THE ASTROPHYSICAL JOURNAL, 419:86–93, 1993 December 10

DENSE GAS IN THE BULGES OF EXTERNAL GALAXIES

TAMARA T. HELFER AND LEO BLITZ
Department of Astronomy, University of Maryland, College Park, MD 20742
Received 1993 March 5; accepted 1993 June 17

ABSTRACT

In order to probe the physical conditions in the high-pressure environments of galactic bulges, we have studied the properties of the dense molecular gas in the bulges of a sample of 19 mostly normal spiral galaxies. We observed the 3 mm emission from the molecules HCN and CS, which trace gas densities of $\sim 10^5$ cm^{-3}. Our high detection rate (68% in HCN, 50% in CS) suggests that most spiral galaxies, not just starburst galaxies, contain appreciable quantities of dense gas in their bulges. The HCN to CO ratio of integrated intensities $\mathscr{R}_{HCN,CO}$ measured in the bulges of galaxies can be very sensitive to the resolution of the radio beam used for the observations; the ratio tends to be significantly higher for telescopes with smaller beams. The CS to CO ratios $\mathscr{R}_{CS,CO}$ measured in extragalactic bulges are consistent with that measured over the Milky Way bulge but appear to be at least a factor of 2 larger than in local GMCs in the Galactic disk. Since $\mathscr{R}_{CS,CO}$ in local GMCs is likely to be an upper limit of the average $\mathscr{R}_{CS,CO}$ in the disk of the Milky Way, we conclude that nuclear molecular clouds are not like disk molecular clouds. Despite the similar critical excitation densities of the two molecules used to trace dense gas in this study, we find that the HCN emission is consistently brighter than the CS in these sources by an average of 2.4 in the integrated intensities.

Subject headings: galaxies: ISM — galaxies: spiral — galaxies: structure

1. INTRODUCTION

The bulges of spiral galaxies may have pressures some two to three orders of magnitude higher than those in their disks (Spergel & Blitz 1992). Such an extraordinary difference in gas pressures should be revealed as a larger fraction of dense gas or broader line widths in galactic bulges when compared with galactic disks. In fact, these effects are seen in the Milky Way: diffuse CS emission is seen only within a few degrees of the Galactic center (Bally et al. 1987, 1988), and the line widths of individual molecular features there are typically 5–10 times larger than are seen anywhere else in the Galaxy.

We wish to know to what degree the differences between bulge and disk molecular clouds are peculiar to the Milky Way, and to what degree different galactic environments affect the properties of molecular clouds. Despite an abundance of studies of the amount and distribution of CO in galaxies, however, there is still a rather incomplete understanding of what determines the physics of the molecular component in galaxies. In order to investigate the effects of a possible difference in pressure between bulges and disks and between galaxies with different bulge sizes, we have begun a program to study dense gas emission in external galaxies so that we can compare quantitatively the conditions of the interstellar gas in these regions.

As a first step, we investigated whether normal galaxies have detectable amounts of dense gas in their bulges and which molecular probe might be suited best for studying the dense gas distribution. We have conducted a survey of 19 mostly normal spiral galaxies and one early-type galaxy in HCN and CS, molecules which require densities some 100 times that of CO to be collisionally excited. (CO, the primary tracer of molecular mass in the cold component of the Milky Way as well in other galaxies, has a critical excitation density of $\sim 10^3$ cm^{-3}.) Previous observations of dense gas in galaxies (traced by molecules like CS, HCN, and HCO^+) have focused on emission from starburst or ultraluminous galaxies (e.g., surveys by Nguyen-Q-Rieu, Nakai, & Jackson 1989; Solomon, Downes, & Radford 1992 and many detailed studies of starburst galaxies like NGC 253, M82, IC 342, and Cen A); dense gas in relatively normal galaxies has been surveyed by Mauersberger et al. (1989), Sage, Solomon, & Shore (1990), Nguyen-Q-Rieu et al. (1992), and Israel (1992). This paper presents the results of a preliminary, comparative study of the two dense gas tracers HCN and CS in a sample of normal as well as starburst galaxies.

2. OBSERVATIONS

From a list of the brightest extragalactic CO emitters (Verter 1985 and various references from the literature), we selected 19 spiral galaxies for observation having a range of Hubble types and with bulge sizes generally of the order of or greater than our beam size (1′). The sources are listed in Table 1. With a few exceptions, the CO integrated intensities at the central positions of the selected sources are greater than 15 K km s^{-1} (Table 2). We observed one early-type galaxy, NGC 404, which also had been detected previously in CO (Wiklind & Henkel 1990). Although there are a few starburst or Seyfert galaxies on our list (NGC 253, IC 342, NGC 1068, NGC 7469), most of our sources have unremarkable nuclear activity. We refer to these as "normal" galaxies, with the understanding that many of our sources, like the Milky Way, have low-level nuclear line emission (Filippenko 1992). All of the spiral sources have also been detected as X-ray emitters (Fabbiano, Kim, & Trinchieri 1992). We observed each galaxy in HCN and 12 galaxies in CS at the central position; for good relative calibrations, we observed CO at these positions as well.

The observations were made during 1992 May 5–8 and 1992 June 11–23 with the 3 mm SIS receiver at the NRAO 12 m telescope on Kitt Peak, Arizona.[1] We observed using two 256 × 2 MHz filter banks which measured orthogonal polar-

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1

Source List

Source Name	Hubble Type	R.A.(1950)	Decl.(1950)	V (km s^{-1})[a]	D_{25}[b]	a[c]
M31 BA108	Sb	$00^h41^m57^s.6$	+41°11′06″	−190	190′.55	20′.1
NGC 253[d]	Sc	00 45 08.0	−25 33 42	251	27.54	2.22
NGC 404	dE0/S0	01 06 39.1	+35 27 10	−48	3.47	...
NGC 891	Sb	02 19 25.0	+42 07 12	528	13.49	1.84
NGC 1068[e]	Sb	02 40 07.2	−00 13 30	1137	7.08	0.43
NGC 1097	SBbc	02 44 11.0	−30 29 06	1275	9.33	0.43
IC 342[d]	Scd	03 41 58.6	+67 56 24	34	21.38	0.7
NGC 2903	Sc	09 29 20.4	+21 43 12	556	12.59	0.57
NGC 3628[d]	Sbc	11 17 39.6	+13 52 05	847	14.79	2.3
NGC 4254	Sc	12 16 16.9	+14 41 42	2407	5.37	0.40
NGC 4303	Sc	12 19 21.4	+04 45 05	1569	6.46	0.25
NGC 4321 (M100)	Sc	12 20 22.8	+16 06 00	1508	7.41	0.53
NGC 4527	Sb	12 31 35.5	+02 55 42	1734	6.17	0.8
NGC 4569	Sab	12 34 18.7	+13 26 23	−235	9.55	0.83
NGC 4826	Sab	12 54 16.9	+21 57 05	408	10.00	1.59
NGC 5194 (M51)	Sbc	13 27 46.9	+47 27 17	463	11.22	0.46
NGC 5236 (M83)	SBc	13 34 10.0	−29 36 47	516	12.88	0.40
NGC 5248	Sbc	13 35 03.0	+09 08 30	1153	6.17	0.29
NGC 6946	Sc	20 33 48.8	+59 58 47	52	11.48	0.9
NGC 7469[e]	Sab	23 00 44.4	+08 36 17	4916	1.48	0.3

