\tau_{\text{c}})\) of 0.7 to correct our observed fluxes to true fluxes. The CO-to-H\(_2\) conversion factor \((\alpha)\) 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 \(-30\%). Our fluxes are typically accurate to about 10\%. The distances for these relatively nearby galaxies are 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 them 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 2.

Table 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 also been detected with the JCMT, we find that the masses determined here typically are lower or agree with the masses determined with CO \(J = 2-1\) data in Paper II within a factor of 2. The exceptions are NGC 6951, which is lower here by more than a factor of 3, and NGC 4736, which is higher by almost a factor of 2. The discrepancy in NGC 6951 can likely be attributed to the pointing offset discussed in § 3. The discrepancy in NGC 4736 can likely be attributed to the strong CO emission in the spiral arms falling in the larger beam of the NRAO telescope (Wong & Blitz 2000). 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 2.

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 mass is comparable with the amount of molecular gas in the entire Milky Way, but now contained in its inner 2.5 kpc radius (Danne et al. 1993). The optical size of this galaxy is 4.3 x 3.7 \((D_{25} \times d_{25})\), which corresponds to 43 x 37 kpc at its distance of 34 Mpc. This clearly makes it the largest galaxy in our sample (the second runner up is NGC 5728 at 33 x 19 kpc). Given its rather strong primary bar, it is possible that the large quantity of gas

\(^4\) Ho, Filippenko, & Sargent (1997) gave NGC 2859 the uncertain classification of a "transition object," that is, a galaxy showing signs of both an H\(_n\) and LINER nucleus. However, the lines are weak and the spectra are noisy.
in the inner regions of this galaxy may have been transported inward by the infall mechanisms known to be associated with bar perturbations. The high-resolution CO maps of this galaxy (Leon et al. 2000) detect only $6.7 \times 10^7 \, M_\odot$ 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 $J = 1 - 0$ map of the entire primary bar detects $3.4 \times 10^5 \, M_\odot$. Leon et al. (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 15–20 kpc (major axis) size range with the exception of NGC 2859, NGC 5728, and NGC 5850, which 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 ~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 because 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 2000). We will need spectra covering a wider field of view to verify if this is happening in any of these galaxies.

### Table 4

| Galaxy  | $m_{B(T)}$ | $M_g$ (absolute) | $L_g$ ($L_\odot$) | Mass ($M_\odot$) |
|---------|------------|-----------------|-----------------|----------------|
| NGC 2273 | 12.55 | $-19.44$ | $8.7 \times 10^9$ | $2.6 \times 10^{10}$ |
| NGC 2859 | 11.83 | $-19.87$ | $1.3 \times 10^{10}$ | $3.9 \times 10^{10}$ |
| NGC 2950 | 11.84 | $-19.44$ | $8.7 \times 10^9$ | $2.9 \times 10^{10}$ |
| NGC 3081 | 12.85 | $-19.68$ | $1.1 \times 10^{10}$ | $3.3 \times 10^{10}$ |
| NGC 4340 | 12.10 | $-18.47$ | $3.6 \times 10^9$ | $1.1 \times 10^{10}$ |
| NGC 4371 | 11.79 | $-18.78$ | $4.7 \times 10^9$ | $1.4 \times 10^{10}$ |
| NGC 4736 | 8.99 | $-19.02$ | $5.9 \times 10^8$ | $1.8 \times 10^{10}$ |
| NGC 5728 | 12.57 | $-20.27$ | $1.9 \times 10^{10}$ | $5.7 \times 10^{10}$ |
| NGC 5850 | 11.54 | $-21.18$ | $4.3 \times 10^9$ | $1.3 \times 10^{10}$ |
| NGC 6951 | 11.64 | $-19.75$ | $1.2 \times 10^9$ | $3.6 \times 10^{10}$ |

