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Starbursting nuclear CO disks of early-type spiral galaxies

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Abstract. We have initiated the first CO interferometer survey of early-type spiral galaxies (S0-Sab). We observed five early-type spiral galaxies with HII nuclei (indicating circumnuclear starburst activities). These observations indicate gas masses for the central kiloparsec of ~1−5% of the dynamical masses. Such low gas mass fractions suggest that large-scale gravitational instability in the gas is unlikely to be the driving cause for the starburst activities. We estimated Toomre Q values and found that these galaxies have $Q > 1$ (mostly >3) within the central kiloparsec, indicating that the gas disks are globally gravitationally stable. From the brightness temperatures of the CO emission we estimated the area filling factor of the gas disks within the central kiloparsec to be about 0.05. This small value indicates the existence of lumpy structure, i.e. molecular clouds, in the globally-gravitationally stable disks. The typical surface density of the molecular clouds is as high as ~3000 $M_\odot$ pc^{-2}. In the light of these new observations, we reconsider the nature of the Toomre Q criterion, and conclude that the Toomre Q parameter from CO observations indicates *neither* star formation *nor* molecular cloud formation. This argument should be valid not only for the circumnuclear disks but also for any region in galactic disks. We tentatively explore an alternative model as an initiating mechanism of star formation. Cloud-cloud collisions might account for the active star formation.

Key words. galaxies: ISM – galaxies: nuclei – galaxies: spiral – galaxies: starburst

1. Introduction

Early-type spiral galaxies (S0-Sab) generally have lower total gas masses than late-type spiral galaxies (Sb-Scd), and their global star formation rates (SFR) are generally less than those of late-type spirals (Young & Scoville 1991; Roberts & Haynes 1994). Circumnuclear starbursts (HII nuclei) are also less frequent in early-type spiral galaxies than in late-type spiral galaxies. However, when early-type spiral galaxies *do* host circumnuclear starbursts, their extinction-corrected Hα luminosities (measuring SF activity) are much higher on average than those of late-type spiral galaxies (Ho et al. 1997a; Kennicutt 1998). Similar trends are also seen in 10 μm surveys of nearby galaxies (Devereux 1984; Giuricin et al. 1994).

High resolution CO observations are critical for understanding the active nuclear SF in early-type spiral galaxies. Although several high resolution surveys of molecular gas in galactic centers have recently been completed (Sakamoto et al. 1999a; Sofue et al. 2003; Helfer et al. 2003; Garcia-Burillo et al. 2003), they include very few early-type spiral galaxies, especially with HII nuclei. This paper presents the first results from a CO survey of early-type spiral galaxies with HII nuclei using the Nobeyama Millimeter Array (NMA), specifically addressing the region of the nuclear starburst activity.

2. Samples and CO observations

Our sample of early-type spiral galaxies is selected from the optical-spectroscopic survey of Ho et al. (1997a) with the criteria: (a) morphological type of S0-Sab; (b) hosting an HII-nucleus (Note that HII nucleus here means a circumnuclear region with SF activity but without AGN); (c) not edge-on [$i < 70°$]; (d) distance <25 Mpc; and (e) no obvious interaction. From the complete sample of 11 galaxies satisfying these conditions, we have observed 5 galaxies for the first time and found one already observed and reported (Table 1). (The other five galaxies are NGC 3073, 4245, 4424, 4448, and 4694.)

Table 1 also includes Hα equivalent widths, and star formation rates (SFR) within the central 1 kpc. The SFR is calculated as in Sakamoto et al. (1999b) from the Hα-photometry with $4'' \times 2''$ aperture by Ho et al. (1997b). We made the extinction correction using the Hα/Hβ line intensity ratio, calculated the Hα luminosity from the central kiloparsec region assuming constant line intensity in the area, and used the Hα-to-SFR conversion formula (Kennicutt 1998). This procedure usually gives SFRs consistent with those based on infrared observations (Sakamoto et al. 1999b). There are, however, some caveats for these optical SFRs. They are likely to be lower limits, because some Hα-emission from embedded SF in dust may have been

Table 1. Sample spiral galaxies with HII nuclei.