[a] LSR radio velocity.
[b] Diameter of the major axis at the 25 mag arcsec^{-2} isophote from RC3.
[c] Bulge diameter estimated from Hubble Atlas (where possible) or from POSS Prints.
[d] Starburst.
[e] Seyfert/starburst.

TABLE 2

Summary of Results

Source	I_{CO}[a] (K km s^{-1})	I_{HCN}[a] (K km s^{-1})	I_{CS}[a] (K km s^{-1})	$\mathscr{R}_{HCN, CO}$[b]	$\mathscr{R}_{CS, CO}$[b]	$\mathscr{R}_{HCN, CS}$[b]
NGC 253	102.4 ± 1.2[c]	23.7 ± 0.6	...	0.23 ± 0.01	...	...
NGC 253 disk[d]	48.1 ± 4.1[e]	1.1 ± 0.3	...	0.023 ± 0.007	...	...
NGC 404	1.5 ± 0.2	<0.1[f]	...	<0.067	...	...
M31 BA108	3.6 ± 0.2	<0.1	<0.1	<0.028	<0.028	...
NGC 891	20.5 ± 0.6	0.7 ± 0.2	...	0.034 ± 0.010	...	...
NGC 1068	42.9 ± 0.8	4.8 ± 0.4	1.4 ± 0.2	0.11 ± 0.01	0.033 ± 0.005	3.4 ± 0.6
NGC 1097	21.5 ± 1.3[g]	(0.8 ± 0.2)[h]	...	0.033 ± 0.005	...	...
IC 342	38.7 ± 0.7	2.3 ± 0.4	...	0.059 ± 0.010	...	...
NGC 2903	19.2 ± 0.6	(0.5 ± 0.2)	<0.4	0.026 ± 0.010	<0.021	...
NGC 3628	44.2 ± 1.1	<0.6[i]	<0.2[i]	<0.014[i]	<0.005[i]	...
NGC 4254	22.4 ± 0.5	0.9 ± 0.2	<0.2	0.040 ± 0.009	<0.009	...
NGC 4303	17.4 ± 0.7	<0.4	...	<0.023	...	...
NGC 4321 (M100)	23.8 ± 0.5	0.8 ± 0.2	0.4 ± 0.1	0.034 ± 0.008	0.017 ± 0.004	2.0 ± 0.7
NGC 4527	29.8 ± 0.7	1.2 ± 0.2	(0.3 ± 0.1)	0.040 ± 0.007	0.010 ± 0.003	4.0 ± 1.5
NGC 4569	20.2 ± 0.6	1.0 ± 0.3	<0.4	0.050 ± 0.015	<0.20	...
NGC 4826	25.1 ± 0.6	1.1 ± 0.2	0.6 ± 0.2	0.044 ± 0.008	0.024 ± 0.008	1.8 ± 0.7
NGC 5194 (M51)	30.7 ± 1.1	1.0 ± 0.2	0.7 ± 0.1	0.033 ± 0.007	0.023 ± 0.003	1.4 ± 0.4
NGC 5236 (M83)	67.5 ± 1.5	2.3 ± 0.2	1.0 ± 0.1	0.034 ± 0.003	0.015 ± 0.002	2.3 ± 0.3
NGC 5248	16.8 ± 0.9	0.4 ± 0.1	...	0.024 ± 0.006	...	...
NGC 6946	61.0 ± 0.5	1.5 ± 0.2	0.8 ± 0.1	0.025 ± 0.003	0.013 ± 0.002	1.9 ± 0.3
NGC 6946 disk[j]	9.0 ± 1.7	0.2 ± 0.07	...	0.022 ± 0.009	...	...
NGC 7469	7.8 ± 0.3	<0.4	...	<0.051	...	...
Bulge averages				0.050 ± 0.012	0.019 ± 0.003	2.4 ± 0.3

[a] $I = \int T_R^* dv$.
[b] $\mathscr{R}_{i,j} = I_i/I_j$.
[c] Formal uncertainties are quoted; absolute intensities are uncertain by ≥10%.
[d] Average of two positions ±2′ off central position along major axis.
[e] CO from Rickard & Blitz 1985.
[f] 2 σ upper limits.
[g] Uncertainty due to possible baseline defect.
[h] Marginal detection.
[i] Mistakenly observed with beam switching rather than position switching; the beam may have covered an emitting region in the off position.
[j] 1′.5 off central position.

izations, and we averaged the results to produce final spectra. The spectra were smoothed to an 8 MHz channel resolution; at the frequency of the CO(1–0) transition ($\nu = 115.27$ GHz), this corresponds to a velocity resolution of 20 km s^{-1} over a 1300 km s^{-1} bandwidth. Typical system temperatures on the sky were 400 K at the CO(1–0) transition and 300 K at the HCN(1–0) ($\nu = 88.63$ GHz) and CS(2–1) ($\nu = 97.98$ GHz) transitions. The telescope pointing was checked using continuum observations of planets and quasars and corrections were typically $\sim 10''$. At 3 mm, the telescope half-power beam width, main beam efficiency η_m, and forward spillover and scattering efficiency η_{fss} are 63″, 0.62, and 0.72. To convert from T_R^* to T_{MB}, the reader should multiply T_R^* by $\eta_{fss}/\eta_m = 1.16$.

In order to achieve flat baselines for our HCN and CS observations, we corrected for atmospheric variations by beam switching by $\pm 2'$–$2'.5$ in azimuth at a rate of 1.25–2.5 Hz whenever the sources had bulge sizes small enough to use this technique. For sources with larger bulges, we used position switching. Since there is no blanking of the subreflector during beam switching mode, we observed IRC 10216 as a check and found that the antenna temperatures and integrated intensities both agreed to 1% using the two observing techniques.