Notes.—The value $m_{B(T)}$ is the apparent blue magnitude of the galaxy extrapolated to infinite radius (RC3). We adopt +5.41 for the Sun’s absolute blue magnitude (Allen 1964) and note that a change of ~0.3 in the galactic magnitude would 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).
gas is not confined to the nuclei of these galaxies. A circumnuclear CO morphology is seen in other galaxies (e.g., NGC 7331; Sheth 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 whether this is the case, but the models of Friedli & Martinet (1993) still require that the inner kiloparsecs contain at least 2% gas. If we assume similar disk and bulge profiles for NGC 2859 as those adopted for NGC 5728 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 0.7% 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 ring beyond our NRAO 12 m beam, it will be part of the main disk and will not have much of an impact on the cooling of the nuclear regions. The failure of the large beams of the HI studies to detect any gas in NGC 2950, NGC 4340, or NGC 4371 suggests that the entire disks of these galaxies are very gas poor.

Another 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. We have searched the literature for HI observations of these four galaxies that are undetected in CO. Only NGC 2859 has been detected in HI by various authors (Bieging & Biermann 1977; Giovanardi, Krumm, & Salpeter 1983; Wardle & Knapp 1986; Eskridge & Pogge 1991). An HI mass of 2 × 10^6 M☉ was determined by Bieging & Biermann (1977) for the entire disk of NGC 2859, which corresponds to a gas mass ratio of 0.5% globally, which is still less than required by the models of Friedli & Martinet (1993) and Shaw et al. (1993). Additionally, 60 and 100 μm fluxes suggest global star formation rates less than 0.1 M☉ yr⁻¹ (Eskridge & Pogge 1991; Kennicutt 1998), supporting the claim that these galaxies are gas deficient.

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 Paper I, where the existence of a nuclear molecular feature that aligns with the isophote twists supports the existence of a true nuclear bar in the disk of NGC 2273. In addition, detailed analysis of the NIR isophotes indicates that the variations in position angle and bar ellipticity observed in some galaxies cannot be the result of triaxial stellar bulges but must be produced by nuclear stellar bars (Jungwiert, Combes, & Axon 1997). Observations of deprojected nuclear bar-primary bar offset angles have also ruled out the possibility that the isophote twists are the result of collections of stars trapped in x₂ orbits (Friedli & Martinet 1993).

Finally, if the NIR isophote twists are caused by nuclear stellar bars, but we do not see a significant gas mass fraction in the nucleus, then our observations favor models that can produce nuclear stellar bars without a molecular gas counterpart. Recently, Maciejewski & Sparke (2000) have discovered a small family of orbits that are capable of sustaining nuclear stellar bars. In light of the lack of gas in some of the galaxies discussed here, we believe that of all models so far, this is the most promising explanation for these instances of double-barred galaxies.

It is possible that different mechanisms are at work in different galaxies and that they need to be studied on a case by case basis to determine whether 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 submillimeter interferometer in the southern hemisphere in order to obtain high-resolution CO maps for a larger number of these galaxies. Additionally, high-resolution studies of the star formation histories of these galaxies will help determine which stage these galaxies occupy in the evolution of double-barred galaxies.

4. SUMMARY

In an attempt to find double-barred galaxies that are bright in CO emission, we have obtained 12CO J = 2–1 spectra for nine galaxies with the NRAO 12 m telescope. In the cases where no emission was found with the NRAO 12 m telescope, we obtained higher resolution 12CO J = 3–2 and J = 2–1 spectra with the JCMT. There is only one additional detection in the JCMT spectra of these galaxies despite reaching sensitivities of 4 mK (Tˢ). We detect emission in five of these galaxies. All five galaxies detected exhibit some form of nuclear activity, while the galaxies that were not detected are quiescent and show 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 galaxies, LINERs). 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.

Some 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 find gas masses that range from 7 × 10⁶ to more than ~10⁹ M☉.