Name	Morph.	d (Mpc)	$M_{B_T}^0$ (mag)	D_{25}^0 (kpc)	$EW(H\alpha)$ (Å)	SFR^{500} ($M_\odot$ yr^{-1})	M_{gas}^{500} ($10^7 M_\odot$)	M_{dyn}^{500} ($10^9 M_\odot$)	f_{gas}^{500} (%)	Σ_{gas}^{500} ($M_\odot$ pc^{-2})	Reference
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
NGC 972	SAab	21.4	−20.17	22.10	34.22	1.58	42.6	4.5	9	542	This work
NGC 3593	SA(s)0/a:	5.5	−17.25	7.84	13.13	0.28	12.9	2.4	5	164	KS99
NGC 3729	SB(r)apec	17	−19.24	13.95	76.74	0.99	13.9	2.7	5	177	This work
NGC 4064	SB(s)a:pec	16.9	−19.39	21.97	55.73	0.43	3.1	1.1	3	39	This work
NGC 4274	(R)SB(r)ab	9.7	−19.35	19.53	4.65	−	8.6	5.1	2	109	This work
NGC 4369	(R)SA(rs)a	21.6	−19.40	13.13	29.76	0.39	10.5	4.6	2	134	This work

Note: (1) Galaxy name; (2) Morphological type; (3) Distance based on Virgo infall model of Tully & Shaya (1984). (4) Total absolute B-band magnitude corrected for Galactic and internal reddening and redshift from Ho et al. (1997b); (5) Face-on isophotal diameter at $\mu_B = 25$ mag arcsec^2 in the B-band, corrected for extinction and inclination from RC3 (de Vaucouleurs et al. 1991); (6) Hα equivalent width; (7) Star formation rate within 500 pc of the nucleus; (8) Gas mass within 500 pc of the nucleus, from CO interferometer observations assuming a conversion factor of $X_{CO} = 3.0 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$; (9) Dynamical mass within 500 pc of the nucleus; (10) Gas-to-dynamical mass ratio within 500 pc from the center; (11) Surface gas density averaged within 500 pc from the center; (12) Reference for CO interferometer observations. KS99: Sakamoto et al. (1999b).

missed, and because absorption in the background stellar continuum may lead to underestimation of the Hα-luminosity. The HII nuclei do not host AGNs by definition, and therefore there is no contamination of AGNs in the estimation of SFR.

^{12}CO($J = 1-0$)-line observations were obtained using NMA in November, 2002 through May, 2003. Each object was observed for two 10-hour tracks in the C- and D-array configurations of NMA. The complex gain was calibrated every 20 min using nearby quasars. The fluxes of the quasars were calculated against URANUS; uncertainties in the overall flux scales are ~15%. The visibility data were calibrated using the UVPROC-II software package (Tsutsumi et al. 1997) and mapped with CLEAN in the NRAO/AIPS package. The resultant 3D cubes have resolutions of 4−5″ (natural weighting) and rms noise of ~17 mJy/beam in a 10.4 km s^{-1} channel. (Full channel maps and kinematic maps will be presented in our full survey paper). These interferometric maps include ≳85% of the total single dish CO line fluxes (Okuda, in preparation) for the central 15″ region in each galaxy.

## 3. Molecular gas in starbursting nuclear disks

We detect significant CO emission in the circumnuclear regions of all 5 early-type spiral galaxies. Figure 1 shows CO integrated intensity maps and velocity fields (NGC 3593, the sixth galaxy in our sample, is reported in Sakamoto et al. 1999a). In all 6 galaxies, the CO emission is strongly peaked in the central region at $R < 500$ pc. Linear scales of 1 kpc along major and minor axes are indicated by the crosses in Fig. 1. In Table 1 we include estimates for the dynamical mass (M_{dyn}), gas mass (M_{gas}), and average gas surface density (Σ_{gas}) within a radius of 500 pc from the dynamical center of each galaxy. The gas mass is estimated using CO fluxes within the central 1 kpc aperture on the galactic disks, and a Galactic CO-to-H$_2$ conversion factor of $X_{CO} = 3.0 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ and a factor of 1.36 to account for He and the other elements. The dynamical mass is calculated using the formula $M_{dyn} = RV^2/G$.