3. RESULTS

We detected 13 of 19 spirals observed in HCN; another two galaxies were marginal detections. We also detected six of 12 sources observed in CS with an additional one marginal detection. The individual spectra are presented in Figure 1, and the results of the observations are summarized in Table 2. The errors quoted are formal uncertainties; calibration and pointing errors make absolute intensities uncertain by at least 10%. These are the first published detections of HCN in seven galaxies with unremarkable nuclear activity. There is considerable overlap between our sample and that of Nguyen-Q-Rieu et al. (1992): an additional six galaxies, common to the two studies, had not been detected earlier in HCN.

To compare the fractions of dense gas in the sources, we computed ratios of integrated intensities for the various species (see Table 2). The ratio $\mathscr{R}_{i,j}$ is defined as $\mathscr{R}_{i,j} = I_i/I_j$, where $I = \int T_R^* dv$ is the integrated intensity of the line for each species. The HCN to CO bulge ratio $\mathscr{R}_{\rm HCN,CO}$ ranges from 0.024–0.23 among the detections; of these, the two starburst galaxies NGC 253 and NGC 1068 have by far the highest ratios (0.23 and 0.11, respectively). Excluding these two

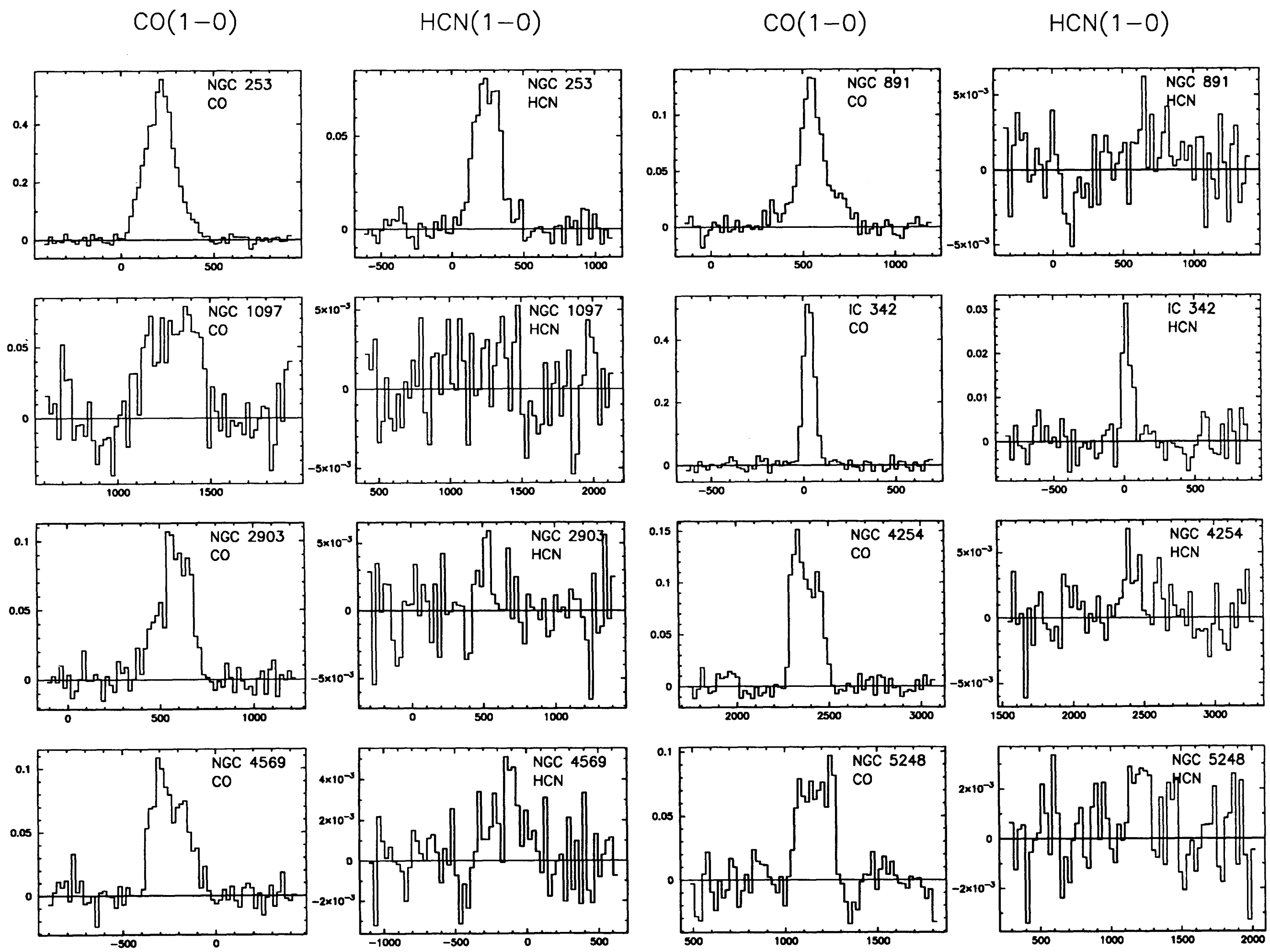

FIG. 1.—The CO(1–0), HCN(1–0), and CS(2–1) spectra of the observed galaxies. The abscissa is velocity in units of km s^{-1}, and the ordinate is T_R^* in K. The velocity resolution is 20 km s^{-1} (8 MHz).