The lack of CO and HI detections places very strict limits on the amounts of gas in these galaxies. For some galaxies, there must be less than a few times 10⁶ M☉ of molecular gas, which (assuming that these galaxies are typical disk galaxies) corresponds to gas mass fractions of 0.05% to 0.8% (depending on the assumed mass distribution). These very low gas mass fractions suggest that, contrary to many models, large amounts of molecular gas are not required to sustain double-bars in the nuclei of some galaxies.

G. R. P. is supported by NSF grant AST 99-81289 and by the State of Maryland via support of the Laboratory for Millimeter-Wave Astronomy. This research has also 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 the anonymous referee for helpful comments that greatly improved the quality of this paper. We also wish to thank Rob Ivison, Susie Scott, Tracy Webb, and the staff of the JCMT for their help with the observations taken remotely during noncosmology weather. G. R. P. wishes to thank the extremely helpful staff at the NRAO 12 m telescope for all their assistance in the remote observing run in 2000 February, which went more smoothly than many observing runs for which he himself was present.

REFERENCES
Allen, C. W. 1964, Astrophysical Quantities (2d ed.; London: Athlone), 1964
Athanassoula, E. 1992, MNRRS, 259, 345
Bieging, J. H., & Biermann, P. 1977, A&A, 60, 361
Braine, J., & Combis, F. 1992, A&A, 264, 433
Combes, F., & Gerin, M. 1985, A&A, 150, 327
Dame, T. M., Koper, E., Israel, F. P., & Thaddeus, P. 1993, ApJ, 418, 730
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, J. R., Buta, R. J., Paturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer)
Elmegreen, D. M., Elmegreen, B. G., Chrome, F. R., Hasselbacher, D. A., & Bissell, B. A. 1996, AJ, 111, 1880
Eskridge, P. B., & Pogge, R. W. 1991, AJ, 101, 2056
Forbes, D. A. 1992, A&AS, 92, 583
Friedli, D., & Martinet, L. 1993, A&A, 277, 27
Giovanardi, C., Krumm, N., & Salpeter, E. E. 1988, AJ, 88, 1719
Goldsmith, P. F., & Langer, W. D. 1978, ApJ, 222, 881
Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, ApJS, 112, 315
Jarvis, B. J., Dubath, P., Martinet, L., & Bacon, R. 1988, A&AS, 74, 513
Jogee, S. 1998, Ph.D. thesis, Yale Univ.
Jogee, S., Kenney, J. D. P., & Smith, B. J. 1999, ApJ, 526, 665
Jungwiert, B., Combis, F., & Axon, D. J. 1997, A&AS, 125, 479
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 (2d ed.; Powell: Cygnus-Quasar)
Kutner, M. L., & Ulrich, B. L. 1981, ApJ, 250, 341
Leon, S., Combis, F., & Friedli, D. 2000, in ASP Conf. Ser. 197, Dynamics of Galaxies: From the Early Universe to the Present, ed. F Combis, G. A. Mamon, & V. Charmandaris (San Francisco: ASP), 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, ApJS, 110, 299
Pérez, E., Márquez, I., Marrero, I., Durret, F., González Delgado, R. M., Masegosa, J., Maza, J., & Moles, M. 2000, A&A, 353, 893
Petitpas, G. R., & Wilson, C. D. 2002, ApJ, 575, 814 (Paper I)
———. 2003, ApJ, 587, 649 (Paper II)
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, in Interstellar Processes, ed. D. J. Hollenbach & H. A. Thronson (Dordrecht: Reidel), 21
Sheth, K. 20. 2000, Ph.D. thesis, Univ. Maryland
Shlosman, I., Frank, J., & Begelman, M. C. 1989, Nature, 338, 45
Smith, B. J., Lester, D. F., Harvey, P. M., & Pogge, R. W. 1991, ApJ, 380, 677
Strong, A. W., et al. 1988, A&A, 207, 1
Wardle, M., & Blitz, L. 2000, ApJS, 111, 115
Wilson, C. D. 1995, ApJ, 448, L97
Wilson, C. D., & Scoville, N. Z. 1990, ApJ, 363, 435
Young, J. S., et al. 1995, ApJS, 98, 219