The velocity at $R = 500$ pc is estimated from the velocity difference between $R = \pm500$ pc along the major axis in position-velocity diagrams.

The circumnuclear regions in these galaxies are regarded as starburst regions by two definitions. First, the gas consumption timescales, $M_{gas}/SFR \sim 2 \times 10^8$ yr on average, are as short as those of starburst galaxies (Kennicutt 1998). Second, the current SFRs ~ 0.7 $M_\odot$ yr^{-1} are larger than past-averaged SFRs, i.e. $M_{star}/10^{10}$ yr ~ 0.3 $M_\odot$ yr^{-1} (assuming $M_{star} \sim M_{dyn}$). In addition, the Hα equivalent widths, ~36 Å, are much larger than typical values ~0−10 Å for early-type spiral galaxies (Kennicutt 1998), indicating that their current SFRs are higher than most other galaxies.

Despite the starbursts, the average gas surface densities at $R < 500$ pc are lower in the early-type spiral galaxies, ~150 $M_\odot$ pc^{-2}, than in late-type spirals with and without HII nuclei (mostly >200 $M_\odot$ pc^{-2}, see Sakamoto et al. 1999b). Even the non-starbursting interacting galaxy NGC 5195 has a much higher surface density of 500 $M_\odot$ pc^{-2} at $R < 500$ pc (Kohno et al. 2002). *Thus, the large-scale gas surface density is not the only determinant of nuclear SF.* These global surface densities are very close to, or higher than, the average surface density of molecular clouds, 170 $M_\odot$ pc^{-2}, in the Galactic disk (Solomon et al. 1987). They, however, are not a sufficient condition for initiating SF.