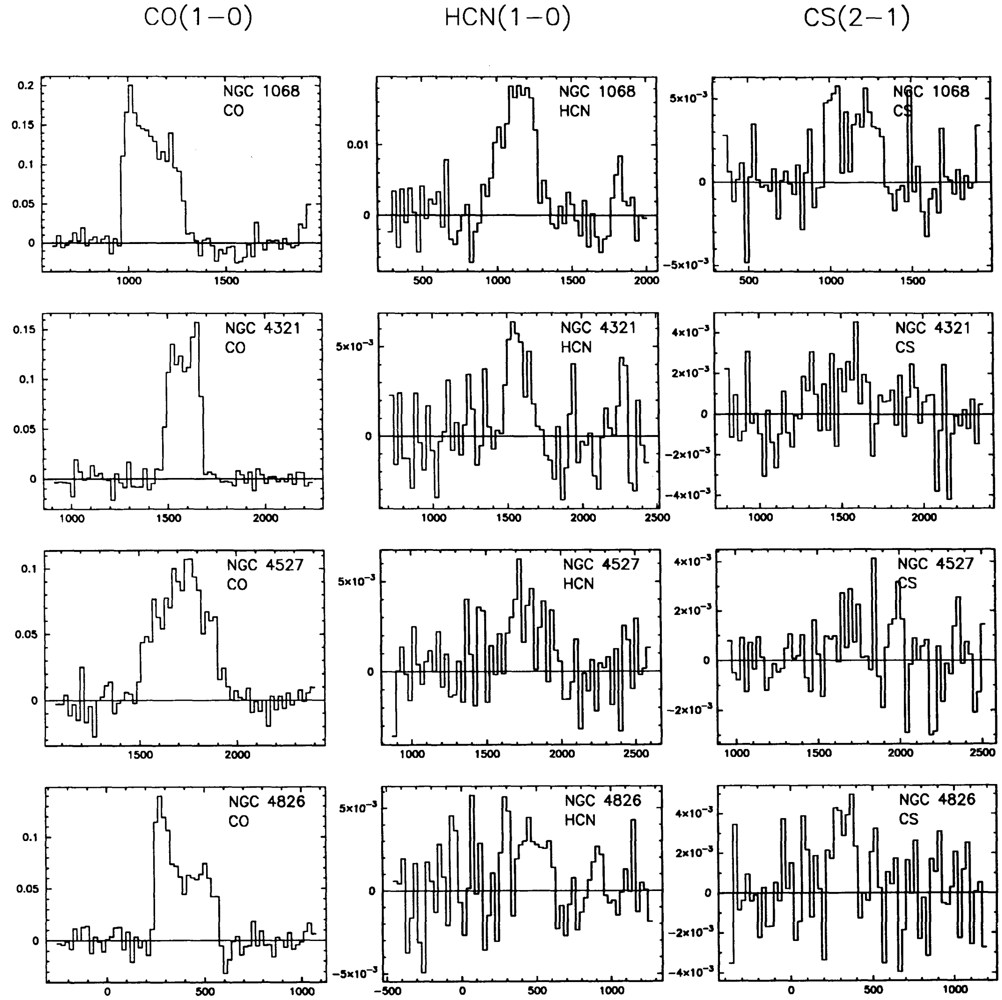

FIG. 1—*Continued*

sources, the ratio has a much more limited range of 0.024–0.059 with an average $\mathscr{R}_{HCN,CO}$ of 0.037 and a formal dispersion of 0.010. The average CS to CO bulge ratio $\mathscr{R}_{CS,CO}$ is 0.019 over a range of 0.010–0.033; the formal dispersion in $\mathscr{R}_{CS,CO}$ is 0.007. The ratios of our entire sample are in reasonable agreement with those from the literature (Table 3). It is apparent, however, that the $\mathscr{R}_{HCN,CO}$ ratio measured for each source can be quite sensitive to the beam size of the telescope used for the observation; Table 4 lists the $\mathscr{R}_{HCN,CO}$ ratio measured at different telescopes for each of seven sources. A source is included in this table only if both the HCN *and* the CO were measured at the same telescope. In five of the seven sources, the measured ratio is considerably higher for the telescope with the smaller beam size. The two exceptions include the starburst galaxy NGC 253 and the starburst/Seyfert NGC 1068, both of which have unusual properties to be considered for this test: the bulge of the nearby galaxy NGC 253 is more than 4′ in diameter, which is some 4 times the diameter of the largest beam listed in Table 4. There is also rich structure associated with a 4′ molecular bar in the center of this source (Scoville et al. 1985). It is likely that the local variations within the bulge of this galaxy contribute as much to the various measurements as do the different beam sizes used for the observations. In NGC 1068, the central CO emission is dominated by a 30″ diameter ring associated with the starburst (Planesas, Scoville, & Myers 1991); this emission is within the 3 mm beam of the NRAO 12 m telescope but outside that of the IRAM 30 m telescope.

Of the HCN nondetections, only two galaxies (NGC 3628 and NGC 4303) are not detected at levels well below that expected from the average $\mathscr{R}_{HCN,CO}$ ratio we measured (see note *i* to Table 2, however); the other two undetected spirals (NGC 7469 and the bright complex BA 108 in M31) as well as the undetected early-type galaxy NGC 404 are constrained instead by the sensitivity of our observations. Three of our CS nondetections are also limited by our sensitivity. Our high detection

TABLE 3

DENSE GAS FRACTIONS IN GALAXIES

Telescope[a]	$\mathscr{R}_{HCN,CO}$	$\mathscr{R}_{CS,CO}$	Reference
NRAO 12 m	0.050 ± 0.012	0.019 ± 0.003	1
SEST 15 m	0.058 ± 0.009	...	2
IRAM 30 m	0.078 ± 0.013	...	3
NRAO 12 m, FCRAO 14 m	...	0.027 ± 0.003	4

[a] See notes to Table 4 for beam sizes at different telescopes.

REFERENCES.—(1) This study; (2) Israel 1992; (3) Solomon et al. 1992 (mostly ultraluminous galaxies); (4) Sage et al. 1990.

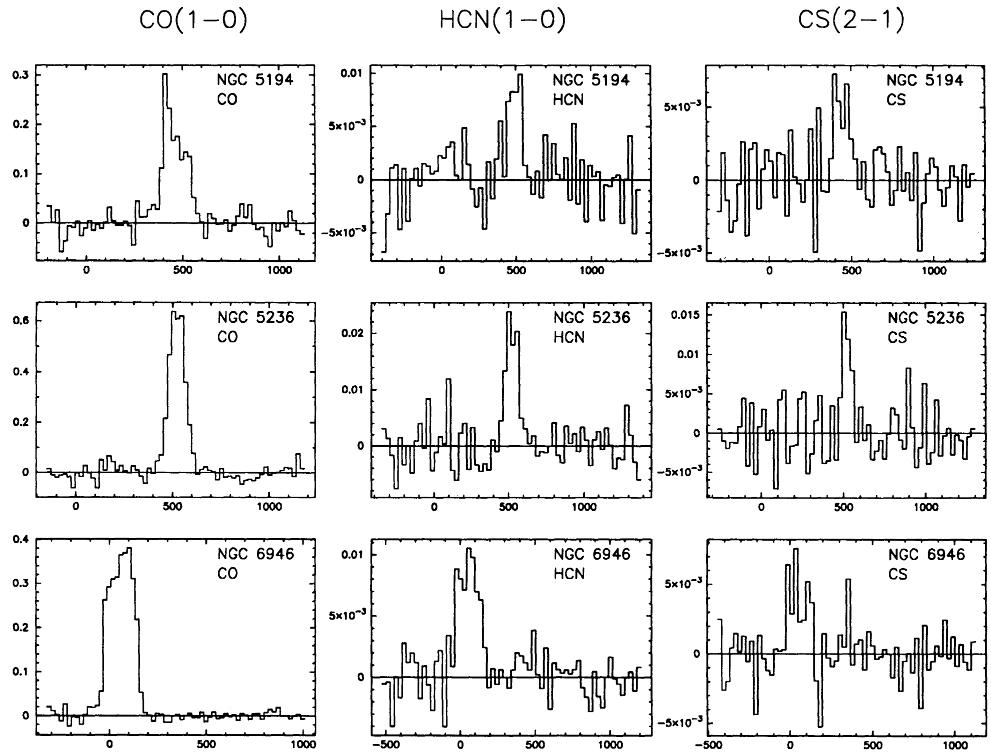

FIG. 1—*Continued*

rate (68% in HCN, 50% in CS) suggests that most disk galaxies, *not* just starburst galaxies, contain large quantities of dense gas in their bulges.

We observed two of the galaxies with the strongest central HCN detections, NGC 253 and NGC 6946, in off-bulge positions. NGC 253 has a disk $\mathscr{R}_{\rm HCN,CO}$ ratio 10 times smaller than its central ratio, but the bulge and disk ratios are indistinguishable within the errors in NGC 6946 (see Table 2).

We also found that, despite the similar critical excitation densities of the two molecules, the HCN is consistently brighter than the CS emission in all the galaxies observed in both molecules by a factor of 2.4 ± 0.3 in the integrated intensities (see Fig. 2). This may reflect a difference in the excitation conditions of the gas or in the formation chemistry of the molecules, or it may reflect a difference in the abundances of the species involved.

TABLE 4

MEASURED $\mathscr{R}_{\rm HCN,CO}$ AS A FUNCTION OF BEAM SIZE

Source	NRO[a]	IRAM[b]	SEST[c]	NRAO[d]	References
IC 342	...	0.090	...	0.059	1, 2
NGC 253	0.13	...	0.092	0.23	3, 4
NGC 1068	...	0.099	...	0.11	2, 5
NGC 2903	...	0.080	...	0.026	2, 6
NGC 3628	...	0.037	...	<0.014[e]	2, 7
NGC 5236	...	...	0.068	0.034	4
NGC 6946	...	0.060	...	0.025	2, 8

[a] $\theta_{89} = 23''$, $\theta_{115} = 15''$ where θ_i = FWHM beam size at i = 89 and 115 GHz

[b] $\theta_{89} = 27''$, $\theta_{115} = 21''$

[c] $\theta_{89} = 56''$, $\theta_{115} = 41''$

[d] $\theta_{89} = 71''$, $\theta_{115} = 55''$; this study

[e] See note *i* to Table 2

REFERENCES: (1) Eckart et al. 1990; (2) Nguyen-Q-Rieu et al. 1992; (3) Nguyen-Q-Rieu et al. 1989; (4) Israel 1992; (5) Planesas, Gómez-González, & Martín-Pintado 1989; (6) Jackson et al. 1991; (7) Boissé et al. 1987; (8) Weliachew et al. 1988.

4. DISCUSSION

The primary result of this study is the indication that most spiral galaxies contain a large amount of gas at densities of $\sim 10^5$ cm^{-3} in their bulges, regardless of the degree of their nuclear activity. This is surprising when compared with conditions in nearby giant molecular clouds (GMCs) in the Milky Way, which have typical densities in the clumps of $\sim 10^{2.5}$–$10^{3.5}$ cm^{-3} (Blitz 1987) and which contain relatively few clumps with detectable dense gas as measured by CS (Lada, Bally, & Stark 1991); our result supports the conjecture that

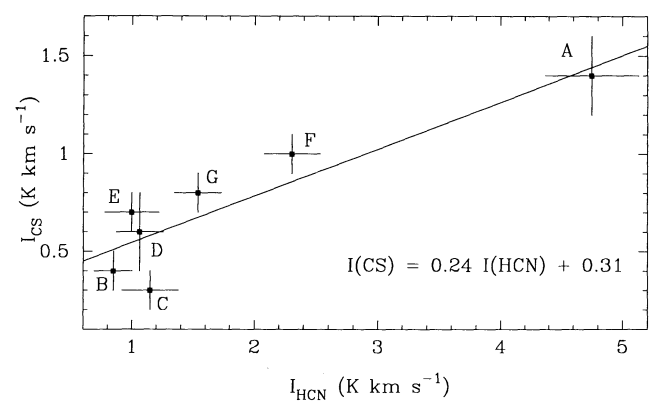

FIG. 2.—CS vs. HCN integrated intensities ($\int T_R^* dv$ in K km s^{-1}) of the observed galaxies: A = NGC 1068, B = NGC 4321, C = NGC 4527, D = NGC 4826, E = NGC 5194, F = NGC 5236, G = NGC 6946.

nuclear molecular clouds are not like disk GMCs. In the following sections, we compare our results with molecular observations of the bulge of the Milky Way as well as with observations of dense gas in two local GMCs. It must be noted, though, that there have been almost no systematic, unbiased studies of dense gas in GMCs in the Milky Way, and a direct quantitative comparison of dense gas ratios in our sample of galaxies with those in Galactic GMCs is severely limited by this lack of data.

4.1. *Comparison with Milky Way Bulge*

Although we have very little information on the large-scale emission of dense gas in the disk of the Milky Way, large-scale emission of CS has been surveyed and mapped extensively toward the inner few degrees of the Galaxy (Bally et al. 1987, 1988). In order to simulate observations with a single radio beam, we obtained CS and CO longitude-velocity FITS images of the Galactic center and analyzed the data over a region that covered some 4°.6 of longitude and ± 300 km s^{-1} in velocity. A detailed discussion of our analysis is given in the Appendix. We found that over this 4°.6 (≈ 700 pc) region, the $\mathscr{R}_{CS,CO}$ ratio is 0.025. Although this is marginally higher than the average 0.019 we measured in the extragalactic bulges, the ratio is well within the range of values we measured for individual sources. Thus, the large-scale emission from the bulges of external galaxies is consistent with that of the Milky Way bulge.

As noted above and seen in Table 4, the measured ratio of dense gas to CO in the bulges of galaxies can be very sensitive to the resolution of the radio beam that is used for the observations. In most of the sources listed in Table 4, the ratio measured is higher for the telescope with the smaller beam size; this may reflect higher pressures and densities at the centers of the bulges, as one might expect if hydrostatic equilibrium plays a role in the mean gas pressure. At the distances of our sources, the 100 GHz beam resolution of the NRAO 12 m telescope corresponds to linear resolutions of ~ 1–6 kpc. (The same observations carried out at the IRAM 30 m telescope would have linear resolutions of 400 pc–2.4 kpc.) In some of our observations, then, we are looking at regions contained well inside the optical bulges, whereas some of our measurements include contributions from galactic disks. The measured ratio of dense gas to CO may therefore be somewhat lower in some of the extragalactic sources than in the Milky Way, since the 0.025 measured for the Milky Way is strictly within the bulge of our Galaxy.