Figure 2 shows the molecular gas masses plotted against dynamical masses at $R < 500$ pc. Late-type spiral galaxies (Sbc-Scd) with HII nuclei (Sakamoto et al. 1999b; Sofue et al. 2003) are also plotted. The solid lines indicate constant gas-to-dynamical mass ratios. The early-type spiral galaxies are distributed between $M_{gas}/M_{dyn} = 0.01$ and 0.1 (mostly in the range 0.02−0.05). Evidence has accumulated for a lower conversion factor X_{CO} in metal rich regions such as galactic centers (Wilson 1995; Arimoto et al. 1996). If we adopt an X_{CO} that is three times as small as the assumed one, M_{gas}/M_{dyn} becomes three times as low. Given these low gas mass
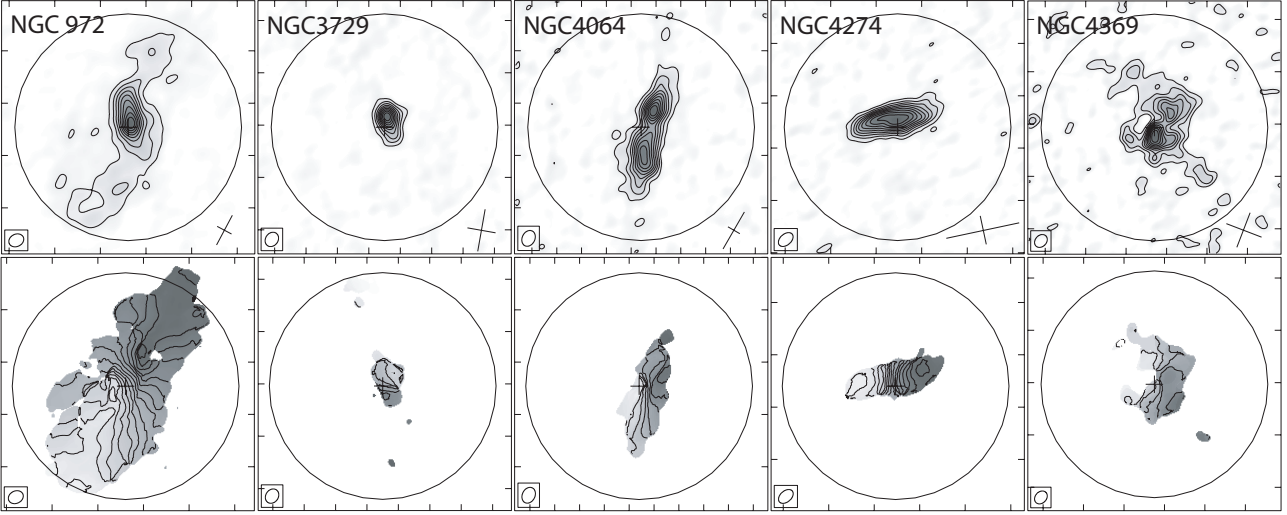
Fig. 1. *Upper panels*: CO integrated intensity maps. Contours represent (0.1, 0.2, 0.3, 0.4, ..., 0.9, 1.0) × peak intensity. The peak intensities are 58.2, 27.6, 14.9, 26.5, 8.57 Jy beam^{-1} km s^{-1} from left to right. Circles and crosses indicate the fields of view (65″) and their centers in the observations, respectively. Crosses at the lower right corners represent 1 kpc along major and minor axes. No primary beam correction has been applied to these maps. *Lower panels*: velocity field maps. These maps are made using >3σ emissions in each 10.4 km s^{-1} channel. Contour intervals are 10 km s^{-1} for NGC 4369 and 20 km s^{-1} for the others. Dark sides are receding.
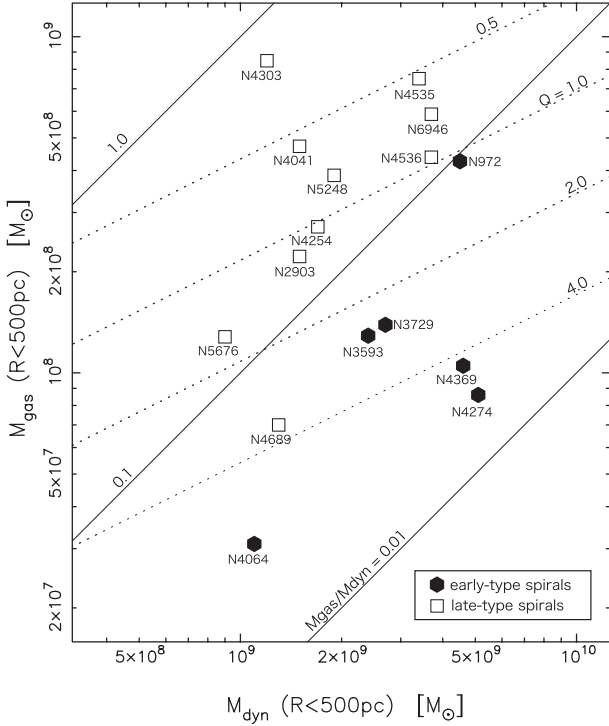
Fig. 2. Molecular gas mass vs. dynamical mass within 500 pc of the nucleus. A Galactic CO-to-H$_2$ conversion factor of $X_{CO} = 3.0 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ is adopted. Solid lines indicate constant gas-to-dynamical mass ratios. Dotted lines indicate constant Toomre Q-values assuming rigid rotation curve and velocity dispersions of $\sigma = 10$ km s^{-1}. $Q > 1$ indicates gravitationally stable, while $Q < 1$ indicates gravitationally unstable. The Q-values become larger if we assume larger σ (i.e. $Q \propto \sigma$) and smaller X_{CO}, which are more likely in the central region.

fractions, *it is unlikely that the circumnuclear gas in these early-type spiral galaxies has undergone large-scale*

gravitational collapse and that this initiated the nuclear star-bursts (see Jog & Solomon 1984; Wada 1992). Our conclusion that this sample of early-type spiral galaxies has low M_{gas}/M_{dyn} is very different from the result by Sakamoto et al. (1999b) who found that the later-type spiral galaxies with HII nuclei mostly have $M_{gas}/M_{dyn} > 0.1$ (see Fig. 2).