4.2. *Comparison with Milky Way Disk GMCs*

In galaxies, single-dish radio beams typically cover tens to hundreds of GMC-sized diameters. The flux measured in any molecular species is therefore a superposition of contributions from many clumps within many GMCs, interclump emission within GMCs as well as any diffuse emission outside GMCs. The large-scale ratio of dense gas to CO has not been measured for the disk of the Milky Way; however, since most molecular mass is contained in GMCs (Sanders, Scoville, & Solomon 1985), then a measurement of this ratio over entire GMCs should provide an upper limit to the ratio for the Milky Way disk.

Although a numerical comparison with Galactic clouds is limited by the lack of surveys of dense gas over entire local GMCs, we were able to estimate the $\mathscr{R}_{CS,CO}$ ratio for two clouds that have large regions surveyed in both molecular species. Lada et al. (1991) published a fully sampled, unbiased CS survey over the regions of brightest CO emission from the Orion B molecular cloud; their study covers $\sim 20\%$ of the area of the CO cloud (Maddelena et al. 1986). Also, an unpublished, high-resolution CS survey taken with the AT&T Bell Laboratories 7 m telescope over the brightest CO emission from the Rosette molecular cloud (Blitz & Stark 1992) covers $\sim 10\%$ of the area of the CO cloud (Blitz & Thaddeus 1980). The details of our analysis are discussed in the Appendix; our best estimate of the global average for Orion B is $\mathscr{R}_{CS,CO} = 0.0081$ and for the Rosette is $\mathscr{R}_{CS,CO} = 0.010$. These values are about a factor of 2 below the average ratio of 0.019 that we measured in the extragalactic bulges; only one of our sources (NGC 4527) has a measured $\mathscr{R}_{CS,CO}$ ratio as low as 0.010. Again, since the averages for Orion B and the Rosette do not include any correction for the presence of any diffuse molecular component between disk GMCs, it is likely that the "true" $\mathscr{R}_{CS,CO}$ average over the local Galactic disk is somewhat lower than the values quoted above. It appears that the bulges of galaxies have a higher fraction of dense gas than is suggested for the local disk environment of the Milky Way.

4.3. *Dense Gas: High Pressure or More Clumps?*

We have shown that the physical conditions in extragalactic bulges appear to be much more like those in the Milky Way bulge than those in the Galactic disk. In the Milky Way, bulge and disk GMCs appear to have very different properties: diffuse CS(2–1) emission is seen only within a few degrees of the Galactic center (Bally et al. 1987, 1988), the line widths of individual molecular features there are typically 5–10 times larger than are seen anywhere else in the Galaxy, and the emissivity of the most common molecular tracer, CO, is some 60 times higher than it is in the solar neighborhood (Sanders, Solomon, & Scoville 1984). In a recent paper, Spergel & Blitz (1992) argued that these disparities in the properties of molecular gas can be understood as the effects of a difference of two and a half orders of magnitude in the pressure of gas near the Sun and that in the inner 500 pc of the Galaxy that is a result of the large stellar potential in the Galactic bulge. The argument is as follows: any gas in steady state in a galaxy is governed by the condition of hydrostatic equilibrium, where the galactic gravitational potential is caused by the stars and the gas in the galaxy. Because the stellar potential is generally much larger in the bulge of a galaxy than in its disk, the gas in the bulge is typically subject to much higher pressures than is the disk gas. This is especially true of gas that is extended enough to be sensitive to the full weight of the stellar potential in the bulge (e.g., the extended hot component seen in the bulge of the Milky Way as well as in many external galaxies); this gas should be at a much higher pressure than its disk counterpart. Pressure equilibrium then requires that all phases of the interstellar medium embedded in the hot gas have nearly equal pressure, including the molecular gas. This implies that the molecular gas in the bulges of galaxies should typically be at much higher pressures than that in the disks of galaxies, even if the scale height of molecular gas is comparable in the two locations.

The common detection of dense gas in extragalactic bulges suggests that the pressures may indeed be quite high there, and if we can extrapolate from the Milky Way, the bulge pressures might be much higher than those in the extragalactic disks. The gas temperature in the dense component is certainly ≥ 3 K and probably is at least 10 K, so that the thermal pressure $nT \geq 3 \times 10^5$ cm^{-3} K. In Galactic GMCs, moreover, we know that the line widths of clumps are dominated by nonthermal bulk motions of the gas (e.g., Blitz 1993). If the intrinsic widths of the molecular lines are ≥ 1 km s^{-1}, then the typical kinetic pressures are at least $\rho v^2/k \geq 2 \times 10^7$ cm^{-3} K. This is indeed quite a high pressure if it represents the ambient pressure of the gas in these bulges.

These pressures are also observed in the star-forming cores of local GMCs, however. Because the mean local interstellar pressure is ~ 1–2×10^4 cm^{-3} K (Bloemen 1987) and the hydrostatic pressure from the self-gravity of the GMCs is $\sim 1 \times 10^5$ cm^{-3} K (Blitz 1993), then conditions in local GMCs imply that either the dense gas is in a state of collapse (i.e., is in the process of forming stars) or there is already a new source of pressure (i.e., recently formed stars) in order to maintain the pressure equilibrium. It could therefore be that the higher ratio of dense molecular gas in galactic bulges is not due to a higher environmental pressure, but that the GMCs themselves are either more massive or smaller than GMCs in the Galactic disk. This ambiguity can be resolved using millimeter-wavelength interferometric observations with which individual GMCs can be identified. What we conclude from our present observations, however, is that the dense gas in the bulges of galaxies is not like the dense gas observed in local GMCs: either the environment is different (i.e., the dense gas is a response to the high-pressure environment of galactic bulges) or the clouds themselves are different (i.e., most of the dense gas is in GMCs that are very massive and/or very small by Galactic standards).

In their study of ultraluminous galaxies, Solomon et al. (1992) show that the HCN luminosity L_{HCN} is well correlated with the far-infrared luminosity L_{FIR} for ultraluminous galaxies as well as for two normal galaxies used as controls. The HCN luminosities in the Solomon et al. survey are an average of an order of magnitude larger than those in our sample of normal galaxies, and there is a spread of a factor of 500 in L_{HCN} over the two samples; however, the galaxies in our study have ratios of L_{HCN}/L_{FIR} similar to those quoted by Solomon et al. It appears that starbursts are unusual only in having large quantities of dense molecular gas and CO, and we conclude that there is no threshold of dense gas required for unusually vigorous star formation in the centers of galaxies.

4.4. *Bulge and Disk Ratios*

We are currently investigating the ratios of dense gas to CO in the disks of galaxies as well as in their bulges. If the dense gas in the bulges is simply a result of a larger amount of molecular material in bulges compared to disks, and the molecular mass is contained in structures like local GMCs, then we might expect the *ratios* $\mathscr{R}_{HCN,CO}$ and $\mathscr{R}_{CS,CO}$ to be independent of galactic radius. Our measurement of $\mathscr{R}_{HCN,CO}$ in the disk of NGC 253 is some 10 times smaller than it is in the bulge, but our disk and bulge measurements of NGC 6946 are similar to each other, and we are not able to make any conclusions about the trend of these ratios in galaxies.

4.5. HCN *versus* CS *as Dense Gas Tracers*

Our sources and a few additional ones from the literature are all stronger emitters of HCN than of CS. Solomon et al. (1992) suggest that CS traces somewhat more dense gas than does HCN and that it is therefore natural that the HCN intensities are stronger than those of CS. This does not appear to be supported by multitransitional studies of nearby objects in the Milky Way, however, whose densities have been modeled in detail using standard radiative transfer techniques (Mundy 1992); furthermore, the critical excitation densities for these two molecules, $n_{crit} = A_{ij}/C_{ij}$, where A_{ij} is the Einstein coefficient for the ij transition and C_{ij} is the collisional rate coefficient for the same transition, are comparable for the two molecules. Since there have been no systematic studies of HCN emission over entire GMCs in the Milky Way, it is unclear how normal are the $\mathscr{R}_{HCN,CS}$ ratios we have measured.

5. CONCLUSIONS

Our study of a sample of 19 spiral galaxies yields the following results:

1. We detected 68% of our sources in dense gas, including 13 of 19 observed in HCN(1–0) and 6 of 12 observed in CS(2–1). If we include two galaxies with marginal detections in HCN, our detection rate is 79%. The lack of HCN detections in an additional two spiral galaxies as well as one early-type galaxy we observed are limited by the sensitivity of our observations rather than by the intrinsic lack of dense gas in these sources.

2. Since our sample contains both starburst and normal galaxies, it appears that even normal galaxies contain an appreciable amount of dense gas in their bulges. Our sample has similar L_{HCN}/L_{FIR} ratios to those quoted by Solomon et al. (1992) in their study of ultraluminous and two normal spirals, and we conclude that starburst galaxies are unusual only in having unusually large quantities of dense molecular gas and CO. There does not appear to be a threshold of dense gas required for unusually vigorous star formation in the centers of galaxies.

3. We measured central HCN to CO integrated intensity ratios $\mathscr{R}_{HCN,CO}$ of 0.024–0.23 and $\mathscr{R}_{CS,CO}$ ratios of 0.010–0.033. The mean and uncertainty in the mean were 0.050 ± 0.003 for $\mathscr{R}_{HCN,CO}$ and 0.019 ± 0.003 for $\mathscr{R}_{CS,CO}$. These results compare reasonably well with ratios measured in the bulges of galaxies from the literature. The $\mathscr{R}_{HCN,CO}$ ratio measured for any source is sensitive to the resolution of the telescope; the ratio can be significantly higher for telescopes with smaller beams.

4. The $\mathscr{R}_{CS,CO}$ ratio over the central ≈ 700 pc region of the Milky Way is 0.025, which is consistent with our observations of extragalactic bulges. The $\mathscr{R}_{CS,CO}$ ratios over the Orion and Rosette Molecular Clouds are ~ 0.0081 and 0.010; the "true" average disk $\mathscr{R}_{CS,CO}$ ratio, which includes contributions from diffuse, intercloud emission, is likely to be somewhat lower. It appears that the bulges of galaxies have a higher fraction of dense gas than is suggested in the local disk environment of the Milky Way.

5. Of those galaxies observed in both species, the HCN emission is consistently stronger than the CS emission by an average of 2.4 ± 0.3 in the integrated intensities. This is surprising since the two molecules have similar critical excitation densities and might be indicative of different excitation conditions in the gas or of a different formation chemistry of the two molecules. The emission of the two species is reasonably well fitted by a linear relation, $I(\mathrm{CS}) = (0.24 \pm 0.01) I(\mathrm{HCN}) + (0.31 \pm 0.01)$ K km s^{-1}.

We thank J. Bally for providing us with the CO and CS FITS images of the Galactic Center from the AT&T Bell Laboratories surveys, and we thank E. Lada for providing us with data from the Lada et al. (1991) CS survey of the Orion B molecular cloud. This research was partially supported by NSF grant AST 89-18912.

APPENDIX

1. ANALYSIS OF GALACTIC CENTER DATA

We obtained CS and CO data from the AT&T Bell Laboratories 7 m telescope surveys of the Galactic center region in the form of FITS images of antenna temperatures T_a^* plotted on a plane of longitude and velocity. Both images had been produced from spectra averaged over Galactic longitudes $b = -0.^\circ4$–$0.^\circ4$. The data covered a longitude range of $l = -1^\circ$ to $3.^\circ6$ and a velocity interval of ± 300 km s^{-1}. While the CO emission continues to the present outside the longitude range presented, most of the CS emission is limited to longitudes of $l = -0.^\circ8$ to $1.^\circ8$. To simulate observations from a single radio beam, we added the temperatures from each point in a given l, v range; to compute the $\mathscr{R}_{\rm CS,CO}$ ratio, we then divided the CS temperature sum by the CO temperature sum. Random fluctuations in the noise temperatures over the maps should thus add to zero, whereas real emission that is present at the 1 σ or 2 σ level will contribute positively to the ratio. The $\mathscr{R}_{\rm CS,CO}$ ratio over the full $4.^\circ6$ longitude range mapped is 0.0251. To check for the effects of line-of-sight absorption in the CO(1–0) data, we computed $\mathscr{R}_{\rm CS,CO}$ over the two velocity intervals $v = -300$ to 10 km s^{-1} and $v = 10$ to $+300$ km s^{-1} and found that the ratios agree to $\pm 1\%$. Over the more limited longitude range where most of the CS emission is present ($-0.^\circ8 \le l \le 1.^\circ8$), we found that $\mathscr{R}_{\rm CS,CO} = 0.0268$.