In order to quantify the gravitational stability of the gas disks, we estimate the Toomre Q parameter averaged within central 1 kpc. We adopt the formula suggested in Sakamoto et al. (1999b) with a small modification. Q is described as

$$Q = \alpha \frac{(M_\sigma M_{dyn})^{1/2}}{M_{gas}}, \tag{1}$$

where $M_\sigma \equiv R\sigma^2/G$ and σ is the velocity dispersion. We assumed a rotation curve of $V \propto R^\beta$, i.e. $\beta = 1$ for rigid rotation and $\beta = 0$ for flat rotation, and then, $\alpha = \sqrt{2(\beta + 1)}$. We notice that α (and thus Q) is insensitive to the rotation curve, and between 1.4 (flat rotation) and 2 (rigid rotation). The dotted lines in Fig. 2 show constant Q values in assuming $\sigma = 10$ km s^{-1} and $\alpha = 2$ (similar to Sakamoto et al. 1999b). As already suggested by the small values of M_{gas}/M_{dyn}, all the early-type spiral galaxies have $Q > 1$ (mostly $Q \gtrsim 3$), indicating that the circumnuclear gas disks are globally gravitationally-stable despite their clear starburst activity. We note that σ is likely to be larger than our assumed value of 10 km s^{-1} (Kenney et al. 1993). If we adopt $\sigma = 30$ km s^{-1} and three times as small X_{CO} (Arimoto et al. 1996), the Qs become nine times as large, resulting in $Q \gtrsim 27$ (i.e. much more stable).

The peak brightness temperature T_b in the channel maps is 1−2 K. Assuming that the CO gas is optically thick as observed in molecular clouds in the Galaxy (Scoville & Sanders 1987) and that the gas excitation temperature T_{ex} is similar to the dust temperature of 30 K in the Galactic center (Gautier et al. 1984), the molecular gas area filling factor is $f \sim 0.05$ ($= T_b/T_{ex} - T_{CMB}$), where the cosmic microwave background

temperature is $T_{CMB} \sim 3$ K. The filling factor could be lower if the dust temperature is higher. *Therefore, the molecular gas is not uniformly distributed but already confined in molecular clouds, although the gas disk is globally gravitationally-stable.* The typical gas surface density of the clouds becomes as high as $\sim 3000\ M_\odot\ pc^{-2}$ ($=\Sigma_{gas}^{500}/f$). This is much larger than the average value, $170\ M_\odot\ pc^{-2}$, for molecular clouds in the Galactic disk and close to the value, $2500\ M_\odot\ pc^{-2}$, for the ones in the Galactic center (Oka et al. 2001, calculated as in Solomon et al. 1987). The presence of molecular clouds in a stable disk is understood, if the disk was gravitationally unstable in the past and heated up after molecular cloud formation. Gravitational interactions among clouds may suffice to increase cloud-cloud velocity dispersions and heat up the global disk (Jog & Ostriker 1988).

4. Discussion

Although we initially expected to detect significantly large gas masses so that gravitational instability within the stellar potential might account for the starbursting, our survey reveals that the early-type spiral galaxies with circumnuclear starbursts have extremely low M_{gas}/M_{dyn} in the central kpc. Thus large-scale gravitational instability is not a likely cause of the starbursts. Although Toomre Q-type gravitational instability is often used for interpreting SF in galactic disks, its relevance for the circumnuclear SF of early-type spiral galaxies is unsupported (see also, Thornley & Wilson 1995; Wong & Blitz 2002; Boissier et al. 2003). These results may suggest reconsidering the nature of the Toomre Q.

If CO is detected, molecular clouds must already exist unless the mass function of molecular clouds is extremely different from those in the Galactic disk (Scoville et al. 1987; Solomon et al. 1987) and in the Galactic center (Oka et al. 2001); we have shown the existence of dense molecular clouds in our sample. Hence Q from CO observations does not indicate molecular cloud formation. In Q-value calculations, a velocity dispersion among molecular clouds $\sim 10\ km\ s^{-1}$ (an effective sound speed c_s for $\sim 10^4$ K) is usually adopted, rather than the molecular gas temperature (~ 10 K, or $c_s \sim 0.3\ km\ s^{-1}$), although the gas temperature should be more relevant for the collapse of protostellar cores. Thus, Q cannot indicate SF directly. Instead, Q obtained in earlier studies might indicate the formation of giant molecular cloud association (GMA), i.e. a group of molecular clouds. Therefore, GMA formation has been implicitly assumed to be necessary and sufficient conditions for SF in earlier Toomre Q arguments. Considering this assumption, we are not confident that the Toomre Q-type gravitational instability is relevant for SF. (Note, however, that a low Q-value means a relatively high gas surface density. Thus, active SF is more likely to be found in low Q-value regions if it is initiated by some other mechanisms than the Toomre Q-type instability.) The above argument should be valid not only for circumnuclear disks but also for any region in galactic disks. Perhaps the internal structure of molecular clouds, e.g. lumpiness and/or turbulence, is more important for star formation than large-scale gravitational instability.

One would think that massive bulges in early-type spiral galaxies could be a key to understanding the galaxy-type dependence of circumnuclear SF activity. In fact, de Jong (1996) found that the bulge effective radius is $100-300$ pc, while the disk scalelength is $1-5$ kpc. Hence bulge potentials could significantly affect gas dynamics within the central kpc, and circumnuclear rotation curves would be flatter in early-type spiral galaxies than in late-type spirals. A flat rotation curve causes a high shear velocity due to differential rotation. For example, assuming an angular velocity $\Omega = 1\ km\ s^{-1}\ pc^{-1}$, the extension of a molecular cloud $a = 20$ pc and the amplitude of the epicyclic motion $l = 10$ pc ($\approx \sigma/\kappa$; random velocity $\sigma \sim 10\ km\ s^{-1}$ and epicyclic frequency $\kappa \sim 1.4\Omega$), the shear velocity, $v = (\Omega - dV/dR)(a + l)$, becomes as high as $30\ km\ s^{-1}$ in a flat rotation curve, but $0\ km\ s^{-1}$ in a rigid rotation curve. Thus the shear velocity dominates the random velocity dispersion in a flat rotation curve. These facts, in addition to the existence of high density molecular clouds in our sample, leads us to speculate on cloud-cloud collisions induced by galactic shear as a cause of starbursting in early-type spiral galaxies. Obviously, cloud collision will enhance lumpiness and star formation in molecular clouds, although the molecular clouds may not contract globally in the strong shear regions.

In the Galaxy there is considerable evidence that the existence of molecular clouds is necessary but not sufficient for SF (Mooney & Solomon 1988; Scoville & Good 1989), and that cloud-cloud collisions might initiate active SF in many instances (Loren 1976; Scoville et al. 1986; Odenwald et al. 1992; Hasegawa et al. 1994). For a thin disk (2D), the timescale for cloud collision is $t_{coll} = 1/nav$, where $n = \Sigma_{gas}/M_C$ is the typical surface number density of molecular clouds, M_C and a are typical cloud mass and diameter, and v is the velocity of a test cloud relative to field clouds. We here adopt $M_C = 10^6\ M_\odot$, $a = 20$ pc, $\Sigma_{gas} = 150\ M_\odot\ pc^{-2}$. These parameters indicate that the surface density of individual molecular clouds is $3000\ M_\odot\ pc^{-2}$, which is close to the observed value. If we assume a shear velocity of $v = 30\ km\ s^{-1}$, the collisional timescale becomes $t_{coll} \sim 10^7$ yr. Given this timescale, the observed SFR of $\sim 1\ M_\odot\ yr^{-1}$ is achieved even if the SF efficiency per collision is as low as 10%. This is consistent with the low SF efficiencies in molecular clouds observed in the Galaxy. Therefore, the cloud collision model induced by galactic shear can reasonably explain the observed SF properties in our sample. Note that the assumed cloud has a tidal diameter of $\sim 20-150$ pc at $R = 100-500$ pc, and thus survives against stellar gravitational potentials. This tentative idea will be revisited in our full survey paper.