2. ANALYSIS OF THE ORION B AND ROSETTE MOLECULAR CLOUDS

The CS survey data of the Orion B and the CS and CO survey data of the Rosette Molecular Clouds were in the form of individual spectra over the regions surveyed at the AT&T Bell Laboratories 7 m telescope. The Orion CS survey (Lada et al. 1991) covered some 3.8 deg^2 of the most intense emission from the 19 deg^2 CO map published by Maddelena et al. (1986). We averaged the CS spectra together to produce a composite spectrum of the region and found that the averaged spectrum had an integrated intensity of $\int T_a^* dv = 0.324 \pm 0.012$ K km s^{-1}. This composite spectrum includes regions where no CS was detected as well as those with measured emission; again, random fluctuations in the data should average to zero, whereas real, low-level emission will contribute positively to the integrated intensity of the composite. In order to estimate the contribution from CS for the 15.2 deg^2 that were not covered in the Orion B survey, we noted the level of typical CO emission over this region from Maddelena's map, then chose a region of similar CO intensity *inside* the 3.8 deg^2 area mapped by Lada et al. and averaged the CS spectra over this limited region. The average integrated intensity from this region was 0.050 ± 0.012 K km s^{-1}. We assumed that this value was typical for the unmapped 15.2 deg^2 area. The CO integrated intensity averaged over the entire 19 deg^2 area was 13.0 K km s^{-1} (Maddelena et al. 1986). The $\mathscr{R}_{\rm CS,CO}$ ratio is then $\mathscr{R}_{\rm CS,CO} = (0.324$ K km s$^{-1} \times 3.8$ deg$^2 + 0.050$ K km s$^{-1} \times 15.2$ deg$^2)/(13.0$ K km s$^{-1} \times 19.0$ deg$^2) = 0.0081$.

We performed a similar analysis on the CS and CO survey data from the Rosette Molecular Cloud (Blitz & Stark 1992). Here the CS average integrated intensity was $\int T_a^* dv = 0.342$ K km s^{-1} over the mapped area of 0.582 deg^2. This time it proved more difficult to find a suitable region of the CS map that might be typical of emission outside the area surveyed, however, since the CS had been surveyed selectively in the densest region of the cloud, we chose a small region at the edge of the CS survey for this purpose. When we averaged the spectra over this small region. We could not detect a signal in the composite. The 1 σ limit on the CS integrated intensity was ± 0.088 K km s^{-1} in this region. The composite CO spectrum over the entire 4.68 deg^2 surveyed had an integrated intensity of 11.792 K km s^{-1}. We can place rough lower and upper limits on the $\mathscr{R}_{\rm CS,CO}$ ratio over the whole Rosette Molecular Cloud as follows: if we assume that the CS emission outside the region surveyed is identically zero, then we derive a lower limit of $(\mathscr{R}_{\rm CS,CO})_{\rm lower} = (0.342$ K km s$^{-1} \times 0.582$ deg$^2)/(11.792$ K km s$^{-1} \times 4.68$ deg$^2) = 0.0036$. If we assume the ratio over the limited area of the CS survey is representative of the cloud, we derive an upper limit of $(\mathscr{R}_{\rm CS,CO})_{\rm upper} = (0.342$ K km s$^{-1} \times 0.582$ deg$^2)/(24.424$ K km s$^{-1} \times 0.582$ deg$^2) = 0.014$. Alternatively, we adopted an intermediate as representative of the cloud: we assumed that the regions of the CO cloud not mapped in CS are emitting CS at the 1 σ level quoted above; then the $\mathscr{R}_{\rm CS,CO}$ ratio over the whole cloud is $(0.342$ K km s$^{-1} \times 0.582$ deg$^2 + 0.088$ K km s$^{-1} \times 4.10$ deg$^2)/(11.792$ K km s$^{-1} \times 4.68$ deg$^2)$, or $\mathscr{R}_{\rm CS,CO} = 0.010$.

REFERENCES

Bally, J., Stark, A. A., Wilson, R. W., & Henkel, C. 1987, ApJS, 65, 13
———. 1988, ApJ, 324, 223
Blitz, L. 1987, in Physical Processes in Interstellar Clouds, ed. G. E. Morfill & M. Scholer (Dordrecht: Reidel), 35
———. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: Univ. of Arizona Press), 12
Blitz, L., & Stark, A. A. 1992, private communication
Blitz, L., & Thaddeus, P. 1980, ApJ, 241, 676
Bloemen, J. B. G. M. 1987, ApJ, 322, 694
Boissé, P., Casoli, F., & Combes, F. 1987, A&A, 173, 229
Eckart, A., Downes, D., Genzel, R., Harris, A. I., Jaffe, D. T., & Wild, W. 1990, ApJ, 348, 434
Fabbiano, G., Kim, D.-W., & Trinchieri, G. 1992, ApJS, 80, 531
Filippenko, A. 1992, private communication
Israel, F. P. 1992, A&A, 265, 487
Jackson, J. M., Eckart, A., Cameron, M., Wild, W., Ho, P. T. P., Pogge, R. W., & Harris, A. I. 1991, ApJ, 375, 105
Lada, E. A., Bally, J., & Stark, A. A. 1991, ApJ, 368, 432
Maddelena, R. J., Morris, M., Moscowitz, J., & Thaddeus, P. 1986, ApJ, 303, 375
Mauersberger, R., Henkel, C., Wilson, T. L., & Harju, J. 1989, A&A, 226, L5
Mundy, L. G. 1992, private communication
Nguyen-Q-Rieu, Jackson, J. M., Henkel, C., Truong-Bach, & Mauersberger, R. 1992, ApJ, 399, 521
Nguyen-Q-Rieu, Nakai, N., & Jackson, J. M. 1989, A&A, 220, 57
Planesas, P., Gómez-González, J., & Martín-Pintado, J. 1989, A&A, 216, 1
Planesas, P., Scoville, N., & Myers, S. T. 1991, ApJ, 369, 364
Rickard, L. J, & Blitz, L. 1985, ApJ, 292, L57
Sage, L. J., Shore, S. N., & Solomon, P. M. 1990, ApJ, 351, 422
Sanders, D. B., Scoville, N. Z., & Solomon, P. M. 1985, ApJ, 289, 373
Sanders, D. B., Solomon, P. M., & Scoville, N. Z. 1984, ApJ, 276, 182
Scoville, N. Z., Soifer, B. T., Neugebauer, G., Young, J. S., Matthews, K., & Yerka, J. 1985, ApJ, 289, 129
Solomon, P. M., Downes, D., & Radford, S. J. E. 1992, ApJ, , 387, L55
Spergel, D. N., & Blitz, L. 1992, Nature, 357, 665
Verter, F. 1985, ApJS, 57, 261
Weliachew, L., Casoli, F., & Combes, F. 1988, A&A, 199, 29
Wiklind, T., & Henkel, C. 1990, A&A, 227, 394