The results from our first CO survey of early-type spiral galaxies require a mechanism for triggering active SF in low gas density regions. The mechanism cannot be the Toomre Q-type gravitational instability, and we have discussed a tentative model based on cloud-cloud collisions. We are extending the CO survey with the Nobeyama Millimeter Array and Nobeyama 45 m telescope. We will observe all early-type spiral galaxies with central starburst in Ho et al. (1997a). In addition to the CO survey, higher resolution observations of the distribution of SF regions within the central kpc at infrared wavelengths, and observations of physical conditions in the gas at

some other molecular lines, e.g. rare CO isotopes and HCN (denser gas tracer, i.e. proximate sites of SF), will be complementary to fully understand the circumnuclear SF.

References

Arimoto, N., Sofue, Y., & Tsujimoto, T. 1996, PASJ, 48, 275

Boissier, S., Prantzos, N., Boselli, A., & Gavazzi, G. 2003, MNRAS, 346, 1215

de Jong, R. S. 1996, A&A, 45

Devereux, N. 1984, ApJ, 323, 91

Garcia-Burillo, S., Combes, F., Hunt, L. K., et al. 2003, A&A, 407, 485

Gautier, T. N., Hauser, M. G., Beichman, C. A., Low, F. J., et al. 1984, ApJ, 278, 57

Giuricin, G., Tamburini, L., Mardirossian, F., Mezzetti, M., & Monaco, P. 1994, ApJ, 427, 202

Hasegawa, T., Sato, F., Whiteoak, J. B., & Miyawaki, R. 1994, ApJ, 429, 77

Helfer, H. T., Thornley, M. D., Regan, M. W., et al. 2003, ApJS, 145, 259

Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997a, ApJ, 487, 579

Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997b, ApJS, 112, 315

Jog, C. J., & Ostriker, J. P. 1988, ApJ, 328, 404

Jog, C. J., & Solomon, P. M. 1984, ApJ, 276, 114

Kenney, J. D. P., Carlstrom, J. E., & Young, J. S. 1993, ApJ, 418, 687

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

Kennicutt, R. C. 1998, ARA&A, 36, 189

Kohno, K., Tosaki, T., Matsushita, S., et al. 2002, PASJ, 54, 541

Loren, R. B. 1976, ApJ, 209, 446

Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285

Mooney, T. J., & Solomon, P. M. 1988, ApJ, 334, 51

Odenwald, S., Fischer, J., Lockman, F. J., & Stemwedel, S. 1992, ApJ, 397, 174

Oka, T., Hasegawa, T., Sato, F., et al. 2001, ApJ, 562, 348

Roberts, M. S., & Haynes, M. P. 1994, ARA&A, 32, 115

Sakamoto, K., Okumura, S. K., Ishizuki, S., & Scoville, N. Z. 1999a, ApJS, 124, 403

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

Scoville, N. Z., & Good, J. C. 1989, ApJ, 339, 149

Scoville, N. Z., & Sanders, D. B. 1987, Interstellar Process, ed. D. Hollenbach, & H. Thronson (Durdrecht: Reidel)

Scoville, N. Z., Sanders, D. B., & Clemens, D. P. 1986, ApJ, 310, 77

Scoville, N. Z., Yun, M. S., Clemens, D. P., Sanders, D. B., & Waller, W. H. 1987, ApJS, 63, 821

Sofue, Y., Koda, J., Nakanishi, H., et al. 2003, PASJ, 55, 17

Solomon, P. M., Rivolo, A. R., Barrett, J., & Yahil, A. 1987, ApJ, 319, 730

Thornley, M. D., & Wilson, C. D. 1995, ApJ, 447, 616

Toomre, A. 1964, ApJ, 139, 1217

Tsutsumi, T., Morita, K.-I., & Umeyama, S. 1997, in Astronomical Data Analysis Software and Systems VI, ed. G. Hunt, & H. E. Payne (San Francisco: ASP), ASP Conf. Ser., 125, 50

Tully, R. B., & Shaya, E. J. 1984, ApJ, 281, 31

Wada, K., & Habe, A. 1992, MNRAS, 258, 82

Wilson, C. D. 1995, ApJ, 448, 97

Wong, T., & Blitz, L. 2002, ApJ, 569, 157

Young, J. S., & Scoville, N. Z. 1991, ARA&A, 29, 581